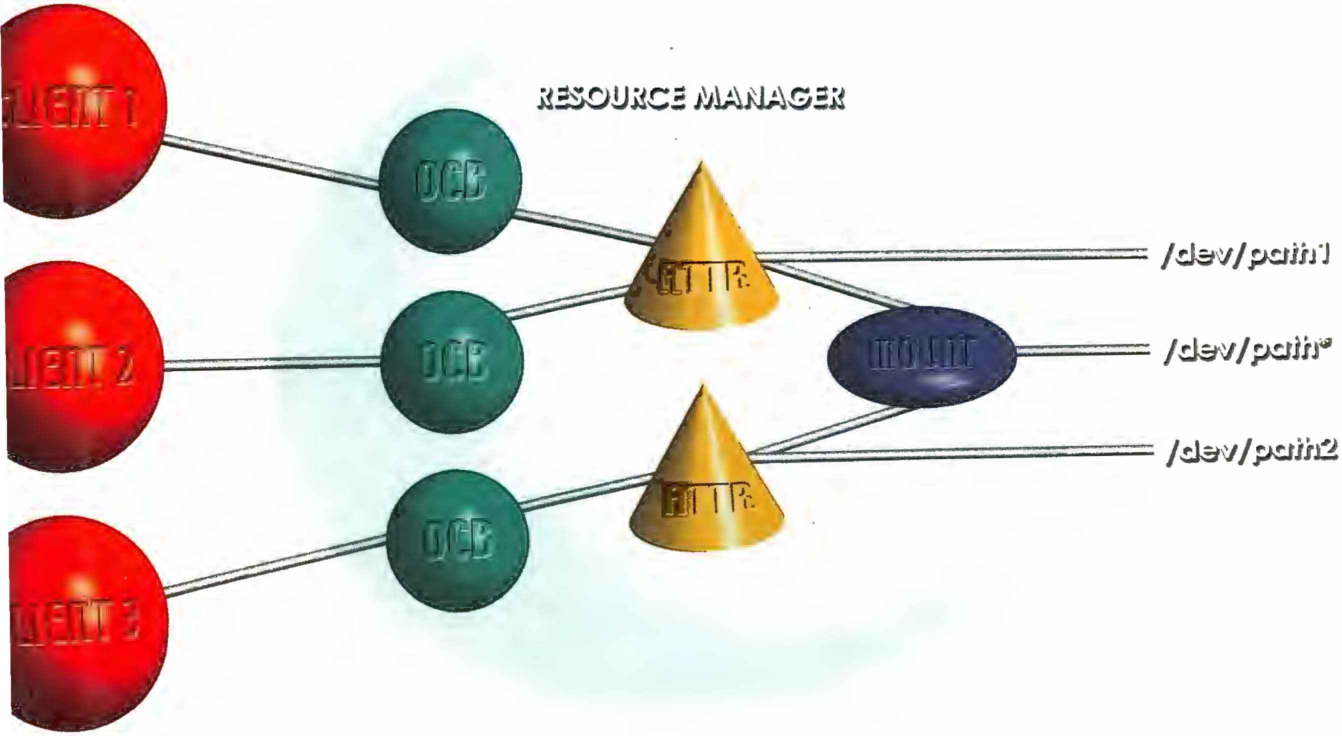
GETTING STARTED

with

QNX® Neutrino® 2

A Guide for Realtime Programmers

by Rob Krten



Getting Started with QNX Neutrino 2

A Guide for Realtime Programmers

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Foreword

Foreword

When I found myself staring at the first draft of this book I started thinking that it was going to be a difficult read because I'd spent so many years intimately involved with the design and development of QNX Neutrino. But I was wrong! I found this book easy to read and very enjoyable because of the way Rob combines the QNX philosophy ("Why things are the way they are") with good habits applicable to any realtime programming project. This book is suitable for people who've never seen Neutrino before, or those who've used it extensively.

For people who've never used Neutrino, the book gives an excellent tutorial on how to use it. Since Rob himself comes from a QNX 2 and QNX 4 background, his book is also great for people who've used a QNX operating system before, because they share a common ground.

As for myself, I was first introduced to QNX at an insurance company in the mid-1980s. This insurance company primarily used an IBM mainframe, but they wanted to shorten the time required to calculate quotes on corporate insurance. To do this they used networks of 8MHz 80286 ATs running QNX 2. They distributed their data using QNX native networking, allowing access to all customer data files from any QNX machine. This system was well-designed using the QNX client/server philosophy and I was hooked on QNX.

When I joined QSSL at the start of 1991, QNX 4 had just been released. QNX 4 was developed to conform to the just-approved POSIX 1003.1 specification which would make it easier to port public domain UNIX code than it was with QNX 2, and it would conform to a genuine standard. In a few years we started thinking about the next-generation operating system. The current group of less than 15 developers started meeting to discuss anything we'd like to do differently and things that we'd need in the future. We wanted to support the newer POSIX specifications and make it easier to write drivers. We also didn't want to lock ourselves to the x86 processor or "fix" anything that wasn't broken. The ideas that Dan Dodge and

Gordon Bell started out with when they created QNX are still in Neutrino today -- ideas like message-passing, having a small, lean kernel, providing fast, realtime response, etc. Complicating the design was the goal of Neutrino being even more modular than QNX 4 (for example, we wanted to provide a fully-functional kernel that you could link against, allowing for more deeply embedded systems than QNX 4). In 1994 Dan Dodge and I started working on the updated kernel and process manager.

As those of you who've been using QNX products for a long time already know, writing device drivers for QNX 2 was a hair-raising experience. You had to be *very* careful! In fact, most developers started with the QSSL-supplied source for the spool device and carefully tweaked it to do whatever they wanted. Only a few people tried writing disk drivers, as this required specialized assembly language stubs. Because of this, almost nobody ended up writing drivers for QNX 2. In QNX 4, writing drivers was made *much* easier by making all I/O operations go through a standard, well-defined, message-passing interface. When you did an *open()*, the server received an open message. When you did a *read()*, the server received a read message. QNX 4 capitalized on the message passing theme by using it to decouple clients from servers. I remember when I first saw the beta version 3.99 (a QNX 4 pre-release version) and thinking, "Wow! This is elegant!" In fact, I was so enamored with this, that I immediately wrote a QNX 2 read-only filesystem using the new message-passing interface; it was easy now!

For Neutrino, the process manager was being designed with three main separate functions: pathname space management, process creation (attributes, destruction, etc.), and memory space management. It also included several sub-services (**/dev/null**, **/dev/zero**, image filesystem, etc.). Each of these acted independently, but all shared the common code for processing the messages. This common code was very useful, so we decided to take all the common code and make a cover library for it. The "Resource Manager" library (or, as Rob likes to pronounce it, to my utter dismay, *rez-mugger* `:-)`) was born.

We also found that most resource managers wanted to provide POSIX semantics for their devices or filesystems, so we wrote another layer on top of the resource manager layer called the *iofunc*()* functions. This lets anybody write a resource manager, and have it automatically inherit POSIX functionality, without any additional work. At about this time Rob was writing the Neutrino courses, and he wanted to write a completely minimal resource manager example, `/dev/null`. His main slide was, "All you have to do is provide *read()* and *write()* message handlers, and you have a complete `/dev/null`!" I took that as a personal challenge, and removed even that requirement — the resource manager library now implements `/dev/null` in about half a dozen function calls. Since this library is shipped with Neutrino, everyone can write fully POSIX-compatible device drivers with minimal effort.

While the resource manager concept was significant in the evolution of Neutrino, and would indeed provide a solid base for the operating system, the fledgling OS needed more. Filesystems, connectivity (such as TCP/IP) and common devices (serial, console) were all being developed in parallel. After a lot of work, with lots of long hours, Neutrino 1.00 was released in early 1996. Over the next few years, more and more R&D staff were working on Neutrino. We've added SMP support, multiplatform support (x86, PowerPC and MIPS currently, with more to come), and the dispatch interface (that allows combining resource managers and other IPC methods), all covered in this book.

In August of 1999, we released QNX Neutrino 2.00; just in time for Rob's book! `:-)`

I think this book will be a "must have" for anyone who is writing programs for Neutrino.

Peter van der Veen
On a plane somewhere between Ottawa and San Jose
September 1999

Preface

Preface

A few years after I started using computers, the very first IBM PC came out. I must have been one of the first people in Ottawa to buy this box, with 16kB of RAM and no video card, because the salesman wasn't experienced enough to point out that the machine would be totally useless without the video card! Although the box wasn't useful, it did say "IBM" on it (at the time reserved solely for mainframes and the like), so it was impressive on its own. When I finally had enough money to buy the video card, I was able to run BASIC on my parents' TV. To me, this was the height of technology — especially with a 300 baud accoustically coupled modem! So, you can imagine my chagrin, when my friend Paul Trunley called me up and said, "Hey, log in to my computer!" I thought to myself, "Where did *he* get a VAX from?" since that was the only conceivable machine I knew about that would fit in his parents' house and let you "log in" to. So I called it up. It was a PC running an obscure operating system called "QUNIX," with a revision number less than 1.00. It let me "log in." I was hooked!

What has always struck me about the QNX family of operating systems is the small memory footprint, the efficiency, and the sheer elegance of the implementation. I would often entertain (or bore, more likely) dinner guests with stories about all the programs running concurrently on my machine in the basement, as we ate. Those who were knowledgeable about computers would speculate about how huge the disk must be, how I must have near infinite memory, etc. After dinner, I'd drag them downstairs and show them a simple PC with (at the time) 8 MB of RAM and a 70 MB hard disk. This would sometimes impress them. Those who where not impressed would then be shown how much RAM and disk space was still *available*, and how most of the used disk space was just data I had accumulated over the years.

As time passed, I've had the privilege of working at a number of companies, most of which were involved with some form of QNX development; (from telecoms, to process control, to frame grabber drivers, ...), with the single most striking characteristic being the simplicity of the designs and implementation. In my opinion, this is due to the key engineers on the projects having a good understanding of the QNX operating system — if you have a clean, elegant architecture to base your designs on, chances are that your designs will also end up being clean and elegant (unless the problem is *really* ugly).

In November, 1995, I had the good fortune to work directly for QNX Software Systems Limited (QSSL), writing the training material for their two QNX Neutrino courses, and presenting them over the next three years.

It's these past 19 years or so that gave me the inspiration and courage to write the first book, *Getting Started with QNX 4 — A Guide for Realtime Programmers,* which was published in May, 1998. With this new book on QNX Neutrino, I hope to share some of the concepts and ideas I've learned, so that you can gain a good, solid understanding of how the QNX Neutrino OS works, and how you can use it to your advantage. Hopefully, as you read the book, light bulbs will turn on in your head, making you say "Aha! That's why they did it this way!"

A little history

QSSL, the company that created the QNX operating system, was founded in 1980 by Dan Dodge and Gordon Bell (both graduates of the University of Waterloo in Ontario, Canada). Initially, the company was called Quantum Software Systems Limited, and the product was called "QUNIX" ("Quantum UNIX"). After a polite letter from AT&T's lawyers (who owned the "UNIX" trademark at the time), the product's name changed to "QNX." Some time after that, the company's name itself changed to "QNX Software Systems Limited" — in those days, everyone and their dog seemed to have a company called "Quantum" something or other.

The first commercially successful product was simply called "QNX" and ran on 8088 processors. Then, "QNX 2" (QNX version 2) came out in the early 1980s. It's still running in many mission-critical systems to this day. Around 1991, a new operating system, "QNX 4," was introduced, with enhanced 32-bit operations and POSIX support.

In 1995, the latest member of the QNX family, QNX Neutrino, was introduced. On September 26th, 2000, the QNX Realtime Platform (consisting of the QNX Neutrino operating system, Photon windowing system, development tools and compilers, etc.) was released for free for noncommercial purposes. As of this second printing (July 2001) there have been over 1 million downloads! (Go to `http://get.qnx.com/` to get your free copy.)

Who this book is for

This book is suitable for anyone wishing to gain a good fundamental understanding of the key features of the QNX Neutrino OS and how it works. Readers with a modest computer background should still get a lot out of the book (although the discussion in each chapter gets more and more technical as the chapter progresses). Even diehard hackers should find some interesting twists, especially with the two fundamental features of QNX Neutrino, the message-passing nature of the operating system and the way device drivers are structured.

I've tried to explain things in an easy-to-read "conversational" style, anticipating some of the common questions that come up and answering them with examples and diagrams. Because a complete understanding of the C language isn't required, but is definitely an asset, there are quite a few code samples sprinkled throughout.

What's in this book?

This book introduces you to what the QNX Neutrino operating system is and how it functions. It contains chapters covering process states, threads, scheduling algorithms, message passing, operating system modularity, and so on. If you've never used QNX Neutrino before, but are familiar with realtime operating systems, then you'll want to pay particular attention to the chapters on message passing and resource managers, since these are concepts fundamental to QNX Neutrino.

Processes and Threads

An introduction to processes and threads in QNX Neutrino, realtime, scheduling, and prioritization. You'll learn about scheduling states and QNX Neutrino's scheduling algorithms, as well as the functions you use to control scheduling, create processes and threads, and modify processes and threads that are already running. You'll see how QNX Neutrino implements SMP (Symmetrical Multi-Processing), and the advantages (and pitfalls) that this brings.

"Scheduling and the real world" discusses how threads are scheduled on a running system, and what sorts of things can cause a running thread to be rescheduled.

Message Passing

An introduction to QNX Neutrino's most fundamental feature, message passing. You'll learn what message passing is, how to use it to communicate between threads, and how to pass messages over a network. Priority inversion, the bane of realtime systems everywhere, and other advanced topics are also covered here.

☞ This is one of the most important chapters in this book!

Clocks, Timers, and Getting a Kick Every So Often

Learn all about the system clock and timers, and how to get a timer to send you a message. Lots of practical information here, and code samples galore.

Interrupts

This chapter will teach you how to write interrupt handlers for QNX Neutrino, and how interrupt handlers affect thread scheduling.

Resource Managers

Learn all about QNX Neutrino resource managers (also known variously as "device drivers" and "I/O managers"). You'll need to read and understand the Message Passing chapter before you write your own resource managers. The source for several complete resource managers is included.

☞ Resource managers are another important aspect of every QNX Neutrino-based system.

QNX 4 to QNX Neutrino

This is an invaluable guide for anyone porting their QNX 4 application to QNX Neutrino, or having to maintain code on both platforms. (QNX 4 is QSSL's previous-generation operating system, also the subject of my previous book, *Getting Started with QNX 4*.) Even if you're designing a new application, there may be demand from your customer base to support it on *both* QNX 4 *and* QNX Neutrino — if that happens, this section will help you avoid common pitfalls and show you how to write code that's portable to both operating systems.

Calling 911

Where you can turn to when you get stuck, find a bug, or need help with your design.

Glossary

Contains definitions of the terms used throughout this book.

Index

You can probably guess what this is for...

Other references

In addition to the custom kernel interface, QNX Neutrino implements a wide range of industry standards. This lets you support your favorite publishers when looking for information about standard functions from ANSI, POSIX, TCP/IP, etc.

Online references

On the web:

`http://www.parse.com/`

The PARSE Software Devices web site; you can get this book's errata and examples from `http://www.parse.com/books/book_v3/index.html`. Also, check out our onsite training services and the free software section.

`http://www.qnx.com/`

QSSL's own web site; surf here for all the latest QNX Neutrino information.

`http://qdn.qnx.com`

The QNX Developer's Network (QDN) is QSSL's online, interactive technical support service. Provides a searchable knowledge base.

`http://www.qnxstart.com/`

The QNXStart web site; for the QNX developer community. You can find lots of discussion forums, tips, and source code here.

`http://search.yahoo.com/bin/search?p=QNX`

Search the Yahoo! Internet index for QNX-related topics.

For FTP:

`ftp.parse.com`

The PARSE Software Devices FTP site. You can download the source code examples from this book in a convenient archive found on this site.

`ftp.qnx.com`

Official QNX updates and a wide selection of third-party demos and ports.

On USENET:

`comp.os.qnx`

The QNX operating system newsgroup (a lot of QNX Neutrino discussion, as well as some QNX 4 and even QNX 2 discussions).

About PARSE Software Devices

PARSE Software Devices is an established research and development organization providing training, and contract/consulting services to the international R&D community. Our main capabilities are:

- training (course presentation and development)
- systems architecture, design, and programming services

Contact PARSE Software Devices at `info@parse.com` for information about our training and contract services.

Note that this book is available for OEM use, site licenses, and online use as well — contact `books@parse.com` for more information.

About Rob Krten

Rob Krten has been doing embedded systems work, mostly on contract, since 1986 and systems-level programming since 1981. During his three year contract at QSSL, he designed and presented QSSL's courses on "Realtime Programming under the Neutrino Kernel" and "Writing a Resource Manager." He also wrote the prototype version of QSSL's QNX Neutrino Native Networking Manager (`npm-qnet`) software, as well as a significant portion of QSSL's *Building Embedded Systems* book.

Both this book and his previous book, *Getting Started with QNX 4 — A Guide for Realtime Programmers,* have received a Society for

Technical Communications (STC; `http://www.stc.org/`) Award of Merit.

See Rob's online resume to see where he's been lately: `http://www.parse.com/~rk/rk_resume.html`

Rob has a wide variety of interests, from computer-generated music to graphics to virtual filesystems. He is also an *avid* PDP-series minicomputer collector; if you have any PDP-series minicomputer systems, parts, or documentation, please send him an email to `rk@parse.com`! You can check out his homepage at `http://www.parse.com/~rk/` to see what he's up to (this week `:-)`).

About Chris Herborth

After spending almost four years working in QSSL's technical publications group, Chris decided it was time to strike out on his own. Combining his skills in technical writing, editing, and programming, Arcane Dragon Software was born.

After deciding that he'd rather have a regular paycheck and benefits, Chris has moved on to become Texar Corporation's (`http://www.texar.com/`) Senior Technical Writer.

Chris is a BeOS Masters Award winner (one of two "Outstanding Contributions" awards ever given), and the winner of five Society for Technical Communications awards (four of Merit and one of Excellence). He's also served as technical editor for Rob Krten's *Getting Started with QNX 4* (PARSE), Scot Hacker's *The BeOS Bible* (Peachpit), and several books for Martin Brown: *BeOS: Porting UNIX Applications* (Morgan-Kauffman), *Python: Annotated Archives* (Osborne McGraw-Hill) and *Python: The Complete Reference* (Osborne McGraw-Hill).

Acknowledgments

This book would not have been possible without the help and support I received from the following people, who contributed numerous suggestions and comments: Luc Bazinet, James Chang, Dan Dodge, Dave Donohoe, Steven Dufresne, Thomas Fletcher, David Gibbs, Marie Godfrey, Bob Hubbard, Mike Hunter, Pradeep Kathail, Steve Marsh, Danny N. Prairie, and Andrew Vernon. (Apologies in advance if I've missed anyone.)

I'd like to particularly thank Brian Stecher, who patiently reviewed at least three complete drafts of this book in detail, and Peter van der Veen, who spent many nights at my place (granted, I *did* bribe him with beer and pizza), giving me insight into the detailed operations of QNX Neutrino's resource managers.

Thanks to Kim Fraser for once again providing the cover artwork.

Additionally, my thanks goes out to John Ostrander for his excellent grammatical suggestions and detailed proof-reading of of the book `:-)`

And of course, a special thank-you goes to my editor, Chris Herborth, for finding the time to edit this book, help out with the sometimes obscure SGML/LaTeX tools, etc., all while doing dozens of other things at the same time! *[I told you to remind me not to do that again! – chrish]*

I'd also like to gratefully acknowledge the patience and understanding of my wife, Christine, for putting up with me while I crawled off into the basement and ignored her for hours on end!

Typographical conventions

Throughout this book, we use certain typographical conventions to distinguish technical terms. In general, the conventions we use conform to those found in IEEE POSIX publications. The following table summarizes our conventions.

Reference	Example
Code examples	`if( stream == NULL )`
Command options	`-lR`
Commands	`make`
Environment variables	**PATH**
File and pathnames	`/dev/null`
Function names	*exit()*
Keyboard chords	Ctrl – Alt – Delete
Keyboard input	`something you type`
Keyboard keys	Enter
Program output	`login:`
Programming constants	NULL
Programming data types	`unsigned short`
Programming literals	`0xFF`, `"message string"`
Variable names	*stdin*

☞ Notes point out something important or useful.

Chapter 1

Processes and Threads

In this chapter...

Process and thread fundamentals

Before we start talking about threads, processes, time slices, and all the other wonderful "scheduling concepts," let's establish an analogy.

What I want to do first is illustrate *how* threads and processes work. The best way I can think of (short of digging into the design of a realtime system) is to imagine our threads and processes in some kind of situation.

A process as a house

Let's base our analogy for processes and threads using a regular, everyday object — a house.

A house is really a container, with certain attributes (such as the amount of floor space, the number of bedrooms, and so on).

If you look at it that way, the house really doesn't actively *do* anything on its own — it's a passive object. This is effectively what a process is. We'll explore this shortly.

The occupants as threads

The people living in the house are the *active* objects — they're the ones using the various rooms, watching TV, cooking, taking showers, and so on. We'll soon see that's how threads behave.

Single threaded

If you've ever lived on your own, then you know what this is like — you *know* that you can do *anything* you want in the house at *any* time, because there's nobody else in the house. If you want to turn on the stereo, use the washroom, have dinner — whatever — you just go ahead and do it.

Multi threaded

Things change dramatically when you add another person into the house. Let's say you get married, so now you have a spouse living there too. You can't just march into the washroom at any given point; you need to check first to make sure your spouse isn't in there!

If you have two responsible adults living in a house, generally you can be reasonably lax about "security" — you know that the other adult will respect your space, won't try to set the kitchen on fire (deliberately!), and so on.

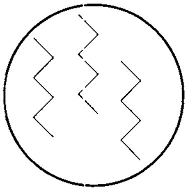
Now, throw a few kids into the mix and suddenly things get a lot more interesting.

Back to processes and threads

Just as a house occupies an area of real estate, a process occupies memory. And just as a house's occupants are free to go into any room they want, a processes' threads all have common access to that memory. If a thread allocates something (mom goes out and buys a game), all the other threads immediately have access to it (because it's present in the common address space — it's in the house). Likewise, if the process allocates memory, this new memory is available to all the threads as well. The trick here is to recognize whether the memory *should* be available to all the threads in the process. If it is, then you'll need to have all the threads synchronize their access to it. If it isn't, then we'll assume that it's specific to a particular thread. In that case, since only *that* thread has access to it, we can assume that no synchronization is required — the thread isn't going to trip itself up!

As we know from everyday life, things aren't quite that simple. Now that we've seen the basic characteristics (summary: everything is shared), let's take a look at where things get a little more interesting, and why.

The diagram below shows the way that we'll be representing threads and processes. The process is the circle, representing the "container" concept (the address space), and the three squigley lines are the threads. You'll see diagrams like this throughout the book.



A process as a container of threads.

Mutual exclusion

If you want to take a shower, and there's someone already using the bathroom, you'll have to wait. How does a thread handle this?

It's done with something called *mutual exclusion*. It means pretty much what you think — a number of threads are mutually exclusive when it comes to a particular resource.

If you're taking a shower, you want to have *exclusive access* to the bathroom. To do this, you would typically go into the bathroom and lock the door from the inside. Anyone else trying to use the bathroom would get stopped by the lock. When you're done, you'd unlock the door, allowing someone else access.

This is just what a thread does. A thread uses an object called a *mutex* (an acronym for *MUT*ual *EX*clusion). This object is like the lock on a door — once a thread has the mutex locked, no other thread can get the mutex, until the owning thread releases (unlocks) it. Just like the door lock, threads waiting to obtain the mutex will be barred.

Another interesting parallel that occurs with mutexes and door locks is that the mutex is really an "advisory" lock. If a thread doesn't obey the *convention* of using the mutex, then the protection is useless. In our house analogy, this would be like someone breaking into the washroom through one of the walls ignoring the convention of the door and lock.

Priorities

What if the bathroom is currently locked and a number of people are waiting to use it? Obviously, all the people are sitting around outside, waiting for whoever is in the bathroom to get out. The real question is, "What happens when the door unlocks? Who gets to go next?"

You'd figure that it would be "fair" to allow whoever is waiting the longest to go next. Or it might be "fair" to let whoever is the oldest go next. Or tallest. Or most important. There are any number of ways to determine what's "fair."

We solve this with threads via two factors: priority and length of wait.

Suppose two people show up at the (locked) bathroom door at the same time. One of them has a pressing deadline (they're already late for a meeting) whereas the other doesn't. Wouldn't it make sense to allow the person with the pressing deadline to go next? Well, of course it would. The only question is how you decide who's more "important." This can be done by assigning a *priority* (let's just use a number like Neutrino does — one is the lowest usable priority, and 63 is the highest as of this version). The people in the house that have pressing deadlines would be given a *higher priority*, and those that don't would be given a *lower priority*.

Same thing with threads. If a number of threads are waiting, and the mutex becomes unlocked, we would give the mutex to the waiting thread with the highest priority. Suppose, however, that both people have the *same* priority. Now what do you do? Well, in that case, it would be "fair" to allow the person who's been waiting the longest to go next. This is not only "fair," but it's also what the Neutrino kernel does. In the case of a bunch of threads waiting, we go *primarily* by priority, and *secondarily* by length of wait.

The mutex is certainly not the only *synchronization* object that we'll encounter. Let's look at some others.

Semaphores

Let's move from the bathroom into the kitchen, since that's a socially acceptable location to have more than one person at the same time. In the kitchen, you may not want to have *everyone* in there at once. In fact, you probably want to limit the number of people you can have in the kitchen (too many cooks, and all that).

Let's say you don't ever want to have more than two people in there simultaneously. Could you do it with a mutex? Not as we've defined it. Why not? This is actually a very interesting problem for our analogy. Let's break it down into a few steps.

A semaphore with a count of 1

The bathroom can have one of two situations, with two states that go hand-in-hand with each other:

- the door is unlocked and nobody is in the room
- the door is locked and one person is in the room

No other combination is possible — the door can't be locked with nobody in the room (how would we unlock it?), and the door can't be unlocked with someone in the room (how would they ensure their privacy?). This is an example of a semaphore with a count of one — there can be at most only one person in that room, or one thread using the semaphore.

The key here (pardon the pun) is the way we characterize the lock. In your typical bathroom lock, you can lock and unlock it only from the inside — there's no outside-accessible key. Effectively, this means that ownership of the mutex is an *atomic* operation — there's *no chance* that while you're in the process of getting the mutex some other thread will get it, with the result that you *both* own the mutex. In our house analogy this is less apparent, because humans are just so much smarter than ones and zeros.

What we need for the kitchen is a different type of lock.

A semaphore with a count greater than 1

Suppose we installed the traditional key-based lock in the kitchen. The way this lock works is that if you have a key, you can unlock the door and go in. Anyone who uses this lock agrees that when they get inside, they will immediately lock the door from the inside so that anyone on the outside will always require a key.

Well, now it becomes a simple matter to control how many people we want in the kitchen — hang two keys outside the door! The kitchen is always locked. When someone wants to go into the kitchen, they see if there's a key hanging outside the door. If so, they take it with them, unlock the kitchen door, go inside, and use the key to lock the door.

Since the person going into the kitchen must have the key with them when they're in the kitchen, we're directly controlling the number of people allowed into the kitchen at any given point by limiting the number of keys available on the hook outside the door.

With threads, this is accomplished via a *semaphore.* A "plain" semaphore works just like a mutex — you either own the mutex, in which case you have access to the resource, or you don't, in which case you don't have access. The semaphore we just described with the kitchen is a *counting semaphore* — it keeps track of the count (by the number of keys available to the threads).

A semaphore as a mutex

We just asked the question "Could you do it with a mutex?" in relation to implementing a lock with a count, and the answer was no. How about the other way around? Could we use a semaphore as a mutex?

Yes. In fact, in some operating systems, that's exactly what they do — they don't have mutexes, only semaphores! So why bother with mutexes at all?

To answer that question, look at *your* washroom. How did the builder of your house implement the "mutex"? I suspect you don't have a key hanging on the wall!

Mutexes are a "special purpose" semaphore. If you want one thread running in a particular section of code, a mutex is by far the most efficient implementation.

Later on, we'll look at other synchronization schemes — things called condvars, barriers, and sleepons.

☞ Just so there's no confusion, realize that a mutex has other properties, such as priority inheritence, that differentiate it from a semaphore.

The kernel's role

The house analogy is excellent for getting across the concept of synchronization, but it falls down in one major area. In our house, we had many threads running *simultaneously*. However, in a real live system, there's typically only one CPU, so only one "thing" can run at once.

Single CPU

Let's look at what happens in the real world, and specifically, the "economy" case where we have one CPU in the system. In this case, since there's only one CPU present, only one thread can run at any given point in time. The kernel decides (using a number of rules, which we'll see shortly) which thread to run, and runs it.

Multiple CPU (SMP)

If you buy a system that has multiple, identical CPUs all sharing memory and devices, you have an *SMP box* (SMP stands for *S*ymmetrical *M*ulti *P*rocessor, with the "symmetrical" part indicating that all the CPUs in the system are identical). In this case, the number of threads that can run concurrently (simultaneously) is limited by the number of CPUs. (In reality, this was the case with the single-processor box too!) Since each processor can execute only one thread at a time, with multiple processors, multiple threads can execute simultaneously.

Let's ignore the number of CPUs present for now — a useful abstraction is to design the system as if multiple threads really were running simultaneously, even if that's not the case. A little later on, in the "Things to watch out for when using SMP" section, we'll see some of the non-intuitive impacts of SMP.

The kernel as arbiter

So who decides which thread is going to run at any given instant in time? That's the kernel's job.

The kernel determines which thread should be using the CPU at a particular moment, and *switches context* to that thread. Let's examine what the kernel does with the CPU.

The CPU has a number of registers (the exact number depends on the processor family, e.g., x86 versus MIPS, and the specific family member, e.g., 80486 versus Pentium). When the thread is running, information is stored in those registers (e.g., the current program location).

When the kernel decides that another thread should run, it needs to:

1. save the currently running thread's registers and other context information
2. load the new thread's registers and context into the CPU

But how does the kernel decide that another thread should run? It looks at whether or not a particular thread is capable of using the CPU at this point. When we talked about mutexes, for example, we introduced a blocking state (this occurred when one thread owned the mutex, and another thread wanted to acquire it as well; the second thread would be blocked).

From the kernel's perspective, therefore, we have one thread that *can* consume CPU, and one that *can't*, because it's blocked, waiting for a mutex. In this case, the kernel lets the thread that can run consume CPU, and puts the other thread into an internal list (so that the kernel can track its request for the mutex).

Obviously, that's not a very interesting situation. Suppose that a number of threads *can* use the CPU. Remember that we delegated access to the mutex based on priority and length of wait? The kernel uses a similar scheme to determine which thread is going to run next. There are two factors: priority and scheduling algorithm, evaluated in that order.

Prioritization

Consider two threads capable of using the CPU. If these threads have different priorities, then the answer is really quite simple — the kernel gives the CPU to the highest priority thread. Neutrino's priorities go from one (the lowest usable) and up, as we mentioned when we talked about obtaining mutexes. Note that priority zero is reserved for the idle thread, — you can't use it. (If you want to know the minimum and maximum values for your system, use the functions *sched_get_priority_min()* and *sched_get_priority_max()* — they're prototyped in `<sched.h>`. In this book, we'll assume one as the lowest usable, and 63 as the highest.)

If another thread with a higher priority suddenly becomes able to use the CPU, the kernel will immediately context-switch to the higher priority thread. We call this *preemption* — the higher-priority thread preempted the lower-priority thread. When the higher-priority thread is done, and the kernel context-switches back to the lower-priority thread that was running before, we call this *resumption* — the kernel resumes running the previous thread.

Now, suppose that two threads are capable of using the CPU and have the exact same priority.

Scheduling algorithms

Let's assume that one of the threads is currently using the CPU. We'll examine the rules that the kernel uses to decide when to context-switch in this case. (Of course, this entire discussion really applies only to threads at the same priority — the *instant* that a higher-priority thread is ready to use the CPU it gets it; that's the whole point of having priorities in a realtime operating system.)

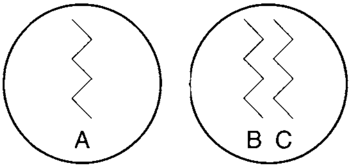
There are two *scheduling algorithms* (policies) that the Neutrino kernel understands: Round Robin (or just "RR") and FIFO (First-In, First-Out).

FIFO

In the FIFO scheduling algorithm, a thread is allowed to consume CPU for as long as it wants. This means that if that thread is doing a very long mathematical calculation, and no other thread of a higher priority is ready, that thread could potentially run *forever.* What about threads of the same priority? They're locked out as well. (It should be obvious at this point that threads of a lower priority are locked out too.)

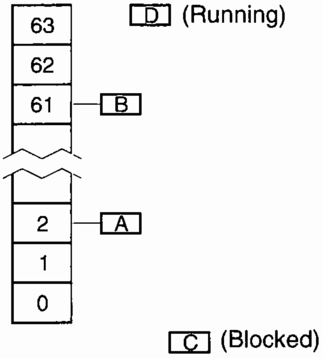
If the running thread quits or voluntarily gives up the CPU, *then* the kernel looks for other threads at the same priority that are capable of using the CPU. If there are no such threads, *then* the kernel looks for lower-priority threads capable of using the CPU. Note that the term "voluntarily gives up the CPU" can mean one of two things. If the thread goes to sleep, or blocks on a semaphore, etc., then yes, a lower-priority thread could run (as described above). But there's also a "special" call, *sched_yield()* (based on the kernel call *SchedYield()*), which gives up CPU *only* to another thread of the same priority — a lower-priority thread would never be given a chance to run if a higher-priority was ready to run. If a thread does in fact call *sched_yield()*, and no other thread at the same priority is ready to run, the original thread continues running. Effectively, *sched_yield()* is used to give another thread of the *same priority* a crack at the CPU.

In the diagram below, we see three threads operating in two different processes:



Three threads in two different processes.

If we assume that threads "A" and "B" are READY, and that thread "C" is blocked (perhaps waiting for a mutex), and that thread "D" (not shown) is currently executing, then this is what a portion of the READY queue that the Neutrino kernel maintains will look like:



Two threads on the READY queue, one blocked, one running.

This shows the kernel's internal READY queue, which the kernel uses to decide who to schedule next. Note that thread "C" is not on the READY queue, because it's blocked, and thread "D" isn't on the READY queue either because it's running.

Round Robin

The RR scheduling algorithm is identical to FIFO, *except* that the thread will not run forever *if* there's another thread at the same priority. It runs only for a predefined *timeslice* (which is fixed and cannot be changed; you can determine its value by using the function *sched_rr_get_interval()*).

What happens is that the kernel starts an RR thread, and notes the time. If the RR thread is running for a while, the time allotted to it will be up (the timeslice will have expired). The kernel looks to see if there is another thread at the same priority that's ready. If there is, the kernel runs it. If not, then the kernel will continue running the RR thread (i.e., the kernel grants the thread another timeslice).

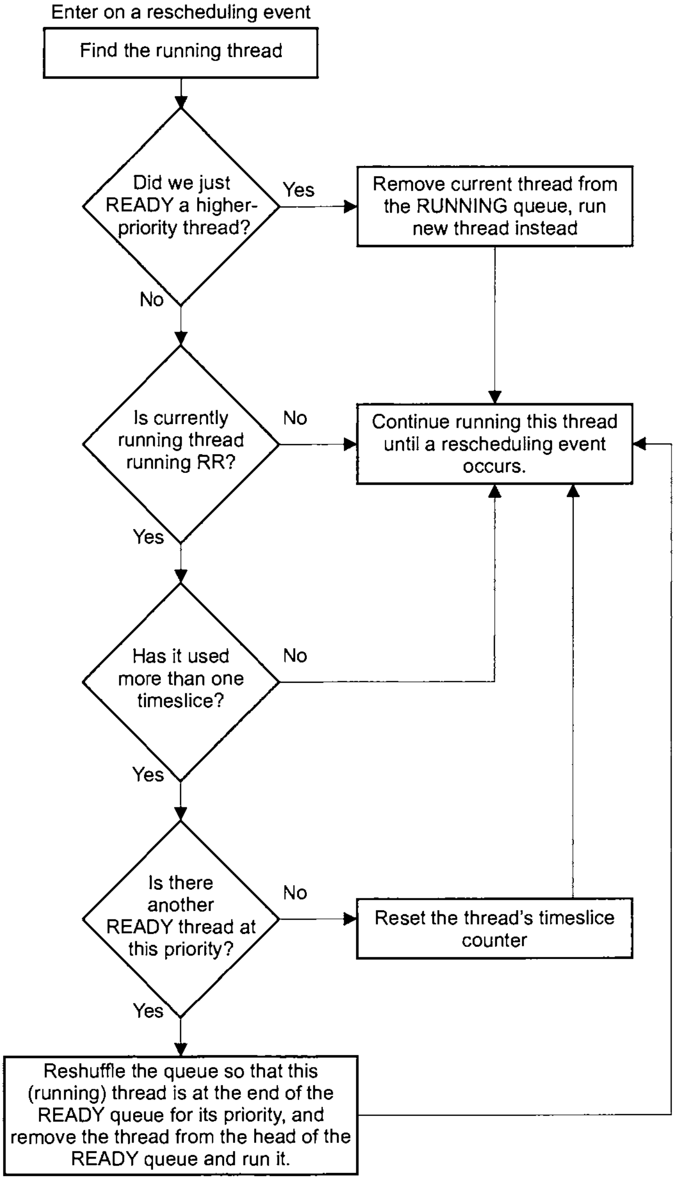
The rules

Let's summarize the scheduling rules (for a single CPU), in order of importance:

- Only one thread can run at a time.
- The highest-priority ready thread will run.

- A thread will run until it blocks or exits.
- An RR thread will run for its timeslice, and then the kernel will reschedule it (if required).

The following flowchart shows the decisions that the kernel makes:


Enter on a rescheduling event
Find the running thread
Did we just READY a higher-priority thread?
Yes
Remove current thread from the RUNNING queue, run new thread instead
No
Is currently running thread running RR?
No
Continue running this thread until a rescheduling event occurs.
Yes
Has it used more than one timeslice?
No
Yes
Is there another READY thread at this priority?
No
Reset the thread's timeslice counter
Yes
Reshuffle the queue so that this (running) thread is at the end of the READY queue for its priority, and remove the thread from the head of the READY queue and run it.

Scheduling roadmap.

For a multiple CPU system, the rules are the same, except that multiple CPUs can run multiple threads concurrently. The order that the threads run (i.e., which threads get to run on the multiple CPUs) is determined in the exact same way as with a single CPU — the highest-priority READY thread will run on a CPU. If there's another high-priority thread that's ready to run, and there's an available CPU, that thread will run on the next CPU. And so on. If there aren't enough threads to go around, that's no problem — the "idle" CPUs will run the idle thread (at priority zero, which is lower than any user thread can go). If there aren't enough CPUs to go around, then only the *N*-most highest-priority threads will run, where *N* is the number of CPUs available. The other threads will be ready to run, but won't actually be running. Note that thread scheduling on an SMP system is an area that's still undergoing some research, so it's possible that it may change in the future.

Kernel states

We've been talking about "running," "ready," and "blocked" loosely — let's now formalize these thread states.

RUNNING

Neutrino's RUNNING state simply means that the thread is now actively consuming the CPU. On an SMP system, there will be multiple threads running; on a single-processor system, there will be one thread running.

READY

The READY state means that this thread *could* run right now — except that it's not, because another thread, (at the same or higher priority), is running. If two threads were capable of using the CPU, one thread at priority 10 and one thread at priority 7, the priority 10 thread would be RUNNING and the priority 7 thread would be READY.

The blocked states

What do we call the blocked state? The problem is, there's not just *one* blocked state. Under Neutrino, there are in fact over a dozen blocking states.

Why so many? Because the kernel keeps track of *why* a thread is blocked.

We saw two blocking states already — when a thread is blocked waiting for a mutex, the thread is in the MUTEX state. When a thread is blocked waiting for a semaphore, it's in the SEM state. These states simply indicate which queue (and which resource) the thread is blocked on.

If a number of threads are blocked on a mutex (in the MUTEX blocked state), they get no attention from the kernel *until* the thread that owns the mutex releases it. At that point one of the blocked threads is made READY, and the kernel makes a rescheduling decision (if required).

Why "if required?" The thread that just released the mutex could very well still have other things to do *and* have a higher priority than that of the waiting threads. In this case, we go to the second rule, which states, "The highest-priority ready thread will run," meaning that the scheduling order has not changed — the higher-priority thread continues to run.

Kernel states, the complete list

Here's the complete list of kernel blocking states, with brief explanations of each state. By the way, this list is available in `<sys/neutrino.h>` — you'll notice that the states are all prefixed with STATE_ (for example, "READY" in this table is listed in the header file as STATE_READY):

If the state is:	The thread is:
CONDVAR	Waiting for a condition variable to be signalled.
DEAD	Dead. Kernel is waiting to release the thread's resources.
INTR	Waiting for an interrupt.
JOIN	Waiting for the completion of another thread.
MUTEX	Waiting to acquire a mutex.

continued...

If the state is:	The thread is:
NANOSLEEP	Sleeping for a period of time.
NET_REPLY	Waiting for a reply to be delivered across the network.
NET_SEND	Waiting for a pulse or message to be delivered across the network.
READY	Not running on a CPU, but is ready to run (one or more higher or equal priority threads are running).
RECEIVE	Waiting for a client to send a message.
REPLY	Waiting for a server to reply to a message.
RUNNING	Actively running on a CPU.
SEM	Waiting to acquire a semaphore.
SEND	Waiting for a server to receive a message.
SIGSUSPEND	Waiting for a signal.
SIGWAITINFO	Waiting for a signal.
STACK	Waiting for more stack to be allocated.
STOPPED	Suspended (SIGSTOP signal).
WAITCTX	Waiting for a register context (usually floating point) to become available (only on SMP systems).
WAITPAGE	Waiting for process manager to resolve a fault on a page.
WAITTHREAD	Waiting for a thread to be created.

The important thing to keep in mind is that when a thread is blocked, regardless of *which* state it's blocked in, it consumes *no* CPU. Conversely, the only state in which a thread consumes CPU is in the RUNNING state.

We'll see the SEND, RECEIVE, and REPLY blocked states in the Message Passing chapter. The NANOSLEEP state is used with functions like *sleep()*, which we'll look at in the chapter on Clocks, Timers, and Getting a Kick Every So Often. The INTR state is used with *InterruptWait()*, which we'll take a look at in the Interrupts chapter. Most of the other states are discussed in this chapter.

Threads and processes

Let's return to our discussion of threads and processes, this time from the perspective of a real live system. Then, we'll take a look at the function calls used to deal with threads and processes.

We know that a process can have one or more threads. (A process that had zero threads wouldn't be able to *do* anything — there'd be nobody home, so to speak, to actually perform any useful work.) A Neutrino system can have one or more processes. (The same discussion applies — a Neutrino system with zero processes wouldn't do anything.)

So what do these processes and threads do? Ultimately, they form a *system* — a collection of threads and processes that performs some goal.

At the highest level, the system consists of a number of processes. Each process is responsible for providing a service of some nature — whether it's a filesystem, a display driver, data acquisition module, control module, or whatever.

Within each process, there may be a number of threads. The number of threads varies. One designer using only one thread may accomplish the same functionality as another designer using five threads. Some problems lend themselves to being multi-threaded, and are in fact relatively simple to solve, while other processes lend themselves to being single-threaded, and are difficult to make multi-threaded.

The topic of designing with threads could easily occupy another book — we'll just stick with the basics here.

Why processes?

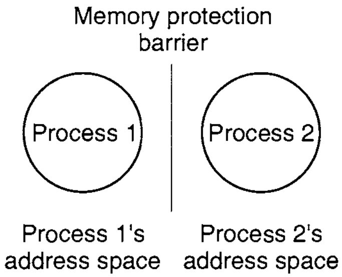
So why not just have one process with a zillion threads? While some OSes force you to code that way, the advantages of breaking things up into multiple processes are many:

- decoupling and modularity
- maintainability
- reliability

The ability to "break the problem apart" into several independent problems is a powerful concept. It's also at the heart of Neutrino. A Neutrino system consists of many independent modules, each with a certain responsibility. These independent modules are distinct processes. The people at QSSL used this trick to develop the modules in isolation, without the modules relying on each other. The only "reliance" the modules would have on each other is through a small number of well-defined interfaces.

This naturally leads to enhanced maintainability, thanks to the lack of interdependencies. Since each module has its own particular definition, it's reasonably easy to fix one module — especially since it's not tied to any other module.

Reliability, though, is perhaps the most important point. A process, just like a house, has some well-defined "borders." A person in a house has a pretty good idea when they're in the house, and when they're not. A thread has a *very* good idea — if it's accessing memory within the process, it can live. If it steps out of the bounds of the process's address space, it gets killed. This means that two threads, running in different processes, are effectively isolated from each other.


Memory protection barrier
Process 1
Process 2
Process 1's address space
Process 2's address space

Memory protection.

The *process address space* is maintained and enforced by Neutrino's process manager module. When a process is started, the process manager allocates some memory to it and starts a thread running. The memory is marked as being owned by that process.

This means that if there are multiple threads in that process, and the kernel needs to context-switch between them, it's a very efficient operation — we don't have to change the address space, just which thread is running. If, however, we have to change to another thread in another process, then the process manager gets involved and causes an address space switch as well. Don't worry — while there's a bit more overhead in this additional step, under Neutrino this is still very fast.

Starting a process

Let's now turn our attention to the function calls available to deal with threads and processes. Any thread can start a process; the only restrictions imposed are those that stem from basic security (file access, privilege restrictions, etc.). In all probability, you've already started other processes; either from the system startup script, the shell, or by having a program start another program on your behalf.

Starting a process from the command line

For example, from the shell you can type:

```
$ program1
```

This instructs the shell to start a program called **program1** and to wait for it to finish. Or, you could type:

```
$ program2 &
```

This instructs the shell to start `program2` *without* waiting for it to finish. We say that `program2` is running "in the background."

If you want to adjust the priority of a program before you start it, you could use the `nice` command, just like in UNIX:

```
$ nice program3
```

This instructs the shell to start `program3` at a reduced priority.

Or does it?

If you look at what really happens, we told the shell to run a program called `nice` at the regular priority. The `nice` command adjusted its *own* priority to be lower (this is where the name "nice" comes from), and then *it* ran `program3` at that lower priority.

Starting a process from within a program

You don't usually care about the fact that the shell creates processes — this is a basic assumption about the shell. In some application designs, you'll certainly be relying on *shell scripts* (batches of commands in a file) to do the work for you, but in other cases you'll want to create the processes yourself.

For example, in a large multi-process system, you may want to have one master program start all the other processes for your application based on some kind of configuration file. Another example would include starting up processes when certain operating conditions (events) have been detected.

Let's take a look at the functions that Neutrino provides for starting up other processes (or transforming into a different program):

- *system()*
- *exec()* family of functions
- *spawn()* family of functions

- *fork()*
- *vfork()*

Which function you use depends on two requirements: portability and functionality. As usual, there's a tradeoff between the two.

The common thing that happens in all the calls that create a new process is the following. A thread in the original process calls one of the above functions. Eventually, the function gets the process manager to create an address space for a new process. Then, the kernel starts a thread in the new process. This thread executes a few instructions, and calls *main()*. (In the case of *fork()* and *vfork()*, of course, the new thread begins execution in the new process by returning from the *fork()* or *vfork()*; we'll see how to deal with this shortly.)

Starting a process with the *system()* call

The *system()* function is the simplest; it takes a command line, the same as you'd type it at a shell prompt, and executes it.

In fact, *system()* actually starts up a shell to handle the command that you want to perform.

The editor that I'm using to write this book makes use of the *system()* call. When I'm editing, I may need to "shell out," check out some samples, and then come back into the editor, all without losing my place. In this editor, I may issue the command **:!pwd** for example, to display the current working directory. The editor runs this code for the **:!pwd** command:

```
system ("pwd");
```

Is *system()* suited for everything under the sun? Of course not, but it's useful for a lot of your process-creation requirements.

Starting a process with the *exec()* and *spawn()* calls

Let's look at some of the other process-creation functions.

The next process-creation functions we should look at are the *exec()* and *spawn()* families. Before we go into the details, let's see what the differences are between these two groups of functions.

The *exec()* family *transforms* the current process into another one. What I mean by that is that when a process issues an *exec()* function call, that process ceases to run the current program and begins to run another program. The process ID doesn't change — that process *changed* into another program. What happened to all the threads in the process? We'll come back to that when we look at *fork()*.

The *spawn()* family, on the other hand, doesn't do that. Calling a member of the *spawn()* family creates *another* process (with a new process ID) that corresponds to the program specified in the function's arguments.

Let's look at the different variants of the *spawn()* and *exec()* functions. In the table that follows, you'll see which ones are POSIX and which aren't. Of course, for maximum portability, you'll want to use only the POSIX functions.

Spawn	POSIX?	Exec	POSIX?
spawn()	Yes		
spawnl()	No	*execl()*	Yes
spawnle()	No	*execle()*	Yes
spawnlp()	No	*execlp()*	Yes
spawnlpe()	No	*execlpe()*	No
spawnp()	Yes		

continued...

Spawn	POSIX?	Exec	POSIX?
spawnv()	No	*execv()*	Yes
spawnve()	No	*execve()*	Yes
spawnvp()	No	*execvp()*	Yes
spawnvpe()	No	*execvpe()*	No

While these variants might appear to be overwhelming, there *is* a pattern to their suffixes:

A suffix of:	Means:
`l` (lowercase "L")	The argument list is specified via a list of parameters given in the call itself, terminated by a NULL argument.
`e`	An environment is specified.
`p`	The **PATH** environment variable is used in case the full pathname to the program isn't specified.
`v`	The argument list is specified via a pointer to an argument vector.

The argument list is a list of command-line arguments passed to the program.

Also, note that in the C library, the *spawnlp()*, *spawnvp()*, and *spawnlpe()* functions all call *spawnvpe()*, which in turn calls the POSIX function *spawnp()*. The functions *spawnle()*, *spawnv()*, and *spawnl()* all eventually call *spawnve()*, which then calls the POSIX function *spawn()*. Finally, the POSIX function *spawnp()* calls the POSIX function *spawn()*. So, the root of all spawning functionality is the *spawn()* call.

Let’s now take a look at the various *spawn()* and *exec()* variants in detail so that you can get a feel for the various suffixes used. Then, we’ll see the *spawn()* call itself.

“l” suffix

For example, if I want to invoke the **ls** command with the arguments **-t**, **-r**, and **-l** (meaning “sort the output by time, in reverse order, and show me the long version of the output”), I could specify it as either:

```
/* To run ls and keep going: */
spawnl (P_WAIT, "/bin/ls", "/bin/ls", "-t", "-r", "-l", NULL);

/* To transform into ls: */
execl ("/bin/ls", "/bin/ls", "-t", "-r", "-l", NULL);
```

or, using the **v** suffix variant:

```
char *argv [] =
{
    "/bin/ls",
    "-t",
    "-r",
    "-l",
    NULL
};

/* To run ls and keep going: */
spawnv (P_WAIT, "/bin/ls", argv);

/* To transform into ls: */
execv ("/bin/ls", argv);
```

Why the choice? It’s provided as a convenience. You may have a parser already built into your program, and it would be convenient to pass around arrays of strings. In that case, I’d recommend using the “**v**” suffix variants. Or, you may be coding up a call to a program where you know what the parameters are. In that case, why bother setting up an array of strings when you *know* exactly what the arguments are? Just pass them to the “**l**” suffix variant.

Note that we passed the actual pathname of the program (**/bin/ls**) *and* the name of the program *again* as the first argument. We passed the name again to support programs that behave differently based on how they're invoked.

For example, the GNU compression and decompression utilities (**gzip** and **gunzip**) are actually links to the same executable. When the executable starts, it looks at **argv [0]** (passed to *main()*) and decides whether it should compress or decompress.

"e" suffix

The "**e**" suffix versions pass an *environment* to the program. An environment is just that — a kind of "context" for the program to operate in. For example, you may have a spelling checker that has a dictionary of words. Instead of specifying the dictionary's location every time on the command line, you could provide it in the environment:

```
$ export DICTIONARY=/home/rk/.dict

$ spellcheck document.1
```

The **export** command tells the shell to create a new environment variable (in this case, **DICTIONARY**), and assign it a value (**/home/rk/.dict**).

If you ever wanted to use a different dictionary, you'd have to alter the environment before running the program. This is easy from the shell:

```
$ export DICTIONARY=/home/rk/.altdict

$ spellcheck document.1
```

But how can you do this from your own programs? To use the "**e**" versions of *spawn()* and *exec()*, you specify an array of strings representing the environment:

```
char *env [] =
{
    "DICTIONARY=/home/rk/.altdict",
    NULL
};

// To start the spell-checker:
spawnle (P_WAIT, "/usr/bin/spellcheck", "/usr/bin/spellcheck",
          "document.1", NULL, env);

// To transform into the spell-checker:
execle ("/usr/bin/spellcheck", "/usr/bin/spellcheck",
        "document.1", NULL, env);
```

"p" suffix

The "**p**" suffix versions will search the directories in your **PATH** environment variable to find the executable. You've probably noticed that all the examples have a hard-coded location for the executable — **/bin/ls** and **/usr/bin/spellcheck**. What about other executables? Unless you want to first find out the *exact* path for that particular program, it would be best to have the user tell your program all the places to search for executables. The standard **PATH** environment variable does just that. Here's the one from a minimal system:

```
PATH=/proc/boot:/bin
```

This tells the shell that when I type a command, it should first look in the directory **/proc/boot**, and if it can't find the command there, it should look in the binaries directory **/bin** part. **PATH** is a colon-separated list of places to look for commands. You can add as many elements to the **PATH** as you want, but keep in mind that all pathname components will be searched (in order) for the executable.

If you don't know the path to the executable, then you can use the "**p**" variants. For example:

```
// Using an explicit path:
execl ("/bin/ls", "/bin/ls", "-l", "-t", "-r", NULL);

// Search your PATH for the executable:
execlp ("ls", "ls", "-l", "-t", "-r", NULL);
```

If *execl()* can't find **ls** in **/bin**, it returns an error. The *execlp()* function will search all the directories specified in the **PATH** for **ls**, and will return an error only if it can't find **ls** in any of those directories. This is also great for multiplatform support — your program doesn't have to be coded to know about the different CPU names, it just finds the executable.

What if you do something like this?

```
execlp ("/bin/ls", "ls", "-l", "-t", "-r", NULL);
```

Does it search the environment? No. You told *execlp()* to use an *explicit* pathname, which overrides the normal **PATH** searching rule. If it doesn't find **ls** in **/bin** that's it, no other attempts are made (this is identical to the way *execl()* works in this case).

Is it dangerous to mix an explicit path with a plain command name (e.g., the path argument **/bin/ls**, and the command name argument **ls**, instead of **/bin/ls**)? This is usually pretty safe, because:

- a large number of programs ignore **argv [0]** anyway
- those that do care usually call *basename()*, which strips off the directory portion of **argv [0]** and returns just the name.

The only compelling reason for specifying the full pathname for the first argument is that the program can print out diagnostics including this first argument, which can instantly tell you where the program was invoked from. This may be important when the program can be found in multiple locations along the **PATH**.

The *spawn()* functions all have an extra parameter; in all the above examples, I've always specified P_WAIT. There are four flags you can pass to *spawn()* to change its behavior:

P_WAIT
: The calling process (your program) is blocked until the newly created program has run to completion and exited.

P_NOWAIT
: The calling program *doesn't* block while the newly created program runs. This allows you to start a program in the background, and continue running while the other program does its thing.

P_NOWAITO
: Identical to P_NOWAIT, except that the SPAWN_NOZOMBIE flag is set, meaning that you

don't have to worry about doing a *waitpid()* to clear the process's exit code.

P_OVERLAY

This flag turns the *spawn()* call into the corresponding *exec()* call! Your program transforms into the specified program, with no change in process ID.

It's generally clearer to use the *exec()* call if that's what you meant — it saves the maintainer of the software from having to look up P_OVERLAY in the *C Library Reference*!

"plain" spawn()

As we mentioned above, *all spawn()* functions eventually call the plain *spawn()* function. Here's the prototype for the *spawn()* function:

```
#include <spawn.h>

pid_t
spawn (const char *path,
       int fd_count,
       const int fd_map [],
       const struct inheritance *inherit,
       char * const argv [],
       char * const envp []);
```

We can immediately dispense with the *path*, *argv*, and *envp* parameters — we've already seen those above as representing the location of the executable (the *path* member), the argument vector (*argv*), and the environment (*envp*).

The *fd_count* and *fd_map* parameters go together. If you specify zero for *fd_count*, then *fd_map* is ignored, and it means that all file descriptors (except those modified by *fcntl()*'s FD_CLOEXEC flag) will be inherited in the newly created process. If the *fd_count* is non-zero, then it indicates the number of file descriptors contained in *fd_map*; only the specified ones will be inherited.

The *inherit* parameter is a pointer to a structure that contains a set of flags, signal masks, and so on. For more details, you should consult the C Library Reference.

Starting a process with the *fork()* call

Suppose you want to create a new process that's identical to the currently running process and have it run concurrently. You could approach this with a *spawn()* (and the P_NOWAIT parameter), giving the newly created process enough information about the exact state of your process so it could set itself up. However, this can be extremely complicated; describing the "current state" of the process can involve lots of data.

There is an easier way — the *fork()* function, which duplicates the current process. All the code is the same, and the data is the same as the creating (or *parent*) process's data.

Of course, it's impossible to create a process that's *identical in every way* to the parent process. Why? The most obvious difference between these two processes is going to be the process ID — we can't create two processes with the same process ID. If you look at *fork()*'s documentation in the *C Library Reference*, you'll see that there is a list of differences between the two processes. You should read this list to be sure that you know these differences if you plan to use *fork()*.

If both sides of a *fork()* look alike, how do you tell them apart? When you call *fork()*, you create another process executing the same code at the same location (i.e., both are about to return from the *fork()* call) as the parent process. Let's look at some sample code:

```
int main (int argc, char **argv)
{
    int retval;

    printf ("This is most definitely the parent process\n");
    fflush (stdout);
    retval = fork ();
    printf ("Which process printed this?\n");

    return (EXIT_SUCCESS);
}
```

After the *fork()* call, *both* processes are going to execute the second *printf()* call! If you run this program, it prints something like this:

```
This is most definitely the parent process
Which process printed this?
Which process printed this?
```

Both processes print the second line.

The only way to tell the two processes apart is the *fork()* return value in *retval*. In the newly created *child* process, *retval* is zero; in the parent process, *retval* is the child's process ID.

Clear as mud? Here's another code snippet to clarify:

```
printf ("The parent is pid %d\n", getpid ());
fflush (stdout);

if (child_pid = fork ()) {
    printf ("This is the parent, child pid is %d\n",
            child_pid);
} else {
    printf ("This is the child, pid is %d\n",
            getpid ());
}
```

This program will print something like:

```
The parent is pid 4496
This is the parent, child pid is 8197
This is the child, pid is 8197
```

You can tell which process you are (the parent or the child) after the *fork()* by looking at *fork()*'s return value.

Starting a process with the *vfork()* call

The *vfork()* function can be a lot less resource intensive than the plain *fork()*, because it shares the parent's address space.

The *vfork()* function creates a child, but then suspends the parent thread until the child calls *exec()* or exits (via *exit()* and friends). Additionally, *vfork()* will work on physical memory model systems, whereas *fork()* can't —*fork()* needs to create the same address space, which just isn't possible in a physical memory model.

Process creation and threads

Suppose you have a process and you haven't created any threads yet (i.e., you're running with one thread, the one that called *main()*). When you call *fork()*, another process is created, also with one thread. This is the simple case.

Now suppose that in your process, you've called *pthread_create()* to create another thread. When you call *fork()*, it will now return ENOSYS (meaning that the function is not supported)! Why?

Well, believe it or not, this *is* POSIX compatible — POSIX says that *fork() can* return ENOSYS. What actually happens is this: the Neutrino C library isn't built to handle the forking of a process with threads. When you call *pthread_create()*, the *pthread_create()* function sets a flag, effectively saying, "Don't let this process *fork()*, because I'm not prepared to handle it." Then, in the library *fork()* function, this flag is checked, and, if set, causes *fork()* to return ENOSYS.

The reason this is intentionally done has to do with threads and mutexes. If this restriction weren't in place (and it may be lifted in a future release) the newly created process would have the same number of threads as the original process. This is what you'd expect. However, the complication occurs because some of the original threads may own mutexes. Since the newly created process has the identical contents of the data space of the original process, the library would have to keep track of which mutexes were owned by which threads in the original process, and then duplicate that ownership in the new process. This isn't impossible — there's a function called *pthread_atfork()* that allows a process to deal with this; however, the functionality of calling *pthread_atfork()* isn't being used by all the mutexes in the Neutrino C library as of this writing.

So what should you use?

Obviously, if you're porting existing code, you'll want to use whatever the existing code uses. For new code, you should avoid *fork()* if at all possible. Here's why:

- *fork()* doesn't work with multiple threads, as discussed above.
- When *fork()* does work with multiple threads, you'll need to register a *pthread_atfork()* handler and lock every single mutex *before* you fork, complicating the design.
- The child of *fork()* duplicates *all* open file descriptors. As we'll see in the Resource Manager chapter later, this causes a lot of work — most of which will be unnecessary if the child then immediately does an *exec()* and closes all the file descriptors anyway.

The choice between *vfork()* and the *spawn()* family boils down to portability, and what you want the child and parent to be doing. The *vfork()* function will pause until the child calls *exec()* or exits, whereas the *spawn()* family of functions can allow both to run concurrently. The *vfork()* function, however, is subtly different between operating systems.

Starting a thread

Now that we've seen how to start another process, let's see how to start another thread.

Any thread can create another thread in the same process; there are no restrictions (short of memory space, of course!). The most common way of doing this is via the POSIX *pthread_create()* call:

```
#include <pthread.h>

int
pthread_create (pthread_t *thread,
                const pthread_attr_t *attr,
                void *(*start_routine) (void *),
                void *arg);
```

The *pthread_create()* function takes four arguments:

thread a pointer to a **pthread_t** where the thread ID is stored

attr an *attributes structure*

start_routine the routine where the thread begins

arg an argument passed to the thread's *start_routine*

Note that the *thread* pointer and the attributes structure (*attr*) are optional — you can pass them as NULL.

The *thread* parameter can be used to store the thread ID of the newly created thread. You'll notice that in the examples below, we'll pass a NULL, meaning that we don't care what the ID is of the newly created thread. If we did care, we could do something like this:

```
pthread_t tid;

pthread_create (&tid, ...
printf ("Newly created thread id is %d\n", tid);
```

This use is actually quite typical, because you'll often want to know which thread ID is running which piece of code.

☞ A small subtle point. It's possible that the newly created thread may be running *before* the thread ID (the *tid* parameter) is filled. This means that you should be careful about using the *tid* as a global variable. The usage shown above is okay, because the *pthread_create()* call has returned, which means that the *tid* value is stuffed correctly.

The new thread begins executing at *start_routine()*, with the argument *arg*.

The thread attributes structure

When you start a new thread, it can assume some well-defined defaults, or you can explicitly specify its characteristics.

Before we jump into a discussion of the thread attribute functions, let's look at the `pthread_attr_t` data type:

```
typedef struct {
    int                  flags;
    size_t               stacksize;
    void                 *stackaddr;
    void                 (*exitfunc) (void *status);
    int                  policy;
    struct sched_param   param;
    unsigned             guardsize;
} pthread_attr_t;
```

Basically, the fields are used as follows:

flags Non-numerical (Boolean) characteristics (e.g., whether the thread should run "detached" or "joinable").

stacksize, *stackaddr*, and *guardsize*

Stack specifications.

exitfunc Function to execute at thread exit.

policy and *param*

Scheduling parameters.

The following functions are available:

Attribute administration

pthread_attr_destroy()
pthread_attr_init()

Flags (Boolean characteristics)

pthread_attr_getdetachstate()
pthread_attr_setdetachstate()
pthread_attr_getinheritsched()
pthread_attr_setinheritsched()
pthread_attr_getscope()
pthread_attr_setscope()

Stack related

pthread_attr_getguardsize()
pthread_attr_setguardsize()
pthread_attr_getstackaddr()
pthread_attr_setstackaddr()
pthread_attr_getstacksize()
pthread_attr_setstacksize()
pthread_attr_getstacklazy()
pthread_attr_setstacklazy()

Scheduling related

pthread_attr_getschedparam()
pthread_attr_setschedparam()
pthread_attr_getschedpolicy()
pthread_attr_setschedpolicy()

This looks like a pretty big list (20 functions), but in reality we have to worry about only half of them, because they're paired: "get" and "set" (with the exception of *pthread_attr_init()* and *pthread_attr_destroy()*).

Before we examine the attribute functions, there's one thing to note. You must call *pthread_attr_init()* to initialize the attribute structure before using it, set it with the appropriate *pthread_attr_set*()* function(s), and *then* call *pthread_create()* to create the thread. Changing the attribute structure *after* the thread's been created has no effect.

Thread attribute administration

The function *pthread_attr_init()* must be called to initialize the attribute structure before using it:

```
...

pthread_attr_t  attr;
...
pthread_attr_init (&attr);
```

You *could* call *pthread_attr_destroy()* to "uninitialize" the thread attribute structure, but almost no one ever does (unless you have POSIX compliant code).

In the descriptions that follow, I've marked the default values with "*(default)*."

The "flags" thread attribute

The three functions, *pthread_attr_setdetachstate()*, *pthread_attr_setinheritsched()*, and *pthread_attr_setscope()* determine whether the thread is created "joinable" or "detached," whether the thread inherits the scheduling attributes of the creating thread or uses the scheduling attributes specified by *pthread_attr_setschedparam()* and *pthread_attr_setschedpolicy()*, and finally whether the thread has a scope of "system" or "process."

To create a "joinable" thread (meaning that another thread can synchronize to its termination via *pthread_join()*), you'd use:

```
(default)
pthread_attr_setdetachstate (&attr, PTHREAD_CREATE_JOINABLE);
```

To create one that can't be joined (called a "detached" thread), you'd use:

```
pthread_attr_setdetachstate (&attr, PTHREAD_CREATE_DETACHED);
```

If you want the thread to inherit the scheduling attributes of the creating thread (that is, to have the same scheduling algorithm and the same priority), you'd use:

```
(default)
pthread_attr_setinheritsched (&attr, PTHREAD_INHERIT_SCHED);
```

To create one that uses the scheduling attributes specified in the attribute structure itself (which you'd set using *pthread_attr_setschedparam()* and *pthread_attr_setschedpolicy()*), you'd use:

```
pthread_attr_setinheritsched (&attr, PTHREAD_EXPLICIT_SCHED);
```

Finally, you'd never call *pthread_attr_setscope()*. Why? Because Neutrino supports only "system" scope, and it's the default when you initialize the attribute. ("System" scope means that all threads in the system compete against each other for CPU; the other value, "process," means that threads compete against each other for CPU within the process, and the kernel schedules the processes.)

If you do insist on calling it, you can call it only as follows:

```
(default)
pthread_attr_setscope (&attr, PTHREAD_SCOPE_SYSTEM);
```

The "stack" thread attributes

The thread attribute stack parameters are prototyped as follows:

```
int
pthread_attr_setguardsize (pthread_attr_t *attr, size_t gsize);

int
pthread_attr_setstackaddr (pthread_attr_t *attr, void *addr);

int
pthread_attr_setstacksize (pthread_attr_t *attr, size_t ssize);

int
pthread_attr_setstacklazy (pthread_attr_t *attr, int lazystack);
```

These functions all take the attribute structure as their first parameter; their second parameters are selected from the following:

gsize The size of the "guard" area.

addr The address of the stack, if you're providing one.

ssize The size of the stack.

lazystack Indicates if the stack should be allocated on demand or up front from physical memory.

The guard area is a memory area immediately after the stack that the thread can't write to. If it does (meaning that the stack was about to overflow), the thread will get hit with a SIGSEGV. If the guardsize is 0, it means that there's no guard area. This also implies that there's no stack overflow checking. If the guardsize is nonzero, then it's set to at least the system-wide default guardsize (which you can obtain with a call to *sysconf()* with the constant _SC_PAGESIZE). Note that the guardsize will be at least as big as a "page" (for example, 4k on an x86 processor). Also, note that the guard page doesn't take up any *physical* memory — it's done as a virtual address (MMU) "trick."

The *addr* is the address of the stack, in case you're providing it. You can set it to NULL meaning that the system will allocate (and will free!) the stack for the thread. The advantage of specifying a stack is that you can do postmortem stack depth analysis. This is accomplished by allocating a stack area, filling it with a "signature" (for example, the string "STACK" repeated over and over), and letting the thread run. When the thread has completed, you'd look at the stack area and see how far the thread had scribbled over your signature, giving you the maximum depth of the stack used during this particular run.

The *ssize* parameter specifies how big the stack is. If you provide the stack in *addr*, then *ssize* should be the size of that data area. If you don't provide the stack in *addr* (meaning you passed a NULL), then the *ssize* parameter tells the system how big a stack it should allocate for you. If you specify a 0 for *ssize*, the system will select the default stack size for you. Obviously, it's bad practice to specify a 0 for *ssize* *and* specify a stack using *addr* — effectively you're saying "Here's a pointer to an object, and the object is some default size." The problem is that there's no binding between the object size and the passed value.

☞ If a stack is being provided via *addr*, no automatic stack overflow protection exists for that thread (i.e., there's no guard area). However, you can certainly set this up yourself using *mmap()* and *mprotect()*.

Finally, the *lazystack* parameter indicates if the physical memory should be allocated as required (use the value PTHREAD_STACK_LAZY) or all up front (use the value PTHREAD_STACK_NOTLAZY). The advantage of allocating the stack "on demand" (as required) is that the thread won't use up more physical memory than it absolutely has to. The disadvantage (and hence the advantage of the "all up front" method) is that in a low-memory environment the thread won't mysteriously die some time during operating when it needs that extra bit of stack, and there isn't any memory left. If you are using PTHREAD_STACK_NOTLAZY, you'll most likely want to set the actual size of the stack instead of accepting the default, because the default is quite large.

The "scheduling" thread attributes

Finally, if you do specify PTHREAD_EXPLICIT_SCHED for *pthread_attr_setinheritsched()*, then you'll need a way to specify both the scheduling algorithm and the priority of the thread you're about to create.

This is done with the two functions:

```
int
pthread_attr_setschedparam (pthread_attr_t *attr,
                            const struct sched_param *param);

int
pthread_attr_setschedpolicy (pthread_attr_t *attr,
                             int policy);
```

The *policy* is simple — it's one of SCHED_FIFO, SCHED_RR, or SCHED_OTHER.

☞ SCHED_OTHER is currently mapped to SCHED_RR.

The *param* is a structure that contains one member of relevance here: *sched_priority*. Set this value via direct assignment to the desired priority.

☞ A common bug to watch out for is specifying PTHREAD_EXPLICIT_SCHED and then setting only the scheduling policy. The problem is that in an initialized attribute structure, the value of *param.sched_priority* is 0. This is the same priority as the IDLE process, meaning that your newly created thread will be competing for CPU with the IDLE process.

Been there, done that, got the T-shirt. `:-)`

Enough people have been bitten by this that QSSL has made priority zero reserved for only the idle thread. You simply cannot run a thread at priority zero.

A few examples

Let's take a look at some examples. We'll assume that the proper include files (`<pthread.h>` and `<sched.h>`) have been included, and that the thread to be created is called *new_thread()* and is correctly prototyped and defined.

The most common way of creating a thread is to simply let the values default:

```
pthread_create (NULL, NULL, new_thread, NULL);
```

In the above example, we've created our new thread with the defaults, and passed it a NULL as its one and only parameter (that's the third NULL in the *pthread_create()* call above).

Generally, you can pass anything you want (via the *arg* field) to your new thread. Here we're passing the number 123:

```
pthread_create (NULL, NULL, new_thread, (void *) 123);
```

A more complicated example is to create a non-joinable thread with round-robin scheduling at priority 15:

```
pthread_attr_t attr;

// initialize the attribute structure
pthread_attr_init (&attr);

// set the detach state to "detached"
pthread_attr_setdetachstate (&attr, PTHREAD_CREATE_DETACHED);

// override the default of INHERIT_SCHED
pthread_attr_setinheritsched (&attr, PTHREAD_EXPLICIT_SCHED);
pthread_attr_setschedpolicy (&attr, SCHED_RR);
attr.param.sched_priority = 15;

// finally, create the thread
pthread_create (NULL, &attr, new_thread, NULL);
```

To see what a multithreaded program "looks like," you could run the **pidin** command from the shell. Say our program was called **spud**. If we run **pidin** once before **spud** created a thread and once after **spud** created two more threads (for three total), here's what the output would look like (I've shortened the **pidin** output to show only **spud**):

```
# pidin
pid     tid name                    prio STATE       Blocked
 12301    1 spud                     10r READY

# pidin
pid     tid name                    prio STATE       Blocked
 12301    1 spud                     10r READY
 12301    2 spud                     10r READY
 12301    3 spud                     10r READY
```

As you can see, the process **spud** (process ID 12301) has three threads (under the "tid" column). The three threads are running at priority 10 with a scheduling algorithm of round robin (indicated by the "r" after the 10). All three threads are READY, meaning that they're able to use

CPU but aren't currently running on the CPU (another, higher-priority thread, is currently running).

Now that we know all about creating threads, let's take a look at how and where we'd use them.

Where a thread is a good idea

There are two classes of problems where the application of threads is a good idea.

☞ Threads are like overloading operators in C++ — it may seem like a good idea (at the time) to overload every single operator with some interesting use, but it makes the code hard to understand. Similarly with threads, you could create piles of threads, but the additional complexity will make your code hard to understand, and therefore hard to maintain. Judicious use of threads, on the other hand, will result in code that is functionally very clean.

Threads are great where you can parallelize operations — a number of mathematical problems spring to mind (graphics, digital signal processing, etc.). Threads are also great where you want a program to perform several independent functions while sharing data, such as a web-server that's serving multiple clients simultaneously. We'll examine these two classes.

Threads in mathematical operations

Suppose that we have a graphics program that performs ray tracing. Each raster line on the screen is dependent on the main database (which describes the actual picture being generated). The key here is this: *each raster line is independent of the others*. This immediately causes the problem to stand out as a threadable program.

Here's the single-threaded version:

```
int
main (int argc, char **argv)
{
    int x1;

    ...     // perform initializations
    for (x1 = 0; x1 < num_x_lines; x1++) {
        do_one_line (x1);
    }

    ...     // display results
}
```

Here we see that the program will iterate *x1* over all the raster lines that are to be calculated.

On an SMP system, this program will use only one of the CPUs. Why? Because we haven't told the operating system to do anything in parallel. The operating system isn't smart enough to look at the program and say, "Hey, hold on a second! We have 4 CPUs, and it looks like there are independent execution flows here. I'll run it on all 4 CPUs!"

So, it's up to the system designer (you) to tell Neutrino which parts can be run in parallel. The easiest way to do that would be:

```
int
main (int argc, char **argv)
{
    int x1;

    ...     // perform initializations

    for (x1 = 0; x1 < num_x_lines; x1++) {
        pthread_create (NULL, NULL, do_one_line, (void *) x1);
    }

    ...     // display results
}
```

There are a number of problems with this simplistic approach. First of all (and this is most minor), the *do_one_line()* function would have to be modified to take a **void *** instead of an **int** as its argument. This is easily remedied with a typecast.

The second problem is a little bit trickier. Let's say that the screen resolution that you were computing the picture for was 1280 by 1024. We'd be creating 1280 threads! This is not a problem for Neutrino —

Neutrino "limits" you to 32767 threads per process! However, each thread *must* have a unique stack. If your stack is a reasonable size (say 8k), you'll have used 1280 × 8k (10 megabytes!) of stack. And for what? There are only 4 processors in your SMP system. This means that only 4 of the 1280 threads will run at a time — the other 1276 threads are waiting for a CPU. (In reality, the stack will "fault in," meaning that the space for it will be allocated only as required. Nonetheless, it's a waste — there are still other overheads.)

A much better solution to this would be to break the problem up into 4 pieces (one for each CPU), and start a thread for each piece:

```
int num_lines_per_cpu;
int num_cpus;

int
main (int argc, char **argv)
{
    int cpu;

    ...    // perform initializations

    // get the number of CPUs
    num_cpus = _syspage_ptr -> num_cpu;
    num_lines_per_cpu = num_x_lines / num_cpus;
    for (cpu = 0; cpu < num_cpus; cpu++) {
        pthread_create (NULL, NULL,
                        do_one_batch, (void *) cpu);
    }

    ...    // display results
}

void *
do_one_batch (void *c)
{
    int cpu = (int) c;
    int x1;

    for (x1 = 0; x1 < num_lines_per_cpu; x1++) {
        do_line_line (x1 + cpu * num_lines_per_cpu);
    }
}
```

Here we're starting only *num_cpus* threads. Each thread will run on one CPU. And since we have only a small number of threads, we're not wasting memory with unnecessary stacks. Notice how we got the number of CPUs by dereferencing the "System Page" global variable *_syspage_ptr*. (For more information about what's in the system page, please consult QSSL's *Building Embedded Systems* book or the `<sys/syspage.h>` include file).

Coding for SMP or single processor

The best part about this code is that it will function just fine on a single-processor system — you'll create only one thread, and have it do all the work. The additional overhead (one stack) is well worth the flexibility of having the software "just work faster" on an SMP box.

Synchronizing to the termination of a thread

I mentioned that there were a number of problems with the simplistic code sample initially shown. Another problem with it is that *main()* starts up a bunch of threads and then displays the results. How does the function *know* when it's safe to display the results?

To have the *main()* function poll for completion would defeat the purpose of a realtime operating system:

```
int
main (int argc, char **argv)
{
    ...

    // start threads as before

    while (num_lines_completed < num_x_lines) {
        sleep (1);
    }
}
```

Don't even consider writing code like this!

There are two elegant solutions to this problem: *pthread_join()* and *pthread_barrier_wait()*.

Joining

The simplest method of synchronization is to *join* the threads as they terminate. Joining really means waiting for termination.

Joining is accomplished by one thread waiting for the termination of another thread. The waiting thread calls *pthread_join()*:

```
#include <pthread.h>

int
pthread_join (pthread_t thread, void **value_ptr);
```

To use *pthread_join()*, you pass it the thread ID of the thread that you wish to join, and an optional *value_ptr*, which can be used to store the termination return value from the joined thread. (You can pass in a NULL if you aren't interested in this value — we're not, in this case.)

Where did the thread ID came from? We ignored it in the *pthread_create()* — we passed in a NULL for the first parameter. Let's now correct our code:

```
int num_lines_per_cpu, num_cpus;

int main (int argc, char **argv)
{
    int cpu;
    pthread_t *thread_ids;

    ...    // perform initializations
    thread_ids = malloc (sizeof (pthread_t) * num_cpus);

    num_lines_per_cpu = num_x_lines / num_cpus;
    for (cpu = 0; cpu < num_cpus; cpu++) {
        pthread_create (&thread_ids [cpu], NULL,
                        do_one_batch, (void *) cpu);
    }

    // synchronize to termination of all threads
    for (cpu = 0; cpu < num_cpus; cpu++) {
        pthread_join (thread_ids [cpu], NULL);
    }

    ...    // display results
}
```

You'll notice that this time we passed the first argument to *pthread_create()* as a pointer to a `pthread_t`. This is where the thread ID of the newly created thread gets stored. After the first `for` loop finishes, we have *num_cpus* threads running, plus the thread that's running *main()*. We're not too concerned about the *main()* thread consuming all our CPU; it's going to spend its time waiting.

The waiting is accomplished by doing a *pthread_join()* to each of our threads in turn. First, we wait for *thread_ids [0]* to finish. When it completes, the *pthread_join()* will unblock. The next iteration of the `for` loop will cause us to wait for *thread_ids [1]* to finish, and so on, for all *num_cpus* threads.

A common question that arises at this point is, "What if the threads finish in the reverse order?" In other words, what if there are 4 CPUs, and, for whatever reason, the thread running on the last CPU (CPU 3) finishes first, and then the thread running on CPU 2 finishes next, and so on? Well, the beauty of this scheme is that nothing bad happens.

The first thing that's going to happen is that the *pthread_join()* will block on *thread_ids [0]*. Meanwhile, *thread_ids [3]* finishes. This has absolutely no impact on the *main()* thread, which is still waiting for the first thread to finish. Then *thread_ids [2]* finishes. Still no impact. And so on, until *finally thread_ids [0]* finishes, at which point, the *pthread_join()* unblocks, and we immediately proceed to the next iteration of the `for` loop. The second iteration of the `for` loop executes a *pthread_join()* on *thread_ids [1]*, which will not block — it returns immediately. Why? Because the thread identified by *thread_ids [1]* is *already finished*. Therefore, our `for` loop will "whip" through the other threads, and then exit. At that point, we know that we've synched up with all the computational threads, so we can now display the results.

Using a barrier

When we talked about the synchronization of the *main()* function to the completion of the worker threads (in "Synchronizing to the termination of a thread," above), we mentioned two methods: *pthread_join()*, which we've looked at, and a barrier.

Returning to our house analogy, suppose that the family wanted to take a trip somewhere. The driver gets in the minivan and starts the engine. And waits. The driver waits until *all* the family members have boarded, and only then does the van leave to go on the trip — we can't leave anyone behind!

This is exactly what happened with the graphics example. The main thread needs to wait until all the worker threads have completed, and only then can the next part of the program begin.

Note an important distinction, however. With *pthread_join()*, we're waiting for the *termination* of the threads. This means that the threads are no longer with us; they've exited.

With the *barrier*, we're waiting for a certain number of threads to rendezvous at the barrier. Then, when the requisite number are present, we unblock *all of them*. (Note that the threads continue to run.)

You first create a barrier with *pthread_barrier_init()*:

```
#include <pthread.h>

int
pthread_barrier_init (pthread_barrier_t *barrier,
                      const pthread_barrierattr_t *attr,
                      unsigned int count);
```

This creates a barrier object at the passed address (pointer to the barrier object is in *barrier*), with the attributes as specified by *attr* (we'll just use NULL to get the defaults). The number of threads that must call *pthread_barrier_wait()* is passed in *count*.

Once the barrier is created, we then want each of the threads to call *pthread_barrier_wait()* to indicate that it has completed:

```
#include <pthread.h>

int
```

```
pthread_barrier_wait (pthread_barrier_t *barrier);
```

When a thread calls *pthread_barrier_wait()*, it will block until the number of threads specified initially in the *pthread_barrier_init()* have called *pthread_barrier_wait()* (and blocked too). When the correct number of threads have called *pthread_barrier_wait()*, all those threads will "simultaneously" unblock.

Here's an example:

```
/*
 *  barrier1.c
*/

#include <stdio.h>
#include <time.h>
#include <pthread.h>
#include <sys/neutrino.h>

pthread_barrier_t   barrier;    // the barrier synch object

void *
thread1 (void *not_used)
{
    time_t  now;

    time (&now);
    printf ("thread1 starting at %s", ctime (&now));

    // do the computation
    // let's just do a sleep here...
    sleep (20);
    pthread_barrier_wait (&barrier);
    // after this point, all three threads have completed.
    time (&now);
    printf ("barrier in thread1() done at %s", ctime (&now));
}

void *
thread2 (void *not_used)
{
    time_t  now;

    time (&now);
    printf ("thread2 starting at %s", ctime (&now));

    // do the computation
    // let's just do a sleep here...
    sleep (40);
    pthread_barrier_wait (&barrier);
    // after this point, all three threads have completed.
    time (&now);
    printf ("barrier in thread2() done at %s", ctime (&now));
}

main () // ignore arguments
{
    time_t  now;

    // create a barrier object with a count of 3
    pthread_barrier_init (&barrier, NULL, 3);

    // start up two threads, thread1 and thread2
    pthread_create (NULL, NULL, thread1, NULL);
    pthread_create (NULL, NULL, thread2, NULL);

    // at this point, thread1 and thread2 are running

    // now wait for completion
    time (&now);
    printf ("main() waiting for barrier at %s", ctime (&now));
    pthread_barrier_wait (&barrier);

    // after this point, all three threads have completed.
    time (&now);
    printf ("barrier in main() done at %s", ctime (&now));
    sleep (1);
}
```

The main thread created the barrier object and initialized it with a count of how many threads (*including itself*!) should be synchronized to the barrier before it "breaks through." In our sample, this was a count of 3 — one for the *main()* thread, one for *thread1()*, and one for *thread2()*. Then the graphics computational threads (*thread1()* and *thread2()* in our case here) are started, as before. For illustration, instead of showing source for graphics computations, we just stuck in a `sleep (20);` and `sleep (40);` to cause a delay, as if computations were occuring. To synchronize, the main thread simply blocks itself on the barrier, knowing that the barrier will unblock only after the worker threads have joined it as well.

As mentioned earlier, with the *pthread_join()* the worker threads are done and dead in order for the main thread to synchronize with them. But with the barrier, the threads are alive and well. In fact, they've just unblocked from the *pthread_barrier_wait()* when all have completed. The wrinkle introduced here is that you should be prepared to do something with these threads! In our graphics example, there's nothing for them to do (as we've written it). In real life, you may wish to start the next frame calculations.

Multiple threads on a single CPU

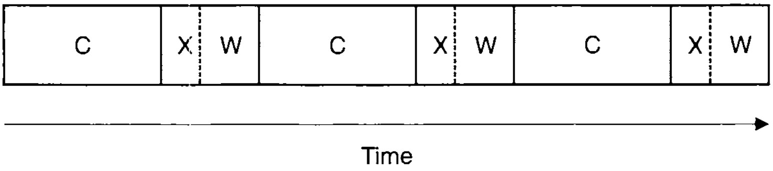
Suppose that we modify our example slightly so that we can illustrate why it's also sometimes a good idea to have multiple threads even on a single-CPU system.

In this modified example, one node on a network is responsible for calculating the raster lines (same as the graphics example, above). However, when a line is computed, its data should be sent over the network to another node, which will perform the display functions. Here's our modified *main()* (from the original example, without threads):

```
int
main (int argc, char **argv)
{
    int x1;

    ...    // perform initializations

    for (x1 = 0; x1 < num_x_lines; x1++) {
        do_one_line (x1);           // "C" in our diagram, below
        tx_one_line_wait_ack (x1);  // "X" and "W" in diagram below
    }
}
```

You'll notice that we've eliminated the display portion and instead added a *tx_one_line_wait_ack()* function. Let's further suppose that we're dealing with a reasonably slow network, but that the CPU doesn't really get involved in the transmission aspects — it fires the data off to some hardware that then worries about transmitting it. The *tx_one_line_wait_ack()* uses a bit of CPU to get the data to the hardware, but then uses *no CPU* while it's waiting for the acknowledgement from the far end.

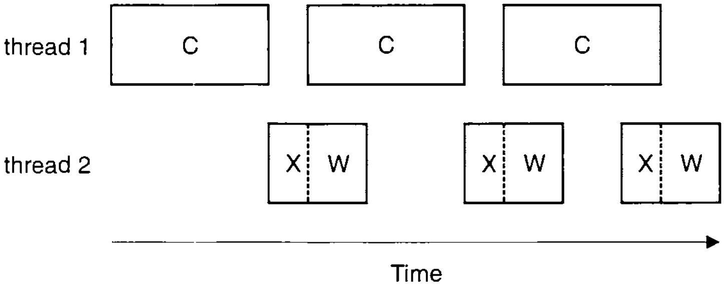
Here's a diagram showing the CPU usage (we've used "C" for the graphics compute part, "X" for the transmit part, and "W" for waiting for the acknowledgement from the far end):



Serialized, single CPU.

Wait a minute! We're wasting precious seconds waiting for the hardware to do its thing!

If we made this multithreaded, we should be able to get much better use of our CPU, right?



Multithreaded, single CPU.

This is much better, because now, even though the second thread spends a bit of its time waiting, we've reduced the total overall time required to compute.

If our times were $T_{compute}$ to compute, T_{tx} to transmit, and T_{wait} to let the hardware do its thing, in the first case our total running time would be:

$$(T_{\mathrm{compute}} + T_{\mathrm{tx}} + T_{\mathrm{wait}}) \times \mathit{num\_x\_lines}$$

whereas with the two threads it would be

$$(T_{\mathrm{compute}} + T_{\mathrm{tx}}) \times \mathit{num\_x\_lines} + T_{\mathrm{wait}}$$

which is shorter by

$$T_{\mathrm{wait}} \times (\mathit{num\_x\_lines} - 1)$$

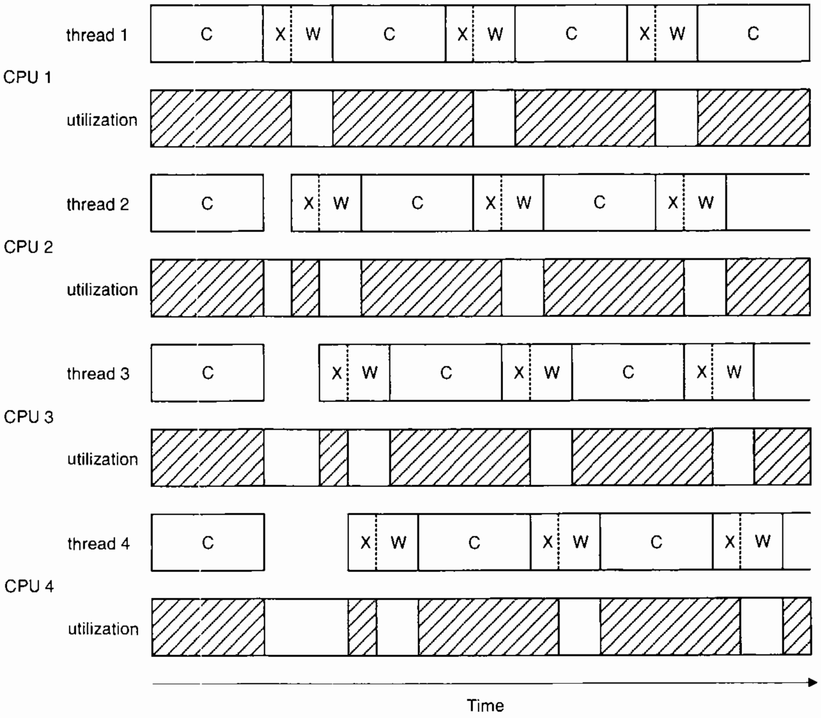
assuming of course that $T_{wait} \leq T_{compute}$.

☞ Note that we will ultimately be constrained by:

$$T_{\mathrm{compute}} + T_{\mathrm{tx}} \times \mathit{num\_x\_lines}$$

because we'll have to incurr at least one full computation, and we'll have to transmit the data out the hardware — while we can use multithreading to overlay the computation cycles, we have only one hardware resource for the transmit.

Now, if we created a four-thread version and ran it on an SMP system with 4 CPUs, we'd end up with something that looked like this:



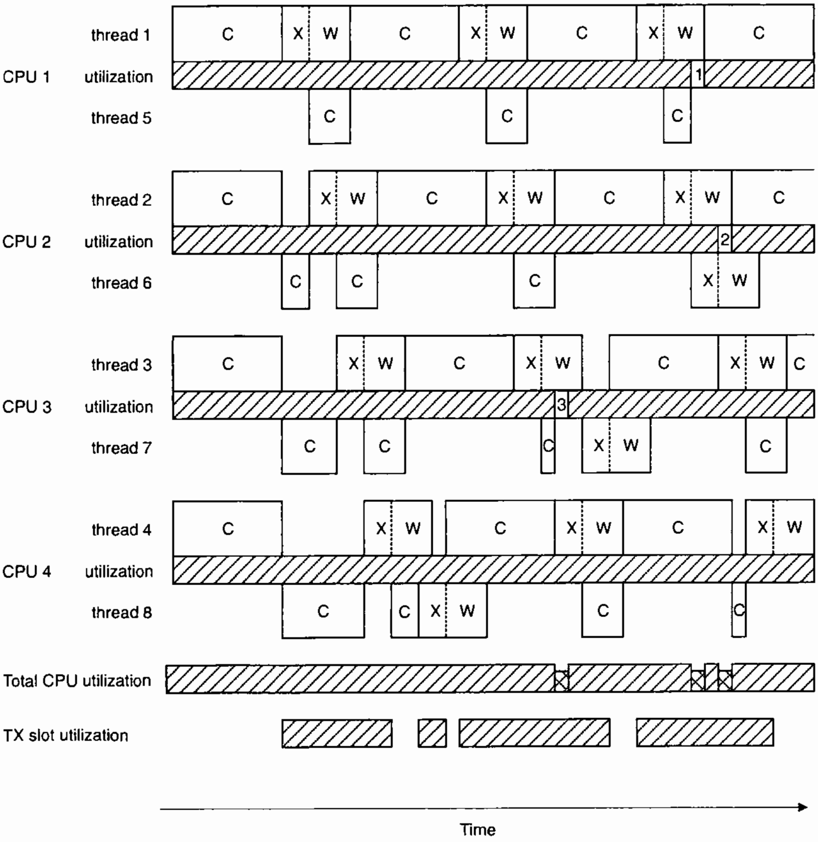
Four threads, four CPUs.

Notice how each of the four CPUs is underutilized (as indicated by the empty rectangles in the "utilization" graph). There are two interesting areas in the figure above. When the four threads start, they each compute. Unfortunately, when the threads are finished each computation, they're contending for the transmit hardware (the "X" parts in the figure are offset — only one transmission may be in progress at a time). This gives us a small anomaly in the startup part. Once the threads are past this stage, they're naturally synchronized to the transmit hardware, since the time to transmit is much smaller than $\frac{1}{4}$ of a compute cycle. Ignoring the small anomaly at the beginning, this system is characterized by the formula:

$$(T_{compute} + T_{tx} + T_{wait}) \times num\_x\_lines \, / \, num\_cpus$$

This formula states that using four threads on four CPUs will be approximately 4 times faster than the single-threaded model we started out with.

By combining what we learned from simply having a multithreaded single-processor version, we would ideally like to have more threads than CPUs, so that the extra threads can "soak up" the idle CPU time from the transmit acknowledge waits (and the transmit slot contention waits) that naturally occur. In that case, we'd have something like this:



Eight threads, four CPUs.

This figure assumes a few things:

- threads 5, 6, 7, and 8 are bound to processors 1, 2, 3, and 4 (for simplification)
- once a transmit begins it does so at a higher priority than a computation
- a transmit is a non-interruptible operation

Notice from the diagram that even though we now have twice as many threads as CPUs, we still run into places where the CPUs are under-utilized. In the diagram, there are three such places where the CPU is "stalled"; these are indicated by numbers in the individual CPU utilization bar graphs:

1 Thread 1 was waiting for the acknowledgement (the "W" state), while thread 5 had completed a calculation and was waiting for the transmitter.

2 Both thread 2 and thread 6 were waiting for an acknowledgement.

3 Thread 3 was waiting for the acknowledgement while thread 7 had completed a calculation and was waiting for the transmitter.

This example also serves as an important lesson — you can't just keep adding CPUs in the hopes that things will keep getting faster. There are limiting factors. In some cases, these limiting factors are simply governed by the design of the multi-CPU motherboard — how much memory and device contention occurs when many CPUs try to access the same area of memory. In our case, notice that the "TX Slot Utilization" bar graph was starting to become full. If we added enough CPUs, they would eventually run into problems because their threads would be stalled, waiting to transmit.

In any event, by using "soaker" threads to "soak up" spare CPU, we now have much better CPU utilization. This utilization approaches:

$$(T_{compute} + T_{tx}) \times \mathit{num\_x\_lines} \, / \, \mathit{num\_cpus}$$

In the computation *per se*, we're limited only by the amount of CPU we have; we're not idling any processor waiting for acknowledgement. (Obviously, that's the ideal case. As you saw in the diagram there are a few times when we're idling one CPU periodically. Also, as noted above,

$$T_{compute} + T_{tx} \times num\_x\_lines$$

is our limit on how fast we can go.)

Things to watch out for when using SMP

While in general you can simply "ignore" whether or not you're running on an SMP architecture or a single processor, there are certain things that *will* bite you. Unfortunately, they may be such low-probability events that they won't show up during development but rather during testing, demos, or the worst: out in the field. Taking a few moments now to program defensively will save problems down the road.

Here are the kinds of things that you're going to run up against on an SMP system:

- Threads really *can* and *do* run concurrently — relying on things like FIFO scheduling or prioritization for synchronization is a no-no.
- Threads and Interrupt Service Routines (ISRs) also *do* run concurrently — this means that not only will you have to protect the thread from the ISR, but you'll also have to protect the ISR from the thread. See the Interrupts chapter for more details.
- Some operations that you'd expect to be atomic aren't, depending on the operation and processor. Notable operations in this list are things that do a read-modify-write cycle (e.g., `++`, `--`, `|=`, `&=` etc.). See the include file `<atomic.h>` for replacements. (Note that this isn't purely an SMP issue; most RISC processors don't necessarily perform the above code in an atomic manner.)

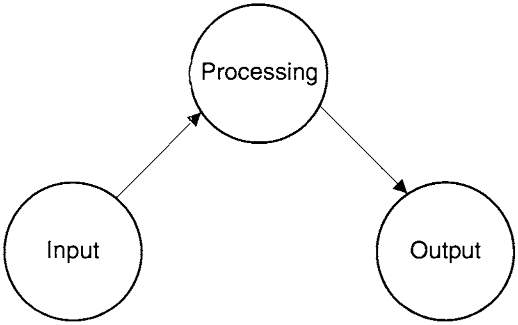
Threads in independent situations

As discussed above in the "Where a thread is a good idea" section, threads also find use where a number of independent processing algorithms are occurring with shared data structures. While strictly speaking you *could* have a number of *processes* (each with one thread) explicitly sharing data, in some cases it's far more convenient to have a number of threads in one process instead. Let's see why and where you'd use threads in this case.

For our examples, we'll evolve a standard input/process/output model. In the most generic sense, one part of the model is responsible for getting input from somewhere, another part is responsible for processing the input to produce some form of output (or control), and the third part is responsible for feeding the output somewhere.

Multiple processes

Let's first understand the situation from a multiple process, one-thread-per-process outlook. In this case, we'd have three processes, literally an input process, a "processing" process, and an output process:

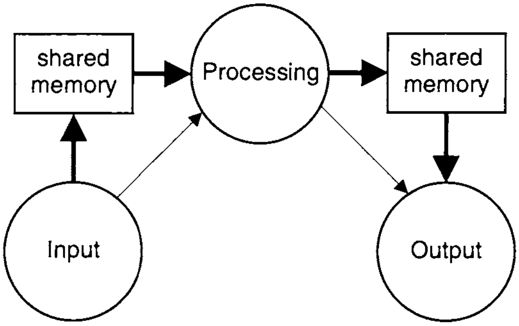


System 1: Multiple operations, multiple processes.

This is the most highly abstracted form, and also the most "loosely coupled." The "input" process has no real "binding" with either of the "processing" or "output" processes — it's simply responsible for gathering input and somehow giving it to the next stage (the "processing" stage). We could say the same thing of the "processing" and "output" processes — they too have no real binding with each other. We are also assuming in this example that the communication path (i.e., the input-to-processing and the processing-to-output data flow) is accomplished over some connectioned protocol (e.g., pipes, POSIX message queues, native Neutrino message passing — whatever).

Multiple processes with shared memory

Depending on the volume of data flow, we may want to optimize the communication path. The easiest way of doing this is to make the coupling between the three processes tighter. Instead of using a general-purpose connectioned protocol, we now choose a shared memory scheme (in the diagram, the thick lines indicate data flow; the thin lines, control flow):

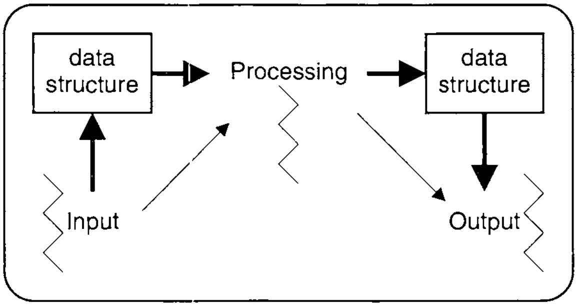


System 2: Multiple operations, shared memory between processes.

In this scheme, we've tightened up the coupling, resulting in faster and more efficient data flow. We may still use a "general-purpose" connectioned protocol to transfer "control" information around — we're not expecting the control information to consume a lot of bandwidth.

Multiple threads

The most tightly-coupled system is represented by the following scheme:



System 3: Multiple operations, multiple threads.

Here we see one process with three threads. The three threads share the data areas implicitly. Also, the control information may be implemented as it was in the previous examples, or it may also be implemented via some of the thread synchronization primitives (we've seen mutexes, barriers, and semaphores; we'll see others in a short while).

Comparisons

Now, let's compare the three methods using various categories, and we'll also describe some of the tradeoffs.

With system 1, we see the loosest coupling. This has the advantage that each of the three processes can be easily (i.e., via the command line, as opposed to recompile/redesign) replaced with a different module. This follows naturally, because the "unit of modularity" is the entire module itself. System 1 is also the only one that can be distributed among multiple nodes in a Neutrino network. Since the communications pathway is abstracted over some connectioned protocol, it's easy to see that the three processes can be executing on any machine in the network. This may be a very powerful *scalability* factor for your design — you may need your system to scale up to having hundreds of machines distributed geographically (or in other ways, e.g., for peripheral hardware capability) and communicating with each other.

Once we commit to a shared memory region, however, we lose the ability to distribute over a network. Neutrino doesn't support network-distributed shared memory objects. So in system 2, we've effectively limited ourselves to running all three processes on the same box. We haven't lost the ability to easily remove or change a component, because we still have separate processes that can be controlled from the command line. But we have added the constraint that all the removable components need to conform to the shared-memory model.

In system 3, we've lost all the above abilities. We definitely can't run different threads from one process on multiple nodes (we *can* run them on different processors in an SMP system, though). And we've lost our configurability aspects — now we need to have an explicit mechanism to define which "input," "processing," or "output" algorithm we want to use (which we can solve with shared objects, also known as DLLs.)

So why would I design my system to have multiple threads like system 3? Why not go for the maximally flexible system 1?

Well, even though system 3 is the most *inflexible*, it *is* most likely going to be the fastest. There are no thread-to-thread context switches for threads in different processes, I don't have to set up memory sharing explicitly, and I don't have to use *abstracted* synchronization methods like pipes, POSIX message queues, or message passing to deliver the data or control information — I can use basic kernel-level thread-synchronization primitives. Another advantage is that when the system described by the one process (with the three threads) starts, I *know* that everything I need has been loaded off the storage medium (i.e., I'm not going to find out later that "Oops, the processing driver is missing from the disk!"). Finally, system 3 is also most likely going to be the smallest, because we won't have three individual copies of "process" information (e.g., file descriptors).

To sum up: know what the tradeoffs are, and use what works for your design.

More on synchronization

We've already seen:

- mutexes
- semaphores
- barriers

Let's now finish up our discussion of synchronization by talking about:

- readers/writer locks
- sleepon locks
- condition variables
- additional Neutrino services

Readers/writer locks

Readers and writer locks are used for exactly what their name implies: multiple readers can be using a resource, with no writers, or one writer can be using a resource with no other writers or readers.

This situation occurs often enough to warrant a special kind of synchronization primitive devoted exclusively to that purpose.

Often you'll have a data structure that's shared by a bunch of threads. Obviously, only one thread can be writing to the data structure at a time. If more than one thread was writing, then the threads could potentially overwrite each other's data. To prevent this from happening, the writing thread would obtain the "rwlock" (the readers/writer lock) in an exclusive manner, meaning that it and only it has access to the data structure. Note that the exclusivity of the access is controlled strictly by voluntary means. It's up to you, the system designer, to ensure that *all* threads that touch the data area synchronize by using the rwlocks.

The opposite occurs with readers. Since reading a data area is a non-destructive operation, any number of threads can be reading the data (even if it's the same piece of data that another thread is reading). An implicit point here is that *no* threads can be writing to the data area while *any* thread or threads are reading from it. Otherwise, the reading threads may be confused by reading a part of the data, getting preempted by a writing thread, and then, when the reading thread resumes, continue reading data, but from a newer "update" of the data. A data inconsistency would then result.

Let's look at the calls that you'd use with rwlocks.

The first two calls are used to initialize the library's internal storage areas for the rwlocks:

```
int
pthread_rwlock_init (pthread_rwlock_t *lock,
                     const pthread_rwlockattr_t *attr);

int
pthread_rwlock_destroy (pthread_rwlock_t *lock);
```

The *pthread_rwlock_init()* function takes the *lock* argument (of type **pthread_rwlock_t**) and initializes it based on the attributes specified by *attr*. We're just going to use an attribute of NULL in our examples, which means, "Use the defaults." For detailed information about the attributes, see the library reference pages for *pthread_rwlockattr_init()*, *pthread_rwlockattr_destroy()*, *pthread_rwlockattr_getpshared()*, and *pthread_rwlockattr_setpshared()*.

When done with the rwlock, you'd typically call *pthread_rwlock_destroy()* to destroy the lock, which invalidates it.

You should never use a lock that is either destroyed or hasn't been initialized yet.

Next we need to fetch a lock of the appropriate type. As mentioned above, there are basically two modes of locks: a reader will want "non-exclusive" access, and a writer will want "exclusive" access. To keep the names simple, the functions are named after the user of the locks:

```
int
pthread_rwlock_rdlock (pthread_rwlock_t *lock);

int
pthread_rwlock_tryrdlock (pthread_rwlock_t *lock);

int
pthread_rwlock_wrlock (pthread_rwlock_t *lock);

int
pthread_rwlock_trywrlock (pthread_rwlock_t *lock);
```

There are four functions instead of the two that you may have expected. The "expected" functions are *pthread_rwlock_rdlock()* and *pthread_rwlock_wrlock()*, which are used by readers and writers, respectively. These are blocking calls — if the lock isn't available for the selected operation, the thread will block. When the lock becomes available in the appropriate mode, the thread will unblock. Because the thread unblocked from the call, it can now assume that it's safe to access the resource protected by the lock.

Sometimes, though, a thread won't want to block, but instead will want to see if it *could* get the lock. That's what the "try" versions are for. It's important to note that the "try" versions *will obtain the lock if they can*, but if they can't, then they won't block, but instead will just return an error indication. The reason they have to obtain the lock if they can is simple. Suppose that a thread wanted to obtain the lock for reading, but didn't want to wait in case it wasn't available. The thread calls *pthread_rwlock_tryrdlock()*, and is told that it could have the lock. If the *pthread_rwlock_tryrdlock() didn't* allocate the lock, then bad things could happen — another thread could preempt the one that was told to go ahead, and the second thread could lock the resource in an incompatible manner. Since the first thread wasn't actually given the lock, when the first thread goes to actually acquire the lock (because it was told it could), it would use *pthread_rwlock_rdlock()*, and now it would block, because the resource was no longer available in that mode. So, if we didn't lock it if we could, the thread that called the "try" version could still potentially block anyway!

Finally, regardless of the way that the lock was used, we need some way of releasing the lock:

```
int
pthread_rwlock_unlock (pthread_rwlock_t *lock);
```

Once a thread has done whatever operation it wanted to do on the resource, it would release the lock by calling *pthread_rwlock_unlock()*. If the lock is now available in a mode that corresponds to the mode requested by another waiting thread, then that thread would be made READY.

Note that we can't implement this form of synchronization with just a mutex. The mutex acts as a single-threading agent, which would be okay for the writing case (where you want only one thread to be using the resource at a time) but would fall flat in the reading case, because only one reader would be allowed. A semaphore couldn't be used either, because there's no way to distinguish the two modes of access — a semaphore would allow multiple readers, but if a writer were to acquire the semaphore, as far as the semaphore is concerned this would be no different from a reader acquiring it, and now you'd have the ugly situation of multiple readers and one *or more* writers!

Sleepon locks

Another common situation that occurs in multithreaded programs is the need for a thread to wait until "something happens." This "something" could be anything! It could be the fact that data is now available from a device, or that a conveyer belt has now moved to the proper position, or that data has been committed to disk, or whatever. Another twist to throw in here is that several threads may need to wait for the given event.

To accomplish this, we'd use either a *condition variable* (which we'll see next) or the much simpler "sleepon" lock.

To use sleepon locks, you actually need to perform several operations. Let's look at the calls first, and then look at how you'd use the locks.

```
int
pthread_sleepon_lock (void);

int
pthread_sleepon_unlock (void);

int
pthread_sleepon_broadcast (void *addr);

int
pthread_sleepon_signal (void *addr);

int
pthread_sleepon_wait (void *addr);
```

☞ Don't be tricked by the prefix *pthread_* into thinking that these are POSIX functions — they're not.

As described above, a thread needs to wait for something to happen. The most obvious choice in the list of functions above is the *pthread_sleepon_wait()*. But first, the thread needs to check if it really *does* have to wait. Let's set up an example. One thread is a producer thread that's getting data from some piece of hardware. The other thread is a consumer thread that's doing some form of processing on the data that just arrived. Let's look at the consumer first:

```
volatile int data_ready = 0;

consumer ()
{
    while (1) {
        while (!data_ready) {
            // WAIT
        }
        // process data
    }
}
```

The consumer is sitting in its main processing loop (the `while (1)`); it's going to do its job forever. The first thing it does is look at the *data_ready* flag. If this flag is a `0`, it means there's no data ready. Therefore, the consumer should wait. Somehow, the producer will wake it up, at which point the consumer should reexamine its *data_ready* flag. Let's say that's exactly what happens, and the consumer looks at the flag and decides that it's a `1`, meaning data is now available. The consumer goes off and processes the data, and then goes to see if there's more work to do, and so on.

We're going to run into a problem here. How does the consumer reset the *data_ready* flag in a synchronized manner with the producer? Obviously, we're going to need some form of exclusive access to the flag so that only one of those threads is modifying it at a given time. The method that's used in this case is built with a mutex, but it's a mutex that's buried in the implementation of the sleepon library, so we can access it only via two functions: *pthread_sleepon_lock()* and *pthread_sleepon_unlock()*. Let's modify our consumer:

```
consumer ()
{
    while (1) {
        pthread_sleepon_lock ();
        while (!data_ready) {
            // WAIT
        }
        // process data
        data_ready = 0;
        pthread_sleepon_unlock ();
    }
}
```

Now we've added the lock and unlock around the operation of the consumer. This means that the consumer can now *reliably* test the *data_ready* flag, with no race conditions, and also reliably set the flag.

Okay, great. Now what about the "WAIT" call? As we suggested earlier, it's effectively the *pthread_sleepon_wait()* call. Here's the second `while` loop:

```
    while (!data_ready) {
        pthread_sleepon_wait (&data_ready);
    }
```

The *pthread_sleepon_wait()* actually does three distinct steps!

1 Unlock the sleepon library mutex.

2 Perform the waiting operation.

3 Re-lock the sleepon library mutex.

The reason it has to unlock and lock the sleepon library's mutex is simple — since the whole idea of the mutex is to ensure mutual exclusion to the *data_ready* variable, this means that we want to lock out the producer from touching the *data_ready* variable while we're testing it. But, if we don't do the unlock part of the operation, the producer would never be able to set it to tell us that data is indeed available! The re-lock operation is done purely as a convenience; this way the user of the *pthread_sleepon_wait()* doesn't have to worry about the state of the lock when it wakes up.

Let's switch over to the producer side and see how it uses the sleepon library. Here's the full implementation:

```
producer ()
{
    while (1) {
        // wait for interrupt from hardware here...
        pthread_sleepon_lock ();
        data_ready = 1;
        pthread_sleepon_signal (&data_ready);
        pthread_sleepon_unlock ();
    }
}
```

As you can see, the producer locks the mutex as well so that it can have exclusive access to the *data_ready* variable in order to set it.

☞ It's *not* the act of writing a `1` to *data_ready* that awakens the client! It's the call to *pthread_sleepon_signal()* that does it.

Let's examine in detail what happens. We've identified the consumer and producer states as:

State	Meaning
CONDVAR	waiting for the underlying condition variable associated with the sleepon
MUTEX	waiting for a mutex
READY	capable of using, or already using, the CPU
INTERRUPT	waiting for an interrupt from the hardware

Action	Mutex owner	Consumer state	Producer state
consumer locks mutex	consumer	READY	INTERRUPT
consumer examines *data_ready*	consumer	READY	INTERRUPT
consumer calls *pthread_sleepon_wait()*	consumer	READY	INTERRUPT
pthread_sleepon_wait() unlocks mutex	free	READY	INTERRUPT
pthread_sleepon_wait() blocks	free	CONDVAR	INTERRUPT
time passes	free	CONDVAR	INTERRUPT
hardware generates data	free	CONDVAR	READY
producer locks mutex	producer	CONDVAR	READY

continued...

Action	Mutex owner	Consumer state	Producer state
producer sets *data_ready*	producer	CONDVAR	READY
producer calls *pthread_sleepon_signal()*	producer	CONDVAR	READY
consumer wakes up, *pthread_sleepon_wait()* tries to lock mutex	producer	MUTEX	READY
producer releases mutex	free	MUTEX	READY
consumer gets mutex	consumer	READY	READY
consumer processes data	consumer	READY	READY
producer waits for more data	consumer	READY	INTERRUPT
time passes (consumer processing)	consumer	READY	INTERRUPT
consumer finishes processing, unlocks mutex	free	READY	INTERRUPT
consumer loops back to top, locks mutex	consumer	READY	INTERRUPT

The last entry in the table is a repeat of the first entry — we've gone around one complete cycle.

What's the purpose of the *data_ready* variable? It actually serves two purposes:

- It's the status flag between the consumer and the producer that indicates the state of the system. If it's set to a `1`, it means that data is available for processing; if it's set to a `0`, it means that no data is available, and the consumer should block.
- It serves as "the place where sleepon synchronization occurs." More formally, the *address* of *data_ready* is used as a unique identifier, that serves as the rendezvous object for sleepon locks. We just as easily could have used "`(void *) 12345`" instead of "`&data_ready`" — so long as the identifier is unique and used consistently, the sleepon library really doesn't care. Actually,

using the address of a variable in a process is a guaranteed way to generate a process-unique number — after all, no two variables in a process will have the same address!

We'll defer the discussion of "What's the difference between *pthread_sleepon_signal()* and *pthread_sleepon_broadcast()* " to the discussion of condition variables next.

Condition variables

Condition variables (or "condvars") are remarkably similar to the sleepon locks we just saw above. In fact, sleepon locks are built on top of condvars, which is why we had a state of CONDVAR in the explanation table for the sleepon example. It bears repeating that the *pthread_cond_wait()* function releases the mutex, waits, and then reacquires the mutex, just like the *pthread_sleepon_wait()* function did.

Let's skip the preliminaries and redo the example of the producer and consumer from the sleepon section, using condvars instead. Then we'll discuss the calls.

```
/*
 * cp1.c
*/

#include <stdio.h>
#include <pthread.h>

int data_ready = 0;
pthread_mutex_t mutex = PTHREAD_MUTEX_INITIALIZER;
pthread_cond_t  condvar = PTHREAD_COND_INITIALIZER;

void *
consumer (void *notused)
{
    printf ("In consumer thread...\n");
    while (1) {
        pthread_mutex_lock (&mutex);
        while (!data_ready) {
            pthread_cond_wait (&condvar, &mutex);
        }
        // process data
        printf ("consumer:  got data from producer\n");
        data_ready = 0;
        pthread_cond_signal (&condvar);
        pthread_mutex_unlock (&mutex);
    }
}

void *
producer (void *notused)
{
    printf ("In producer thread...\n");
    while (1) {
        // get data from hardware
        // we'll simulate this with a sleep (1)
        sleep (1);
        printf ("producer:  got data from h/w\n");
        pthread_mutex_lock (&mutex);
        while (data_ready) {
            pthread_cond_wait (&condvar, &mutex);
        }
        data_ready = 1;
        pthread_cond_signal (&condvar);
        pthread_mutex_unlock (&mutex);
    }
}

main ()
{
    printf ("Starting consumer/producer example...\n");

    // create the producer and consumer threads
    pthread_create (NULL, NULL, producer, NULL);
    pthread_create (NULL, NULL, consumer, NULL);

    // let the threads run for a bit
    sleep (20);
}
```

Pretty much identical to the sleepon example we just saw, with a few variations (we also added some *printf()* functions and a *main()* so that the program would run!). Right away, the first thing that we see is a new data type: **`pthread_cond_t`**. This is simply the declaration of the condition variable; we've called ours *condvar*.

Next thing we notice is that the structure of the consumer is identical to that of the consumer in the previous sleepon example. We've replaced the *pthread_sleepon_lock()* and *pthread_sleepon_unlock()* with the standard mutex versions (*pthread_mutex_lock()* and *pthread_mutex_unlock()*). The *pthread_sleepon_wait()* was replaced with *pthread_cond_wait()*. The main difference is that the sleepon library has a mutex buried deep within it, whereas when we use condvars, we explicitly pass the mutex. We get a lot more flexibility this way.

Finally, we notice that we've got *pthread_cond_signal()* instead of *pthread_sleepon_signal()* (again with the mutex passed explicitly).

Signal versus broadcast

In the sleepon section, we promised to talk about the difference between the *pthread_sleepon_signal()* and *pthread_sleepon_broadcast()* functions. In the same breath, we'll talk about the difference between the two condvar functions *pthread_cond_signal()* and *pthread_cond_broadcast()*.

The short story is this: the "signal" version will wake up only one thread. So, if there were multiple threads blocked in the "wait" function, and a thread did the "signal," then only one of the threads would wake up. Which one? The highest priority one. If there are two or more at the same priority, the ordering of wakeup is indeterminate. With the "broadcast" version, *all* blocked threads will wake up.

It may seem wasteful to wake up all threads. On the other hand, it may seem sloppy to wake up only one (effectively random) thread.

Therefore, we should look at where it makes sense to use one over the other. Obviously, if you have only one thread waiting, as we did in either version of the consumer program, a "signal" will do just fine — one thread will wake up and, guess what, it'll be the only thread that's currently waiting.

In a multithreaded situation, we've got to ask: "Why are these threads waiting?" There are usually two possible answers:

- All the threads are considered equivalent and are effectively forming a "pool" of available threads that are ready to handle some form of request.

Or:

- The threads are all unique and are each waiting for a very specific condition to occur.

In the first case, we can imagine that all the threads have code that might look like the following:

```
/*
 * cv1.c
*/

thread1 ()
{
    for (;;) {
        pthread_mutex_lock (&mutex_data);
        while (data == 0) {
            pthread_cond_wait (&cv_data, &mutex_data);
        }
        // do something
        pthread_mutex_unlock (&mutex_data);
    }
}
// thread2, thread3, etc have the identical code.
```

In this case, it really doesn't matter *which* thread gets the data, provided that one of them gets it and does something with it.

However, if you have something like this, things are a little different:

```
/*
 * cv2.c
*/

thread1 ()
{
    for (;;) {
        pthread_mutex_lock (&mutex_xy);
        while ((x > 7) && (y != 15)) {
            pthread_cond_wait (&cv_xy, &mutex_xy);
        }
        // do something
        pthread_mutex_unlock (&mutex_xy);
    }
}

thread2 ()
{
    for (;;) {
        pthread_mutex_lock (&mutex_xy);
        while (!isprime (x)) {
            pthread_cond_wait (&cv_xy, &mutex_xy);
        }
        // do something
        pthread_mutex_unlock (&mutex_xy);
    }
}

thread3 ()
{
    for (;;) {
        pthread_mutex_lock (&mutex_xy);
        while (x != y) {
            pthread_cond_wait (&cv_xy, &mutex_xy);
        }
        // do something
        pthread_mutex_unlock (&mutex_xy);
    }
}
```

In these cases, waking up one thread isn't going to cut it! We *must* wake up all three threads and have each of them check to see if its predicate has been satisfied or not.

This nicely reflects the second case in our question above ("Why are these threads waiting?"). Since the threads are all waiting on different conditions (*thread1()* is waiting for *x* to be less than or equal to 7 or *y* to be 15, *thread2()* is waiting for *x* to be a prime number, and *thread3()* is waiting for *x* to be equal to *y*), we have no choice but to wake them all.

Sleepons versus condvars

Sleepons have one principal advantage over condvars. Suppose that you want to synchronize many objects. With condvars, you'd typically associate one condvar per object. Therefore, if you had *M* objects, you'd most likely have *M* condvars. With sleepons, the underlying condvars (on top of which sleepons are implemented) are allocated dynamically as threads wait for a particular object. Therefore, using sleepons with *M* objects and *N* threads blocked, you'd have (at most) *N* condvars (instead of *M*).

However, condvars are more flexible than sleepons, because:

1 Sleepons are built on top of condvars anyway.

2 Sleepons have the mutex buried in the library; condvars allow you to specify it explicitly.

The first point might just be viewed as being argumentative. `:-)` The second point, however, is significant. When the mutex is buried in the library, this means that there can be only *one* per process — regardless of the number of threads in that process, or the number of different "sets" of data variables. This can be a very limiting factor, especially when you consider that you must use the *one and only* mutex to access *any and all* data variables that *any* thread in the process needs to touch!

A much better design is to use multiple mutexes, one for each data set, and explicitly combine them with condition variables as required. The true power and danger of this approach is that there is absolutely *no* compile time or run time checking to make sure that you:

- have locked the mutex before manipulating a variable
- are using the correct mutex for the particular variable
- are using the correct condvar with the appropriate mutex and variable

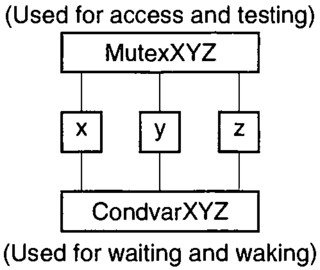
The easiest way around these problems is to have a good design and design review, and also to borrow techniques from object-oriented programming (like having the mutex contained in a data structure, having routines to access the data structure, etc.). Of course, how much of one or both you apply depends not only on your personal style, but also on performance requirements.

The key points to remember when using condvars are:

1 The mutex is to be used for testing and accessing the variables.

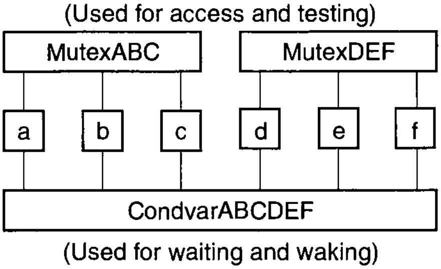
2 The condvar is to be used as a rendezvous point.

Here's a picture:



One-to-one mutex and condvar associations.

One interesting note. Since there *is* no checking, you can do things like associate one set of variables with mutex "ABC," and another set of variables with mutex "DEF," while associating *both* sets of variables with condvar "ABCDEF:"



Many-to-one mutex and condvar associations.

This is actually quite useful. Since the mutex is always to be used for "access and testing," this implies that I have to choose the correct mutex whenever I want to look at a particular variable. Fair enough — if I'm examining variable "C," I obviously need to lock mutex "MutexABC." What if I changed variable "E"? Well, before I change it, I had to acquire the mutex "MutexDEF." Then I changed it, and hit condvar "CondvarABCDEF" to tell others about the change. Shortly thereafter, I would release the mutex.

Now, consider what happens. Suddenly, I have a bunch of threads that had been waiting on "CondvarABCDEF" that now wake up (from their *pthread_cond_wait()*). The waiting function immediately attempts to reacquire the mutex. The critical point here is that there are two mutexes to acquire. This means that on an SMP system, *two concurrent streams* of threads can run, each examining what it considers to be independent variables, using independent mutexes. Cool, eh?

Additional Neutrino services

Neutrino lets you do something else that's elegant. POSIX says that a mutex must operate between threads in the same process, and lets a conforming implementation extend that. Neutrino extends this by allowing a mutex to operate between threads in *different* processes. To understand why this works, recall that there really are two parts to what's viewed as the "operating system" — the kernel, which deals with scheduling, and the process manager, which worries about memory protection and "processes" (among other things). A mutex is really just a synchronization object used between threads. Since the kernel worries only about threads, it really doesn't care that the threads are operating in different processes — this is an issue for the process manager.

So, if you've set up a shared memory area between two processes, and you've initialized a mutex in that shared memory, there's nothing stopping you from synchronizing multiple threads in those two (or more!) processes via the mutex. The same *pthread_mutex_lock()* and *pthread_mutex_unlock()* functions will still work.

Pools of threads

Another thing that Neutrino has added is the concept of thread pools. You'll often notice in your programs that you want to be able to run a certain number of threads, but you also want to be able to control the behavior of those threads within certain limits. For example, in a server you may decide that initially just one thread should be blocked, waiting for a message from a client. When that thread gets a message and is off servicing a request, you may decide that it would be a good idea to create another thread, so that it could be blocked waiting in case another request arrived. This second thread would then be available to handle that request. And so on. After a while, when the requests had been serviced, you would now have a large number of threads sitting around, waiting for further requests. In order to conserve resources, you may decide to kill off some of those "extra" threads.

This is in fact a common operation, and Neutrino provides a library to help with this.

☞ In Neutrino versions before release 2.00, functionality very similar to this was buried inside the resource manager library, but in release 2.00 it was moved out of the resource manager library and into its own set of functions. We'll see the thread pool functions again when we look at the Resource Managers chapter.

It's important for the discussions that follow to realize there are really two distinct operations that threads (that are used in thread pools) perform:

- a blocking (waiting operation)
- a processing operation

The blocking operation doesn't generally consume CPU. In a typical server, this is where the thread is waiting for a message to arrive. Contrast that with the processing operation, where the thread may or may not be consuming CPU (depending on how the process is structured). In the thread pool functions that we'll look at later, you'll see that we have the ability to control the number of threads in the blocking operation as well as the number of threads that are in the processing operations.

Neutrino provides the following functions to deal with thread pools:

```
#include <sys/dispatch.h>

thread_pool_t *
thread_pool_create (thread_pool_attr_t *attr,
                    unsigned flags);
```

```
int
thread_pool_destroy (thread_pool_t *pool);

int
thread_pool_start (void *pool);

int
thread_pool_limits (thread_pool_t *pool,
                    int lowater,
                    int hiwater,
                    int maximum,
                    int increment,
                    unsigned flags);

int
thread_pool_control (thread_pool_t *pool,
                     thread_pool_attr_t *attr,
                     uint16_t lower,
                     uint16_t upper,
                     unsigned flags);
```

As you can see from the functions provided, you first create a thread pool definition using *thread_pool_create()*, and then start the thread pool via *thread_pool_start()*. When you're done with the thread pool, you can use *thread_pool_destroy()* to clean up after yourself. Note that you might never call *thread_pool_destroy()*, as in the case where the program is a server that runs "forever." The *thread_pool_limits()* function is used to specify thread pool behavior and adjust attributes of the thread pool, and the *thread_pool_control()* function is a convenience wrapper for the *thread_pool_limits()* function.

So, the first function to look at is *thread_pool_create()*. It takes two parameters, *attr* and *flags*. The *attr* is an attributes structure that defines the operating characteristics of the thread pool (from **<sys/dispatch.h>**):

```
typedef struct _thread_pool_attr {
    // thread pool functions and handle
    THREAD_POOL_HANDLE_T    *handle;

    THREAD_POOL_PARAM_T
        *(*block_func) (THREAD_POOL_PARAM_T *ctp);

    void
```

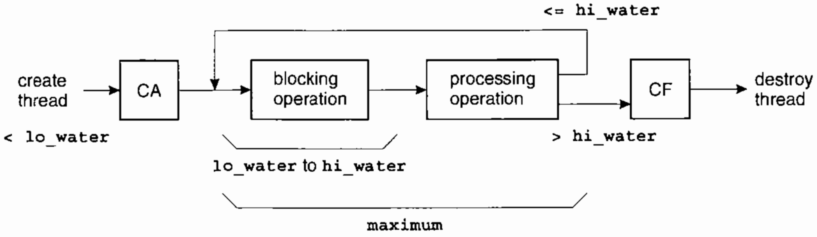
```
        (*unblock_func) (THREAD_POOL_PARAM_T *ctp);

    int
        (*handler_func) (THREAD_POOL_PARAM_T *ctp);

    THREAD_POOL_PARAM_T
        *(*context_alloc) (THREAD_POOL_HANDLE_T *handle);

    void
        (*context_free) (THREAD_POOL_PARAM_T *ctp);

    // thread pool parameters
    pthread_attr_t          *attr;
    unsigned short          lo_water;
    unsigned short          increment;
    unsigned short          hi_water;
    unsigned short          maximum;
} thread_pool_attr_t;
```

I've broken the **thread_pool_attr_t** type into two sections, one that contains the functions and handle for the threads in the thread pool, and another that contains the operating parameters for the thread pool.

Controlling the number of threads

Let's first look at the "thread pool parameters" to see how you control the number and attributes of threads that will be operating in this thread pool. Keep in mind that we'll be talking about the "blocking operation" and the "processing operation" (when we look at the callout functions, we'll see how these relate to each other).

The following diagram illustrates the relationship of the *lo_water*, *hi_water*, and *maximum* parameters:



Thread flow when using thread pools.

(Note that "CA" is the *context_alloc()* function, "CF" is the *context_free()* function, "blocking operation" is the *block_func()* function, and "processing operation" is the *handler_func()*.)

attr This is the attributes structure that's used during thread creation. We've already discussed this structure above (in "The thread attributes structure"). You'll recall that this is the structure that controls things about the newly created thread like priority, stack size, and so on.

lo_water There should always be at least *lo_water* threads sitting in the blocking operation. In a typical server, this would be the number of threads waiting to receive a message, for example. If there are less than *lo_water* threads sitting in the blocking operation (because, for example, we just received a message and have started the processing operation on that message), then more threads are created, according to the *increment* parameter. This is represented in the diagram by the first step labeled "create thread."

increment Indicates how many threads should be created at once if the count of blocking operation threads ever drops under *lo_water*. In deciding how to choose a value for this, you'd most likely start with `1`. This means that if the number of threads in the blocking operation drops under *lo_water*, exactly one more thread would be created by the thread pool. To fine-tune the number that you've selected for *increment*, you could observe the behavior of the process and determine whether this number needs to be anything other than one. If, for example, you notice that your process gets "bursts" of requests, then you might decide that once you've dropped below *lo_water* blocking operation threads, you're probably going to encounter this "burst" of requests, so you might decide to request the creation of more than one thread at a time.

hi_water Indicates the upper limit on the number of threads that should be in the blocking operation. As threads complete their processing operations, they will normally return to the blocking operation. However, the thread pool library keeps count of how many threads are currently in the blocking operation, and if that number ever exceeds *hi_water*, the thread pool library will kill the thread that caused the overflow (i.e., the thread that had just finished and was about to go back to the blocking operation). This is shown in the diagram as the "split" out of the "processing operation" block, with one path going to the "blocking operation" and the other path going to "CF" to destroy the thread. The combination of *lo_water* and *hi_water*, therefore, allows you to specify a range indicating how many threads should be in the blocking operation.

maximum Indicates the absolute maximum number of threads that will ever run concurrently as a result of the thread pool library. For example, if threads were being created as a result of an underflow of the *lo_water* mark, the *maximum* parameter would limit the total number of threads.

One other key parameter to controlling the threads is the *flags* parameter passed to the *thread_pool_create()* function. It can have one of the following values:

POOL_FLAG_EXIT_SELF

The *thread_pool_start()* function will not return, nor will the calling thread be incorporated into the pool of threads.

POOL_FLAG_USE_SELF

The *thread_pool_start()* function will not return, but the calling thread will be incorporated into the pool of threads.

0 The *thread_pool_start()* function will return, with new threads being created as required.

The above descriptions may seem a little dry. Let's look at an example.

We'll just focus on the *lo_water*, *hi_water*, *increment*, and the *maximum* members of the thread pool control structure:

```
/*
 * part of tp1.c
*/

#include <sys/dispatch.h>

int
main ()
{
    thread_pool_attr_t  tp_attr;
    void                *tpp;

    ...
    tp_attr.lo_water  = 3;
    tp_attr.increment = 2;
    tp_attr.hi_water  = 7;
    tp_attr.maximum   = 10;
    ...

    tpp = thread_pool_create (&tp_attr, POOL_FLAG_USE_SELF);
    if (tpp == NULL) {
        fprintf (stderr,
         "%s:  can't thread_pool_create, errno %s\n",
                progname, strerror (errno));
        exit (EXIT_FAILURE);
    }

    thread_pool_start (tpp);
    ...
```

After setting the members, we call *thread_pool_create()* to create a thread pool. This returns a pointer to a thread pool control structure (*tpp*), which we check against NULL (which would indicate an error). Finally we call *thread_pool_start()* with the *tpp* thread pool control structure.

I've specified POOL_FLAG_USE_SELF which means that the thread that called *thread_pool_start()* will be considered an available thread for the thread pool. So, at this point, there is only that one thread in the thread pool library. Since we have a *lo_water* value of 3, the library immediately creates *increment* number of threads (2 in this case). At this point, 3 threads are in the library, and all 3 of them are in the blocking operation. The *lo_water* condition is satisfied, because there are at least that number of threads in the blocking operation; the *hi_water* condition is satisfied, because there are less than that number of threads in the blocking operation; and finally, the *maximum* condition is satisfied as well, because we don't have more than that number of threads in the thread pool library.

Now, one of the threads in the blocking operation unblocks (e.g., in a server application, a message was received). This means that now one of the three threads is no longer in the blocking operation (instead, that thread is now in the processing operation). Since the count of blocking threads is less than the *lo_water*, it trips the *lo_water* trigger and causes the library to create *increment* (2) threads. So now there are 5 threads total (4 in the blocking operation, and 1 in the processing operation).

More threads unblock. Let's assume that none of the threads in the processing operation none completes any of their requests yet. Here's a table illustrating this, starting at the initial state (we've used "Proc Op" for the processing operation, and "Blk Op" for the blocking operation, as we did in the previous diagram, "Thread flow when using thread pools."):

Event	Proc Op	Blk Op	Total
Initial	0	1	1
lo_water trip	0	3	3
Unblock	1	2	3
lo_water trip	1	4	5
Unblock	2	3	5
Unblock	3	2	5
lo_water trip	3	4	7
Unblock	4	3	7
Unblock	5	2	7
lo_water trip	5	4	9
Unblock	6	3	9
Unblock	7	2	9
lo_water trip	7	3	10
Unblock	8	2	10
Unblock	9	1	10
Unblock	10	0	10

As you can see, the library always checks the *lo_water* variable and creates *increment* threads at a time *until* it hits the limit of the *maximum* variable (as it did when the "Total" column reached 10 — no more threads were being created, even though the count had underflowed the *lo_water*).

This means that at this point, there are no more threads waiting in the blocking operation. Let's assume that the threads are now finishing their requests (from the processing operation); watch what happens with the *hi_water* trigger:

Event	Proc Op	Blk Op	Total
completion	9	1	10
completion	8	2	10
completion	7	3	10
completion	6	4	10
completion	5	5	10
completion	4	6	10
completion	3	7	10
completion	2	8	10
hi_water trip	2	7	9
completion	1	8	9
hi_water trip	1	7	8
completion	0	8	8
hi_water trip	0	7	7

Notice how nothing really happened during the completion of processing for the threads *until* we tripped over the *hi_water* trigger. The implementation is that as soon as the thread finishes, it looks at the number of receive blocked threads and decides to kill itself if there are too many (i.e., more than *hi_water*) waiting at that point. The nice thing about the *lo_water* and *hi_water* limits in the structures is that you can effectively have an "operating range" where a sufficient number of threads are available, and you're not unnecessarily creating and destroying threads. In our case, after the operations performed by the above tables, we now have a system that can handle up to 4 requests simultaneously without creating more threads (7 - 4 = 3, which is the *lo_water* trip).

The thread pool functions

Now that we have a good feel for how the number of threads is controlled, let's turn our attention to the other members of the thread pool attribute structure (from above):

```
// thread pool functions and handle
THREAD_POOL_HANDLE_T     *handle;

THREAD_POOL_PARAM_T
    *(*block_func) (THREAD_POOL_PARAM_T *ctp);

void
    (*unblock_func) (THREAD_POOL_PARAM_T *ctp);

int
    (*handler_func) (THREAD_POOL_PARAM_T *ctp);

THREAD_POOL_PARAM_T
    *(*context_alloc) (THREAD_POOL_HANDLE_T *handle);

void
    (*context_free) (THREAD_POOL_PARAM_T *ctp);
```

Recall from the diagram "Thread flow when using thread pools," that the *context_alloc()* function gets called for every new thread being created. (Similarly, the *context_free()* function gets called for every thread being destroyed.)

The *handle* member of the structure (above) is passed to the *context_alloc()* function as its sole parameter. The *context_alloc()* function is responsible for performing any *per-thread* setup required and for returning a context pointer (called *ctp* in the parameter lists). Note that the contents of the context pointer are entirely up to you — the library doesn't care what you put into the context pointer.

Now that the context has been created by *context_alloc()*, the *block_func()* function is called to perform the blocking operation. Note that the *block_func()* function gets passed the results of the *context_alloc()* function. Once the *block_func()* function unblocks, it returns a context pointer, which gets passed by the library to the *handler_func()*. The *handler_func()* is responsible for performing the "work" — for example, in a typical server, this is where the message from the client is processed. The *handler_func()* must return a zero for now — non-zero values are reserved for future expansion by QSSL. The *unblock_func()* is also reserved at this time; just leave it as NULL. Perhaps this pseudo code sample will clear things up (it's based on the same flow as shown in "Thread flow when using thread pools," above):

```
FOREVER DO
    IF (#threads < lo_water) THEN
        IF (#threads_total < maximum) THEN
            create new thread
            context = (*context_alloc) (handle);
        ENDIF
    ENDIF
    retval = (*block_func) (context);
    (*handler_func) (retval);
    IF (#threads > hi_water) THEN
        (*context_free) (context)
        kill thread
    ENDIF
DONE
```

Note that the above is greatly simplified; its only purpose is to show you the data flow of the *ctp* and *handle* parameters and to give some sense of the algorithms used to control the number of threads.

Scheduling and the real world

So far we've talked about scheduling algorithms and thread states, but we haven't said much yet about *why* and *when* things are rescheduled. There's a common misconception that rescheduling just "occurs," without any real causes. Actually, this is a useful abstraction during design! But it's important to understand the conditions that cause rescheduling. Recall the diagram "Scheduling roadmap" (in the "The kernel's role" section).

Rescheduling occurs *only* because of:

- a hardware interrupt
- a kernel call

- a fault

Rescheduling — hardware interrupts

Rescheduling due to a hardware interrupt occurs in two cases:

- timers
- other hardware

The realtime clock generates periodic interrupts for the kernel, causing time-based rescheduling.

For example, if you issue a `sleep (10);` call, a number of realtime clock interrupts will occur; the kernel increments the time-of-day clock at each interrupt. When the time-of-day clock indicates that 10 seconds have elapsed, the kernel reschedules your thread as READY. (This is discussed in more detail in the Clocks, Timers, and Getting a Kick Every So Often chapter.)

Other threads might wait for hardware interrupts from peripherals, such as the serial port, a hard disk, or an audio card. In this case, they are blocked in the kernel waiting for a hardware interrupt; the thread will be rescheduled by the kernel only after that "event" is generated.

Rescheduling — kernel calls

If the rescheduling is caused by a thread issuing a kernel call, the rescheduling is done immediately and can be considered asynchronous to the timer and other interrupts.

For example, above we called `sleep(10);`. This C library function is eventually translated into a kernel call. At that point, the kernel made a rescheduling decision to take your thread off of the READY queue for that priority, and then schedule another thread that was READY.

There are many kernel calls that cause a process to be rescheduled. Most of them are fairly obvious. Here are a few:

- timer functions (e.g., *sleep()*)
- messaging functions (e.g., *MsgSendv()*)

- thread primitives, (e.g., *pthread_cancel()*, *pthread_join()*)

Rescheduling — exceptions

The final cause of rescheduling, a CPU fault, is an *exception*, somewhere between a hardware interrupt and a kernel call. It operates asynchronously to the kernel (like an interrupt) but operates synchronously with the user code that caused it (like a kernel call — for example, a divide-by-zero exception). The same discussion as above (for hardware interrupts and kernel calls) applies to faults.

Summary

Neutrino offers a rich set of scheduling options with threads, the primary scheduling elements. Processes are defined as a unit of resource ownership (e.g., a memory area) and contain one or more threads.

Threads can use any of the following synchronization methods:

- mutexes — allow only one thread to own the mutex at a given point in time.
- semaphores — allow a fixed number of threads to "own" the semaphore.
- sleepons — allow a number of threads to block on a number of objects, while allocating the underlying condvars dynamically to the blocked threads.
- condvars — similar to sleepons except that the allocation of the condvars is controlled by the programmer.
- joining — allows a thread to synchronize to the termination of another thread.
- barriers — allows threads to wait until a number of threads have reached the synchronization point.

Note that mutexes, semaphores, and condition variables can be used between threads in the same or different processes, but that sleepons can be used only between threads in the same process (because the library has a mutex "hidden" in the process's address space).

As well as synchronization, threads can be scheduled (using a priority and a scheduling algorithm), and they'll automatically run on a single-processor box or an SMP box.

Whenever we talk about creating a "process" (mainly as a means of porting code from single-threaded implementations), we're really creating an address space with one thread running in it — that thread starts at *main()* or at *fork()* or *vfork()* depending on the function called.

Chapter 2

Message Passing

In this chapter...

Messaging fundamentals

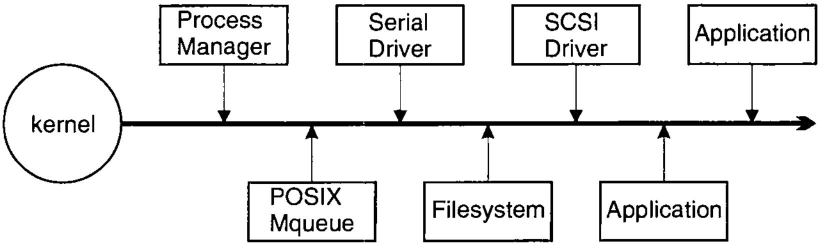
In this chapter, we'll look at the most distinctive feature of Neutrino, *message passing*. Message passing lies at the heart of the operating system's microkernel architecture, giving the OS its modularity.

A small microkernel and message passing

One of the principal advantages of Neutrino is that it's scalable. By "scalable" I mean that it can be tailored to work on tiny embedded boxes with tight memory constraints, right up to large networks of multiprocessor SMP boxes with almost unlimited memory.

Neutrino achieves its scalability by making each service-providing component *modular*. This way, you can include only the components you need in the final system. By using threads in the design, you'll also help to make it scalable to SMP systems (we'll see some more uses for threads in this chapter).

This is the philosophy that was used during the initial design of the QNX family of operating systems and has been carried through to this day. The key is a small *microkernel* architecture, with modules that would traditionally be incorporated into a monolithic kernel as optional components.



Neutrino's modular architecture.

You, the system architect, decide which modules you want. Do you need a filesystem in your project? If so, then add one. If you don't need one, then don't bother including one. Do you need a serial port driver? Whether the answer is yes or no, this doesn't affect (nor is it affected by) your previous decision about the filesystem.

At run time, you can decide which system components are included in the running system. You can dynamically remove components from a live system and reinstall them, or others, at some other time. Is there anything special about these "drivers"? Nope, they're just regular, user-level programs that happen to perform a specific job with the hardware. In fact, we'll see how to write them in the Resource Managers chapter.

The key to accomplishing this is message passing. Instead of having the OS modules bound directly into the kernel, and having some kind of "special" arrangement with the kernel, under Neutrino the modules communicate via message passing among themselves. The kernel is basically responsible only for thread-level services (e.g., scheduling). In fact, message passing isn't used just for this installation and deinstallation trick — it's the fundamental building block for almost all other services (for example, memory allocation is performed by a message to the process manager). Of course, some services are provided by direct kernel calls.

Consider opening a file and writing a block of data to it. This is accomplished by a number of messages sent from the application to an installable component of Neutrino called the filesystem. The message tells the filesystem to open a file, and then another message tells it to write some data (and contains that data). Don't worry though — the Neutrino operating system performs message passing *very* quickly.

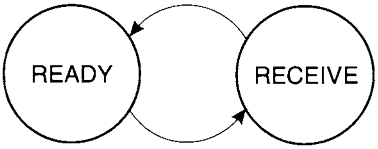
Message passing and client/server

Imagine an application reading data from the filesystem. In QNX lingo, the application is a *client* requesting the data from a *server*.

This client/server model introduces several process states associated with message passing (we talked about these in the Processes and Threads chapter). Initially, the server is waiting for a message to arrive from somewhere. At this point, the server is said to be *receive-blocked* (also known as the RECV state). Here's some sample **pidin** output:

```
pid    tid name                 prio STATE       Blocked
     4   1 devc-pty              10r RECEIVE     1
```

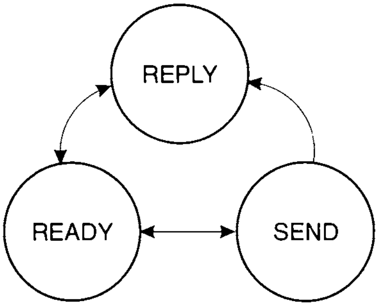
In the above sample, the pseudo-tty server (called **devc-pty**) is process ID 4, has one thread (thread ID 1), is running at priority 10 Round-Robin, and is receive-blocked, waiting for a message from channel ID 1 (we'll see all about "channels" shortly).



State transitions of server.

When a message is received, the server goes into the READY state, and is capable of running. If it happens to be the highest-priority READY process, it gets the CPU and can perform some processing. Since it's a server, it looks at the message it just got and decides what to do about it. At some point, the server will complete whatever job the message told it to do, and then will "reply" to the client.

Let's switch over to the client. Initially the client was running along, consuming CPU, until it decided to send a message. The client changed from READY to either *send-blocked* or *reply-blocked*, depending on the state of the server that it sent a message to.



State transitions of clients.

Generally, you'll see the reply-blocked state much more often than the send-blocked state. That's because the reply-blocked state means:

> The server has received the message and is now processing it. At some point, the server will complete processing and will reply to the client. The client is blocked waiting for this reply.

Contrast that with the send-blocked state:

> The server hasn't yet received the message, most likely because it was busy handling another message first. When the server gets around to "receiving" your (client) message, then you'll go from the send-blocked state to the reply-blocked state.

In practice, if you see a process that is send-blocked it means one of two things:

1. You happened to take a snapshot of the system in a situation where the server was busy servicing a client, and a new request arrived for that server.

This is a normal situation — you can verify it by running **pidin** again to get a new snapshot. This time you'll probably see that the process is no longer send-blocked.

2. The server has encountered a bug and for whatever reason isn't listening to requests anymore.

   When this happens, you'll see many processes that are send-blocked on one server. To verify this, run **pidin** again, observing that there's no change in the blocked state of the client processes.

Here's a sample showing a reply-blocked client and the server it's blocked on:

```
   pid tid name               prio STATE       Blocked
     1   1 to/x86/sys/procnto   0f READY
     1   2 to/x86/sys/procnto  10r RECEIVE     1
     1   3 to/x86/sys/procnto  10r NANOSLEEP
     1   4 to/x86/sys/procnto  10r RUNNING
     1   5 to/x86/sys/procnto  15r RECEIVE     1
 16426   1 esh                 10r REPLY       1
```

This shows that the program **esh** (the embedded shell) has sent a message to process number 1 (the kernel and process manager, **procnto**) and is now waiting for a reply.

Now you know the basics of message passing in a client/server architecture.

So now you might be thinking, "Do I have to write special Neutrino message-passing calls just to open a file or write some data?!?"

You don't have to write *any* message-passing functions, unless you want to get "under the hood" (which I'll talk about a little later). In fact, let me show you some client code that does message passing:

```
#include <fcntl.h>
#include <unistd.h>

int
main (void)
{
    int     fd;

    fd = open ("filename", O_WRONLY);
    write (fd, "This is message passing\n", 24);
    close (fd);

    return (EXIT_SUCCESS);
}
```

See? Standard C code, nothing tricky.

The message passing is done by the Neutrino C library. You simply issue standard POSIX 1003.1 or ANSI C function calls, and the C library does the message-passing work for you.

In the above example, we saw three functions being called and three distinct messages being sent:

- *open()* sent an "open" message
- *write()* sent a "write" message
- *close()* sent a "close" message

We'll be discussing the messages themselves in a lot more detail when we look at resource managers (in the Resource Managers chapter), but for now all you need to know is the fact that different types of messages were sent.

Let's step back for a moment and contrast this to the way the example would have worked in a traditional operating system.

The client code would remain the same and the differences would be hidden by the C library provided by the vendor. On such a system, the *open()* function call would invoke a kernel function, which would then call directly into the filesystem, which would execute some code, and return a file descriptor. The *write()* and *close()* calls would do the same thing.

So? Is there an advantage to doing things this way? Keep reading!

Network-distributed message passing

Suppose we want to change our example above to talk to a different node on the network. You might think that we'll have to invoke special function calls to "get networked." Here's the network version's code:

```
#include <fcntl.h>
#include <unistd.h>

int
main (void)
{
    int     fd;

    fd = open ("/net/wintermute/home/rk/filename", O_WRONLY);
    write (fd, "This is message passing\n", 24);
    close (fd);

    return (EXIT_SUCCESS);
}
```

You're right if you think the code is almost the same in both versions. It is.

In a traditional OS, the C library *open()* calls into the kernel, which looks at the filename and says "oops, this is on a different node." The kernel then calls into the network filesystem (NFS) code, which figures out where **/net/wintermute/home/rk/filename** actually is. Then, NFS calls into the network driver and *sends a message* to the kernel on node **wintermute**, which then repeats the process that we described in our original example. Note that in this case, there are really two filesystems involved; one is the NFS client filesystem, and one is the remote filesystem. Unfortunately, depending on the implementation of the remote filesystem and NFS, certain operations may not work as expected (e.g., file locking) due to incompatibilities.

Under Neutrino, the C library *open()* creates the *same* message that it would have sent to the local filesystem and sends it to the filesystem on node `wintermute`. In the local and remote cases, the *exact* same filesystem is used.

This is another fundamental characteristic of Neutrino: network-distributed operations are essentially "free," as the work to decouple the functionality requirements of the clients from the services provided by the servers is already done, by virtue of message passing.

On a traditional kernel there's a "double standard" where local services are implemented one way, and remote (network) services are implemented in a totally different way.

What it means for you

Message passing is elegant and network-distributed. So what? What does it buy you, the programmer?

Well, it means that your programs inherit those characteristics — they too can become network-distributed with far less work than on other systems. But the benefit that I find most useful is that they let you test software in a nice, modular manner.

You've probably worked on large projects where many people have to provide different pieces of the software. Of course, some of these people are done sooner or later than others.

These projects often have problems at two stages: initially at project definition time, when it's hard to decide where one person's development effort ends and another's begins, and then at testing/integration time, when it isn't possible to do full systems integration testing because all the pieces aren't available.

With message passing, the individual components of a project can be decoupled very easily, leading to a very simple design and reasonably simple testing. If you want to think about this in terms of existing paradigms, it's very similar to the concepts used in Object Oriented Programming (OOP).

What this boils down to is that testing can be performed on a piece-by-piece basis. You can set up a simple program that sends messages to your server process, and since the inputs and outputs of that server process are (or should be!) well documented, you can determine if that process is functioning. Heck, these test cases can even be automated and placed in a regression suite that runs periodically!

The philosophy of Neutrino

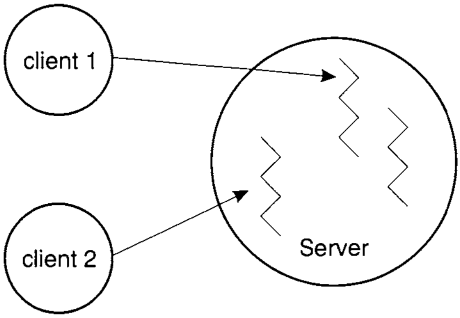
Message passing is at the heart of the philosophy of Neutrino. Understanding the uses and implications of message passing will be the key to making effective use of the OS. Before we go into the details, let's look at a little bit of theory first.

Multiple threads

Although the client/server model is easy to understand, and the most commonly used, there are two other variations on the theme. The first is the use of multiple threads (the topic of this section), and the second is a model called *server/subserver* that's sometimes useful for general design, but really shines in network-distributed designs. The combination of the two can be extremely powerful, especially on a network of SMP boxes!

As we discussed in the Processes and Threads chapter, Neutrino has the ability to run multiple threads of execution in the same process. How can we use this to our advantage when we combine this with message passing?

The answer is fairly simple. We can start a *pool of threads* (using the *thread_pool_*()* functions that we talked about in the Processes and Threads chapter), each of which can handle a message from a client:



Clients accessing threads in a server.

This way, when a client sends us a message, we really don't care *which* thread gets it, as long as the work gets done. This has a number of advantages. The ability to service multiple clients with multiple threads, versus servicing multiple clients with just one thread, is a powerful concept. The main advantage is that the kernel can multitask the server among the various clients, without the server itself having to perform the multitasking.

On a single-processor machine, having a bunch of threads running means that they're all competing with each other for CPU time.

But, on an SMP box, we can have multiple threads competing for multiple CPUs, while sharing the same data area across those multiple CPUs. This means that we're limited only by the number of available CPUs on that particular machine.

Server/subserver

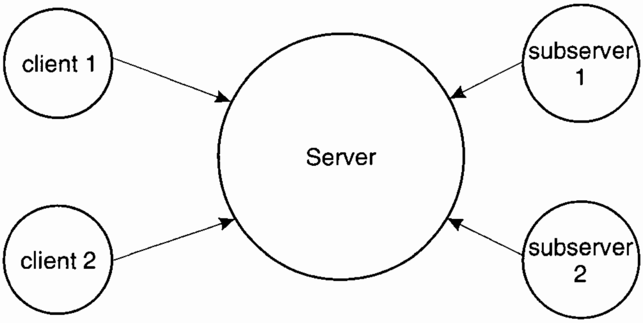
Let's now look at the server/subserver model, and then we'll combine it with the multiple threads model.

In this model, a server still provides a service to clients, but because these requests may take a long time to complete, we need to be able to start a request and still be able to handle new requests as they arrive from other clients.

If we tried to do this with the traditional single-threaded client/server model, once one request was received and started, we wouldn't be able to receive any more requests unless we periodically stopped what we were doing, took a quick peek to see if there were any other requests pending, put those on a work queue, and then continued on, distributing our attention over the various jobs in the work queue. Not very efficient. You're practically duplicating the work of the kernel by "time slicing" between multiple jobs!

Imagine what this would look like if *you* were doing it. You're at your desk, and someone walks up to you with a folder full of work. You start working on it. As you're busy working, you notice that someone else is standing in the doorway of your cubicle with more work of equally high priority (of course)! Now you've got two piles of work on your desk. You're spending a few minutes on one pile, switching over to the other pile, and so on, all the while looking at your doorway to see if someone else is coming around with even more work.

The server/subserver model would make a lot more sense here. In this model, we have a server that creates several other processes (the subservers). These subservers each send a message to the server, but the server doesn't reply to them until it gets a request from a client. Then it passes the client's request to one of the subservers by replying to it with the job that it should perform. The following diagram illustrates this. Note the direction of the arrows — they indicate the direction of the sends!



Server/subserver model.

If you were doing a job like this, you'd start by hiring some extra employees. These employees would all come to you (just as the subservers send a message to the server — hence the note about the arrows in the diagram above), looking for work to do. Initially, you might not have any, so you wouldn't reply to their query. When someone comes into your office with a folder full of work, you say to one of your employees, "Here's some work for you to do." That employee then goes off and does the work. As other jobs come in, you'd delegate them to the other employees.

The trick to this model is that it's *reply-driven* — the work starts when you *reply* to your subservers. The standard client/server model is *send-driven* because the work starts when you send the server a message.

So why would the clients march into *your* office, and not the offices of the employees that you hired? Why are you "arbitrating" the work? The answer is fairly simple: you're the coordinator responsible for performing a particular task. It's up to you to ensure that the work is done. The clients that come to you with their work know you, but they don't know the names or locations of your (perhaps temporary) employees.

As you probably suspected, you can certainly mix multithreaded servers with the server/subserver model. The main trick is going to be determining which parts of the "problem" are best suited to being distributed over a network (generally those parts that won't use up the network bandwidth too much) and which parts are best suited to being distributed over the SMP architecture (generally those parts that want to use common data areas).

So why would we use one over the other? Using the server/subserver approach, we can distribute the work over multiple machines on a network. This effectively means that we're limited only by the number of available machines on the network (and network bandwidth, of course). Combining this with multiple threads on a bunch of SMP boxes distributed over a network yields "clusters of computing," where the central "arbitrator" delegates work (via the server/subserver model) to the SMP boxes on the network.

Some examples

Now we'll consider a few examples of each method.

Send-driven (client/server)

Filesystems, serial ports, consoles, and sound cards all use the client/server model. A C language application program takes on the role of the client and sends requests to these servers. The servers perform whatever work was specified, and reply with the answer.

Some of these traditional "client/server" servers may in fact actually be reply-driven (server/subserver) servers! This is because, to the ultimate client, they *appear* as a standard server, even though the server itself uses server/subserver methods to get the work done. What I mean by that is, the client still sends a message to what it thinks is the "service providing process." What actually happens is that the "service providing process" simply delegates the client's work to a different process (the subserver).

Reply-driven (server/subserver)

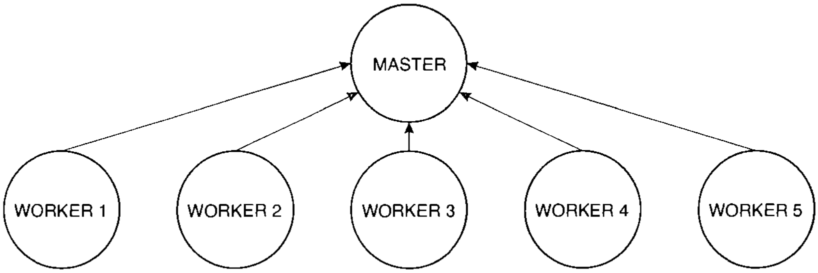
One of the more popular reply-driven programs is a fractal graphics program distributed over the network. The master program divides the screen into several areas, for example, 64 regions. At startup, the master program is given a list of nodes that can participate in this activity. The master program starts up worker (subserver) programs, one on each of the nodes, and then waits for the worker programs to send to the master.

The master then repeatedly picks "unfilled" regions (of the 64 on screen) and delegates the fractal computation work to the worker program on another node by replying to it. When the worker program has completed the calculations, it sends the results back to the master, which displays the result on the screen.

Because the worker program sent to the master, it's now up to the master to again reply with more work. The master continues doing this until all 64 areas on the screen have been filled.

An important subtlety

Because the master program is delegating work to worker programs, the master program can't afford to become blocked on any one program! In a traditional send-driven approach, you'd expect the master to create a program and then send to it. Unfortunately, the master program wouldn't be replied to until the worker program was done, meaning that the master program couldn't send simultaneously to another worker program, effectively negating the advantages of having multiple worker nodes.



One master, multiple workers.

The solution to this problem is to have the worker programs start up, and *ask* the master program if there's any work to do by sending it a message. Once again, we've used the direction of the arrows in the diagram to indicate the direction of the send. Now the worker programs are waiting for the master to reply. When something tells the master program to do some work, it replies to one or more of the workers, which causes them to go off and do the work. This lets the workers go about their business; the master program can still respond to new requests (it's not blocked waiting for a reply from one of the workers).

Multi-threaded server

Multi-threaded servers are indistinguishable from single-threaded servers from the client's point of view. In fact, the designer of a server can just "turn on" multi-threading by starting another thread.

In any event, the server can still make use of multiple CPUs in an SMP configuration, even if it is servicing only one "client." What does that mean? Let's revisit the fractal graphics example. When a subserver gets a request from the server to "compute," there's absolutely nothing stopping the subserver from starting up multiple threads on multiple CPUs to service the one request. In fact, to make the application scale better across networks that have some SMP boxes and some single-CPU boxes, the server and subserver can initially exchange a message whereby the subserver tells the server how many CPUs it has — this lets it know how many requests it can service simultaneously. The server would then queue up more requests for SMP boxes, allowing the SMP boxes to do more work than single-CPU boxes.

Using message passing

Now that we've seen the basic concepts involved in message passing, and learned that even common everyday things like the C library use it, let's take a look at some of the details.

Architecture & structure

We've been talking about "clients" and "servers." I've also used three key phrases:

- "The client *sends* to the server."
- "The server *receives* from the client."
- "The server *replies* to the client."

I specifically used those phrases because they closely reflect the actual function names used in Neutrino message-passing operations.

Here's the complete list of functions dealing with message passing available under Neutrino (in alphabetical order):

- *ChannelCreate()*, *ChannelDestroy()*
- *ConnectAttach()*, *ConnectDetach()*

- *MsgDeliverEvent()*
- *MsgError()*
- *MsgRead()*, *MsgReadv()*
- *MsgReceive()*, *MsgReceivePulse()*, *MsgReceivev()*
- *MsgReply()*, *MsgReplyv()*
- *MsgSend()*, *MsgSendnc()*, *MsgSendsv()*, *MsgSendsvnc()*, *MsgSendvs()*, *MsgSendvsnc()*, *MsgSendv()*, *MsgSendvnc()*
- *MsgWrite()*, *MsgWritev()*

Don't let this list overwhelm you! You can write perfectly useful client/server applications using just a small subset of the calls from the list — as you get used to the ideas, you'll see that some of the other functions can be very useful in certain cases.

☞ A useful minimal set of functions is *ChannelCreate()*, *ConnectAttach()*, *MsgReply()*, *MsgSend()*, and *MsgReceive()*.

We'll break our discussion up into the functions that apply on the client side, and those that apply on the server side.

The client

The client wants to send a request to a server, block until the server has completed the request, and then when the request is completed and the client is unblocked, to get at the "answer."

This implies two things: the client needs to be able to establish a connection to the server and then to transfer data via messages — a message from the client to the server (the "send" message) and a message back from the server to the client (the "reply" message, the server's reply).

Establishing a connection

So, let's look at these functions in turn. The first thing we need to do is to establish a connection. We do this with the function *ConnectAttach()*, which looks like this:

```
#include <sys/neutrino.h>

int ConnectAttach (int nd,
                   pid_t pid,
                   int chid,
                   unsigned index,
                   int flags);
```

ConnectAttach() is given three identifiers: the *nd*, which is the Node Descriptor, the *pid*, which is the process ID, and the *chid*, which is the channel ID. These three IDs, commonly referred to as "ND/PID/CHID," uniquely identify the server that the client wants to connect to. We'll ignore the *index* and *flags* (just set them to 0).

So, let's assume that we want to connect to process ID 77, channel ID 1 on our node. Here's the code sample to do that:

```
int coid;

coid = ConnectAttach (0, 77, 1, 0, 0);
```

As you can see, by specifying a *nd* of zero, we're telling the kernel that we wish to make a connection on our node.

☞ How did I figure out I wanted to talk to process ID 77 and channel ID 1? We'll see that shortly (see "Finding the server's ND/PID/CHID," below).

At this point, I have a *connection ID* — a small integer that uniquely identifies a connection from my client to a specific channel on a particular server.

I can use this connection ID when sending to the server as many times as I like. When I'm done with it, I can destroy it via:

```
ConnectDetach (coid);
```

So let's see how I actually use it.

Sending messages

Message passing on the client is achieved using some variant of the *MsgSend*()* function family. We'll look at the simplest member, *MsgSend()*:

```
#include <sys/neutrino.h>

int MsgSend (int coid,
             const void *smsg,
             int sbytes,
             void *rmsg,
             int rbytes);
```

MsgSend()'s arguments are:

- the connection ID of the target server (*coid*),
- a pointer to the send message (*smsg*),
- the size of the send message (*sbytes*),
- a pointer to the reply message (*rmsg*), and
- the size of the reply message (*rbytes*).

It couldn't get any simpler than that!

Let's send a simple message to process ID 77, channel ID 1:

```
#include <sys/neutrino.h>

char *smsg = "This is the outgoing buffer";
char rmsg [200];
int  coid;

// establish a connection
coid = ConnectAttach (0, 77, 1, 0, 0);
if (coid == -1) {
    fprintf (stderr, "Couldn't ConnectAttach to 0/77/1!\n");
    perror (NULL);
    exit (EXIT_FAILURE);
}
```

```
// send the message
if (MsgSend (coid,
             smsg,
             strlen (smsg) + 1,
             rmsg,
             sizeof (rmsg)) == -1) {
    fprintf (stderr, "Error during MsgSend\n");
    perror (NULL);
    exit (EXIT_FAILURE);
}

if (strlen (rmsg) > 0) {
    printf ("Process ID 77 returns \"%s\"\n", rmsg);
}
```

Let's assume that process ID 77 was an active server expecting that particular format of message on its channel ID 1. After the server received the message, it would process it and at some point reply with a result. At that point, the *MsgSend()* would return a 0 indicating that everything went well. If the server sends us any data in the reply, we'd print it with the last line of code (we're assuming we're getting NUL-terminated ASCII data back).

The server

Now that we've seen the client, let's look at the server. The client used *ConnectAttach()* to create a connection to a server, and then used *MsgSend()* for all its message passing.

Creating the channel

This implies that the server has to create a channel — this is the thing that the client connected to when it issued the *ConnectAttach()* function call. Once the channel has been created, the server usually leaves it up forever.

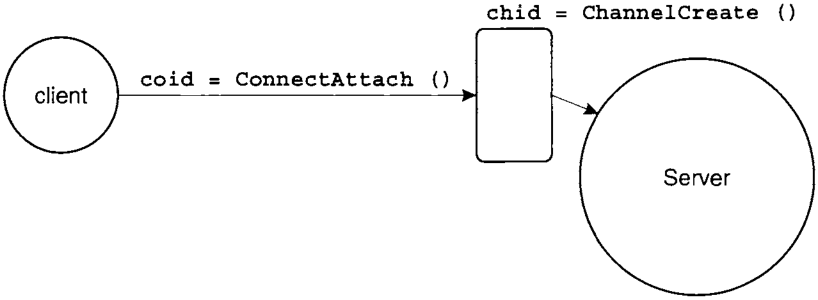
The channel gets created via the *ChannelCreate()* function, and destroyed via the *ChannelDestroy()* function:

```
#include <sys/neutrino.h>

int ChannelCreate  (unsigned flags);

int ChannelDestroy (int chid);
```

We'll come back to the *flags* argument later (in the "Channel flags" section, below). For now, let's just use a 0. Therefore, to create a channel, the server issues:

```
int  chid;

chid = ChannelCreate (0);
```

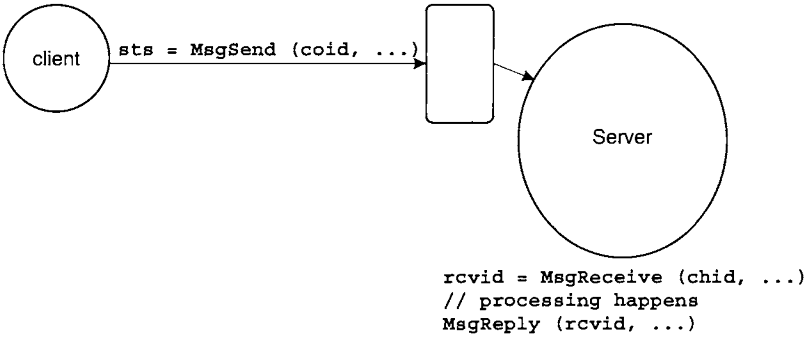
So we have a channel. At this point, clients could connect (via *ConnectAttach()*) to this channel and start sending messages:



Relationship of server channel and client connection.

Message handling

As far as the message-passing aspects are concerned, the server handles message passing in two stages; a "receive" stage and a "reply" stage:



```
sts = MsgSend (coid, ...)
```

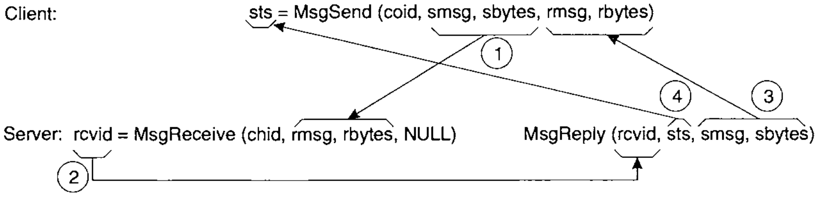
```
rcvid = MsgReceive (chid, ...)
// processing happens
MsgReply (rcvid, ...)
```

Relationship of client and server message-passing functions.

We'll look initially at two simple versions of these functions, *MsgReceive()* and *MsgReply()*, and then later see some of the variants.

```
#include <sys/neutrino.h>

int MsgReceive (int chid,
                void *rmsg,
                int rbytes,
                struct _msg_info *info);

int MsgReply (int rcvid,
              int status,
              const void *msg,
              int nbytes);
```

Let's look at how the parameters relate:



```
sts = MsgSend (coid, smsg, sbytes, rmsg, rbytes)
rcvid = MsgReceive (chid, rmsg, rbytes, NULL)
MsgReply (rcvid, sts, smsg, sbytes)
```

Message data flow.

As you can see from the diagram, there are four things we need to talk about:

1 The client issues a *MsgSend()* and specifies its transmit buffer (the *smsg* pointer and the *sbytes* length). This gets transferred into the buffer provided by the server's *MsgReceive()* function, at *rmsg* for *rbytes* in length. The client is now blocked.

2 The server's *MsgReceive()* function unblocks, and returns with a *rcvid*, which the server will use later for the reply. At this point, the data is available for the server to use.

3 The server has completed the processing of the message, and now uses the *rcvid* it got from the *MsgReceive()* by passing it to the *MsgReply()*. Note that the *MsgReply()* function takes a buffer (*smsg*) with a defined size (*sbytes*) as the location of the data to transmit to the client. The data is now transferred by the kernel.

4 Finally, the *sts* parameter is transferred by the kernel, and shows up as the return value from the client's *MsgSend()*. The client now unblocks.

You may have noticed that there are two sizes for every buffer transfer (in the client send case, there's *sbytes* on the client side and *rbytes* on the server side; in the server reply case, there's *sbytes* on the server side and *rbytes* on the client side.) The two sets of sizes are present so that the programmers of each component can specify the sizes of *their* buffers. This is done for added safety.

In our example, the *MsgSend()* buffer's size was the same as the message string's length. Let's look at the server and see how the size is used there.

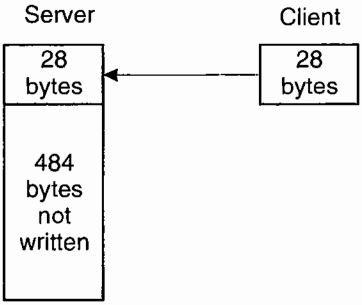
Server framework

Here's the overall structure of a server:

```
#include <sys/neutrino.h>

...
```

```
void
server (void)
{
    int     rcvid;         // indicates who we should reply to
    int     chid;          // the channel ID
    char    message [512]; // big enough for our purposes

    // create a channel
    chid = ChannelCreate (0);

    // this is typical of a server:  it runs forever
    while (1) {

        // get the message, and print it
        rcvid = MsgReceive (chid, message, sizeof (message),
                            NULL);
        printf ("Got a message, rcvid is %X\n", rcvid);
        printf ("Message was \"%s\".\n", message);

        // now, prepare the reply.  We reuse "message"
        strcpy (message, "This is the reply");
        MsgReply (rcvid, EOK, message, sizeof (message));
    }
}
```

As you can see, *MsgReceive()* tells the kernel that it can handle messages up to `sizeof (message)` (or 512 bytes). Our sample client (above) sent only 28 bytes (the length of the string). The following diagram illustrates:



Transferring less data than expected.

The kernel transfers the *minimum* specified by both sizes. In our case, the kernel would transfer 28 bytes. The server would be unblocked and print out the client's message. The remaining 484 bytes (of the 512 byte buffer) will remain unaffected.

We run into the same situation again with *MsgReply()*. The *MsgReply()* function says that it wants to transfer 512 bytes, but our client's *MsgSend()* function has specified that a maximum of 200 bytes can be transferred. So the kernel once again transfers the minimum. In this case, the 200 bytes that the client can accept limits the transfer size. (One interesting aspect here is that once the server transfers the data, if the client doesn't receive *all* of it, as in our example, there's no way to get the data back — it's gone forever.)

☞ Keep in mind that this "trimming" operation is normal and expected behavior.

When we discuss message passing over a network, you'll see that there's a tiny "gotcha" with the amount of data transferred. We'll see this in "Networked message-passing differences," below.

The send-hierarchy

One thing that's perhaps not obvious in a message-passing environment is the need to follow a strict *send-hierarchy*. What this means is that two threads should never send messages to each other; rather, they should be organized such that each thread occupies a "level"; all sends go from one level to a higher level, never to the same or lower level. The problem with having two threads send messages to each other is that eventually you'll run into the problem of deadlock — both threads are waiting for each other to reply to their respective messages. Since the threads are blocked, they'll never get a chance to run and perform the reply, so you end up with two (or more!) hung threads.

The way to assign the levels to the threads is to put the outermost clients at the highest level, and work down from there. For example, if you have a graphical user interface that relies on some database server, and the database server in turn relies on the filesystem, and the filesystem in turn relies on a block filesystem driver, then you've got a natural hierarchy of different processes. The sends will flow from the outermost client (the graphical user interface) down to the lower servers; the replies will flow in the opposite direction.

While this certainly works in the majority of cases, you *will* encounter situations where you need to "break" the send hierarchy. This is *never* done by simply violating the send hierarchy and sending a message "against the flow," but rather by using the *MsgDeliverEvent()* function, which we'll take a look at later.

Receive IDs, channels, and other parameters

We haven't talked about the various parameters in the examples above so that we could focus just on the message passing. Now let's take a look.

More about channels

In the server example above, we saw that the server created just one channel. It could certainly have created more, but generally, servers don't do that. (The most obvious example of a server with two channels is the `qnet` native network manager — definitely an "odd" piece of software!)

As it turns out, there really isn't much need to create multiple channels in the real world. The main purpose of a channel is to give the server a well-defined place to "listen" for messages, and to give the clients a well-defined place to send their messages (via a connection). About the only time that you'd have multiple channels in a server is if the server wanted to provide either different services, or different classes of services, depending on which channel the message arrived on. The second channel could be used, for example, as a place to drop wakeup pulses — this ensures that they're treated as a different "class" of service than messages arriving on the first channel.

In a previous paragraph I had said that you could have a pool of threads running in a server, ready to accept messages from clients, and that it didn't really matter which thread got the request. This is another aspect of the channel abstraction. Under previous versions of the QNX family of operating systems (notably QNX 4), a client would target messages at a server identified by a node ID and process ID. Since QNX 4 is single-threaded, this means that there cannot be confusion about "to whom" the message is being sent. However, once you introduce threads into the picture, the design decision had to be made as to how you would address the threads (really, the "service providers"). Since threads are ephemeral, it really didn't make sense to have the client connect to a particular node ID, process ID, and *thread* ID. Also, what if that particular thread was busy? We'd have to provide some method to allow a client to select a "non-busy thread within a defined pool of service-providing threads."

Well, that's exactly what a channel is. It's the "address" of a "pool of service-providing threads." The implication here is that a bunch of threads can issue a *MsgReceive()* function call on a particular channel, and block, with only one thread getting a message at a time.

Who sent the message?

Often a server will need to know who sent it a message. There are a number of reasons for this:

- accounting
- access control
- context association
- class of service
- etc.

It would be cumbersome (and a security hole) to have the client provide this information with each and every message sent. Therefore, there's a structure filled in by the kernel whenever the *MsgReceive()* function unblocks because it got a message. This structure is of type `struct _msg_info`, and contains the following:

```
struct _msg_info
{
    int     nd;
    int     srcnd;
    pid_t    pid;
    int32_t  chid;
    int32_t  scoid;
    int32_t  coid;
    int32_t  msglen;
    int32_t  tid;
    int16_t  priority;
    int16_t  flags;
    int32_t  srcmsglen;
    int32_t  dstmsglen;
};
```

You pass it to the *MsgReceive()* function as the last argument. If you pass a NULL, then nothing happens. (The information can be retrieved later via the *MsgInfo()* call, so it's not gone forever!)

Let's look at the fields:

nd, *srcnd*, *pid*, and *tid*

Node Descriptors, process ID, and thread ID of the client. (Note that *nd* is the receiving node's node descriptor for the transmitting node; *srcnd* is the transmitting node's node descriptor for the receiving node. There's a very good reason for this `:-)`, which we'll see below in "Some notes on NDs").

priority — The priority of the sending thread.

chid, *coid* — Channel ID that the message was sent to, and the connection ID used.

scoid — Server Connection ID. This is an internal identifier used by the kernel to route the message from the server back to the client. You don't need to know about it, except for the interesting fact that it will be a small integer that uniquely represents the client.

flags — Contains a variety of flag bits, _NTO_MI_ENDIAN_BIG, _NTO_MI_ENDIAN_DIFF, _NTO_MI_NET_CRED_DIRTY, and _NTO_MI_UNBLOCK_REQ. The _NTO_MI_ENDIAN_BIG and _NTO_MI_ENDIAN_DIFF tell you about the endian-ness of the sending machine (in case the message came over the network from a machine with a different endian-ness), _NTO_MI_NET_CRED_DIRTY is used internally; we'll look at _NTO_MI_UNBLOCK_REQ in the section "Using the _NTO_MI_UNBLOCK_REQ", below.

msglen Number of bytes received.

srcmsglen The length of the source message, in bytes, as sent by the client. This may be greater than the value in *msglen*, as would be the case when receiving less data than what was sent. Note that this member is valid only if _NTO_CHF_SENDER_LEN was set in the flags argument to *ChannelCreate()* for the channel that the message was received on.

dstmsglen The length of the client's reply buffer, in bytes. This field is only valid if the _NTO_CHF_REPLY_LEN flag is set in the argument to *ChannelCreate()* for the channel that the message was received on.

The receive ID (a.k.a. the client cookie)

In the code sample above, notice how we:

```
rcvid = MsgReceive (...);
...
MsgReply (rcvid, ...);
```

This is a key snippet of code, because it illustrates the binding between receiving a message from a client, and then being able to (sometime later) reply to that particular client. The *receive ID* is an integer that acts as a "magic cookie" that you'll need to hold onto if you want to interact with the client later. What if you lose it? It's gone. The client will not unblock from the *MsgSend()* until you (the server) die, or if the client has a timeout on the message-passing call (and even then it's tricky; see the *TimerTimeout()* function in the C library reference, and the discussion about its use in the Clocks, Timers, and Getting A Kick Every So Often chapter, under "Kernel timeouts").

☞ Don't depend on the value of the receive ID to have any particular meaning — it may change in future versions of the operating system. You can assume that it will be unique, in that you'll never have two outstanding clients identified by the same receive IDs (in that case, the kernel couldn't tell them apart either when you do the *MsgReply()*).

Also, note that except in one special case (the *MsgDeliverEvent()* function which we'll look at later), once you've done the *MsgReply()*, that particular receive ID ceases to have meaning.

This brings us to the *MsgReply()* function.

Replying to the client

MsgReply() accepts a receive ID, a status, a message pointer, and a message size. We've just finished discussing the receive ID; it identifies who the reply message should be sent to. The status variable indicates the return status that should be passed to the client's *MsgSend()* function. Finally, the message pointer and size indicate the location and size of the *optional* reply message that should be sent.

The *MsgReply()* function may appear to be very simple (and it is), but its applications require some examination.

Not replying to the client

There's absolutely no requirement that you reply to a client *before* accepting new messages from other clients via *MsgReceive()*! This can be used in a number of different scenarios.

In a typical device driver, a client may make a request that won't be serviced for a long time. For example, the client may ask an Analog-to-Digital Converter (ADC) device driver to "Go out and collect 45 seconds worth of samples." In the meantime, the ADC driver shouldn't just close up shop for 45 seconds! Other clients might wish to have requests serviced (for example, there might be multiple analog channels, or there might be status information that should be available immediately, etc.).

Architecturally, the ADC driver will simply queue the receive ID that it got from the *MsgReceive()*, start up the 45-second accumulation process, and go off and handle other requests. When the 45 seconds are up and the samples have been accumulated, the ADC driver can find the receive ID associated with the request and *then* reply to the client.

You'd also want to hold off replying to a client in the case of the reply-driven server/subserver model (where some of the "clients" are the subservers). Since the subservers are looking for work, you'd simply make a note of their receive IDs and store those away. When actual work arrived, then and only then would you reply to the subserver, thus indicating that it should do some work.

Replying with no data, or an *errno*

When you finally reply to the client, there's no requirement that you transfer any data. This is used in two scenarios.

You may choose to reply with no data if the sole purpose of the reply is to unblock the client. Let's say the client just wants to be blocked until some particular event occurrs, but it doesn't need to know which event. In this case, no data is required by the *MsgReply()* function; the receive ID is sufficient:

```
MsgReply (rcvid, EOK, NULL, 0);
```

This unblocks the client (but doesn't return any data) and returns the EOK "success" indication.

As a slight modification of that, you may wish to return an error status to the client. In this case, you can't do that with *MsgReply()*, but instead *must* use *MsgError()*:

```
MsgError (rcvid, EROFS);
```

In the above example, the server detects that the client is attempting to write to a read-only filesystem, and, instead of returning any actual data, simply returns an *errno* of EROFS back to the client.

Alternatively (and we'll look at the calls shortly), you may have already transferred the data (via *MsgWrite()*), and there's no additional data to transfer.

Why the two calls? They're subtly different. While both *MsgError()* and *MsgReply()* will unblock the client, *MsgError()* will *not* transfer any additional data, *will* cause the client's *MsgSend()* function to return -1, and *will* cause the client to have *errno* set to whatever was passed as the second argument to *MsgError()*.

On the other hand, *MsgReply() could* transfer data (as indicated by the 3rd and 4th arguments), and *will* cause the client's *MsgSend()* function to return whatever was passed as the second argument to *MsgReply()*. *MsgReply()* has *no* effect on the client's *errno*.

Generally, if you're returning only a pass/fail indication (and no data), you'd use *MsgError()*, whereas if you're returning data, you'd use *MsgReply()*. Traditionally, when you *do* return data, the second argument to *MsgReply()* will be a positive integer indicating the number of bytes being returned.

Finding the server's ND/PID/CHID

You've noticed that in the *ConnectAttach()* function, we require a Node Descriptor (ND), a process ID (PID), and a channel ID (CHID) in order to be able to attach to a server. So far we haven't talked about how the client finds this ND/PID/CHID information.

If one process creates the other, then it's easy — the process creation call returns with the process ID of the newly created process. Either the creating process can pass its own PID and CHID on the command line to the newly created process or the newly created process can issue the *getppid()* function call to get the PID of its parent and assume a "well-known" CHID.

What if we have two perfect strangers? This would be the case if, for example, a third party created a server and an application that you wrote wanted to talk to that server. The real issue is, "How does a server *advertise* its location?"

There are many ways of doing this; we'll look at four of them, in increasing order of programming "elegance":

1. Open a well-known filename and store the ND/PID/CHID there. This is the traditional approach taken by UNIX-style servers, where they open a file (for example, `/etc/httpd.pid`), write their process ID there as an ASCII string, and expect that clients will open the file and fetch the process ID.
2. Use global variables to advertise the ND/PID/CHID information. This is typically used in multi-threaded servers that need to send themselves messages, and is, by its nature, a very limited case.
3. Use the QNX 4 compatibility functions (*name_attach()* and *name_detach()*, and then the *name_open()* and *name_close()* functions on the client side). This is recommended only for quickly porting QNX 4 programs to Neutrino; therefore we won't discuss this one in the text below.
4. Take over a portion of the pathname space and become a resource manager. We'll talk about this when we look at resource managers in the Resource Managers chapter.

The first approach is very simple, but can suffer from "pathname pollution," where the `/etc` directory has all kinds of `*.pid` files in it. Since files are persistent (meaning they survive after the creating process dies and the machine reboots), there's no obvious method of cleaning up these files, except perhaps to have a "grim reaper" task that runs around seeing if these things are still valid.

There's another related problem. Since the process that created the file can die without removing the file, there's no way of knowing whether or not the process is still alive until you try to send a message to it. Worse yet, the ND/PID/CHID specified in the file may be so stale that it would have been reused by another program! The message that you send to that program will at best be rejected, and at worst may cause damage. So that approach is out.

The second approach, where we use global variables to advertise the ND/PID/CHID values, is not a general solution, as it relies on the client's being able to access the global variables. And since this requires shared memory, it certainly won't work across a network! This generally gets used in either tiny test case programs or in very special cases, but always in the context of a multithreaded program. Effectively, all that happens is that one thread in the program is the client, and another thread is the server. The server thread creates the channel and then places the channel ID into a global variable (the node ID and process ID are the same for all threads in the process, so they don't need to be advertised.) The client thread then picks up the global channel ID and performs the *ConnectAttach()* to it.

The third approach, where we use the *name_attach()* and *name_detach()* functions, should be used only for quickly porting over QNX 4 programs.

The last approach, where the server becomes a resource manager, is definitely the cleanest and is the recommended general-purpose solution. The mechanics of "how" will become clear in the Resource Managers chapter, but for now, all you need to know is that the server registers a particular pathname as its "domain of authority," and a client performs a simple *open()* of that pathname.

☞ I can't emphasize this enough:

POSIX file descriptors are implemented using connection IDs; that is, a file descriptor *is* a connection ID! The beauty of this scheme is that since the file descriptor that's returned from the *open()* is the connection ID, no further work is required on the client's end to be able to use that particular connection. For example, when the client calls *read()* later, passing it the file descriptor, this translates with very little overhead into a *MsgSend()* function.

What about priorities?

What if a low-priority process and a high-priority process send a message to a server at the same time?

☞ Messages are *always* delivered in priority order.

If two processes send a message "simultaneously," the entire message from the higher-priority process is delivered to the server first.

If both processes are at the same priority, then the messages will be delivered in time order (since there's no such thing as absolutely simultaneous on a single-processor machine — even on an SMP box there will be some ordering as the CPUs arbitrate kernel access among themselves).

We'll come back to some of the other subtleties introduced by this question when we look at priority inversions later in this chapter.

Reading and writing data

So far you've seen the basic message-passing primitives. As I mentioned earlier, these are all that you *need*. However, there are a few extra functions that make life much easier.

Let's consider an example using a client and server where we might need other functions.

The client issues a *MsgSend()* to transfer some data to the server. After the client issues the *MsgSend()* it blocks; it's now waiting for the server to reply.

An interesting thing happens on the server side. The server has called *MsgReceive()* to receive the message from the client. Depending on the design that you choose for your messages, the server may or may not know how big the client's message is. Why on earth would the server *not* know how big the message is? Consider the filesystem example that we've been using. Suppose the client does:

```
write (fd, buf, 16);
```

This works as expected if the server does a *MsgReceive()* and specifies a buffer size of, say, 1024 bytes. Since our client sent only a tiny message (28 bytes), we have no problems.

However, what if the client sends something bigger than 1024 bytes, say 1 megabyte?

```
write (fd, buf, 1000000);
```

How is the server going to gracefully handle this? We could, arbitrarily, say that the client isn't allowed to write more than *n* bytes. Then, in the client-side C library code for *write()*, we could look at this requirement and split up the write request into several requests of *n* bytes each. This is awkward.

The other problem with this example would be, "How big should *n* be?"

You can see that this approach has major disadvantages:

- All functions that use message transfer with a limited size will have to be modified in the C library so that the function packetizes the requests. This in itself can be a fair amount of work. Also, it can have unexpected side effects for multi-threaded functions — what if the first part of the message from one thread gets sent, and then another thread in the client preempts the current thread and sends its own message. Where does that leave the original thread?
- All servers must now be prepared to handle the largest possible message size that may arrive. This means that all servers will have to have a data area that's big, or the library will have to break up big requests into many smaller ones, thereby impacting speed.

Luckily, this problem has a fairly simple workaround that also gives us some advantages.

Two functions, *MsgRead()* and *MsgWrite()*, are especially useful here. The important fact to keep in mind is that *the client is blocked*. This means that the client isn't going to go and change data structures while the server is trying to examine them.

☞ In a multi-threaded client, the potential exists for another thread to mess around with the data area of a client thread that's blocked on a server. This is considered a bug (bad design) — the server thread assumes that it has exclusive access to a client's data area until the server thread unblocks the client.

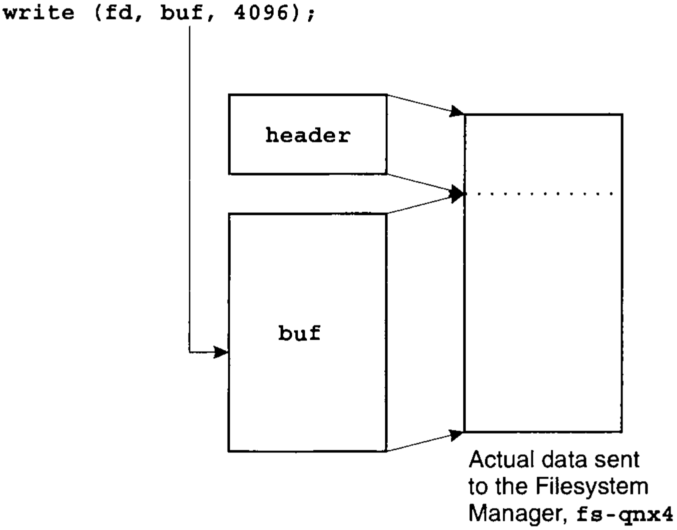
The *MsgRead()* function looks like this:

```
#include <sys/neutrino.h>

int MsgRead (int rcvid,
             void *msg,
             int nbytes,
             int offset);
```

MsgRead() lets your server read data from the blocked client's address space, starting *offset* bytes from the beginning of the client-specified "send" buffer, into the buffer specified by *msg* for *nbytes*. The server doesn't block, and the client doesn't unblock. *MsgRead()* returns the number of bytes it actually read, or -1 if there was an error.

So let's think about how we'd use this in our *write()* example. The C Library *write()* function constructs a message with a header that it sends to the filesystem server, **fs-qnx4**. The server receives a small portion of the message via *MsgReceive()*, looks at it, and decides where it's going to put the rest of the message. The **fs-qnx4** server may decide that the best place to put the data is into some cache buffers it's already allocated.

Let's track an example:



The **fs-qnx4** *message example, showing contiguous data view.*

So, the client has decided to send 4k to the filesystem. (Notice how the C Library stuck a tiny header in front of the data so that the filesystem could tell just what kind of request it actually was — we'll come back to this when we look at multi-part messages, and in even more detail when we look at resource managers.) The filesystem reads just enough data (the header) to figure out what kind of a message it is:

```
// part of the headers, fictionalized for example purposes
struct _io_write {
    uint16_t    type;
    uint16_t    combine_len;
    int32_t     nbytes;
    uint32_t    xtype;
};

typedef union {
    uint16_t           type;
    struct _io_read    io_read;
    struct _io_write   io_write;
    ...
} header_t;
```

```
header_t    header;    // declare the header

rcvid = MsgReceive (chid, &header, sizeof (header), NULL);

switch (header.type) {
...
case _IO_WRITE:
    number_of_bytes = header.io_write.nbytes;
    ...
```

At this point, **fs-qnx4** knows that 4k is sitting in the client's address space (because the message told it in the *nbytes* member of the structure) and that it should be transferred to a cache buffer. The **fs-qnx4** server could issue:

```
MsgRead (rcvid, cache_buffer [index].data,
         cache_buffer [index].size, sizeof (header.io_write));
```

Notice that the message transfer has specified an offset of **sizeof (header.io_write)** in order to skip the write header that was added by the client's C library. We're assuming here that **cache_buffer [index].size** is actually 4096 (or more) bytes.

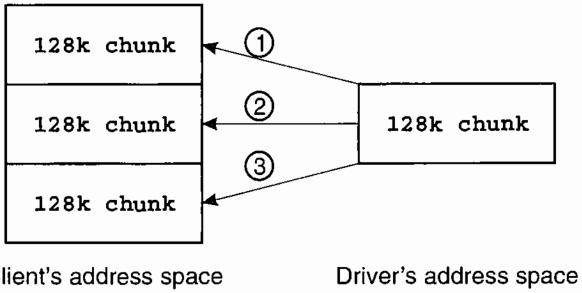
Similarly, for writing data to the client's address space, we have:

```
#include <sys/neutrino.h>

int MsgWrite (int rcvid,
              const void *msg,
              int nbytes,
              int offset);
```

MsgWrite() lets your server write data to the client's address space, starting *offset* bytes from the beginning of the client-specified "receive" buffer. This function is most useful in cases where the server has limited space but the client wishes to get a lot of information from the server.

For example, with a data acquisition driver, the client may specify a 4-megabyte data area and tell the driver to grab 4 megabytes of data. The driver really shouldn't need to have a big area like this lying around just in case someone asks for a huge data transfer.

The driver might have a 128k area for DMA data transfers, and then message-pass it piecemeal into the client's address space using *MsgWrite()* (incrementing the *offset* by 128k each time, of course). Then, when the last piece of data has been written, the driver will *MsgReply()* to the client.



Transferring several chunks with MsgWrite().

Note that *MsgWrite()* lets you write the data components at various places, and then either just wake up the client using *MsgReply()*:

```
MsgReply (rcvid, EOK, NULL, 0);
```

or wake up the client after writing a header at the *start* of the client's buffer:

```
MsgReply (rcvid, EOK, &header, sizeof (header));
```

This is a fairly elegant trick for writing unknown quantities of data, where you know how much data you wrote only when you're done writing it. If you're using this method of writing the header after the data's been transferred, you must remember to leave room for the header at the beginning of the client's data area!

Multipart messages

Until now, we've shown only message transfers happening from one buffer in the client's address space into another buffer in the server's address space. (And one buffer in the server's space into another buffer in the client's space during the reply.)

While this approach is good enough for most applications, it can lead to inefficiencies. Recall that our *write()* C library code took the buffer that you passed to it, and stuck a small header on the front of it. Using what we've learned so far, you'd expect that the C library would implement *write()* something like this (this isn't the real source):

```
ssize_t write (int fd, const void *buf, size_t nbytes)
{
    char        *newbuf;
    io_write_t  *wptr;
    int         nwritten;

    newbuf = malloc (nbytes + sizeof (io_write_t));

    // fill in the write_header at the beginning
    wptr = (io_write_t *) newbuf;
    wptr -> type = _IO_WRITE;
    wptr -> nbytes = nbytes;

    // store the actual data from the client
    memcpy (newbuf + sizeof (io_write_t), buf, nbytes);

    // send the message to the server
    nwritten = MsgSend (fd,
                        newbuf,
                        nbytes + sizeof (io_write_t),
                        newbuf,
                        sizeof (io_write_t));
    free (newbuf);
    return (nwritten);
}
```

See what happened? A few bad things:

- The *write()* now has to be able to *malloc()* a buffer big enough for both the client data (which can be fairly big) and the header. The size of the header isn't the issue — in this case, it was 12 bytes.
- We had to *copy* the data twice: once via the *memcpy()*, and then again during the message transfer.

- We had to establish a pointer to the `io_write_t` type and point it to the beginning of the buffer, rather than access it natively (this is a minor annoyance).

Since the kernel is going to copy the data anyway, it would be nice if we could tell it that one part of the data (the header) is located at a certain address, and that the other part (the data itself) is located somewhere else, *without* the need for us to manually assemble the buffers and to copy the data.

As luck would have it, Neutrino implements a mechanism that lets us do just that! The mechanism is something called an *IOV*, standing for "Input/Output Vector."

Let's look at some code first, then we'll discuss what happens:

```
#include <sys/neutrino.h>

ssize_t write (int fd, const void *buf, size_t nbytes)
{
    io_write_t  whdr;
    iov_t       iov [2];

    // set up the IOV to point to both parts:
    SETIOV (iov + 0, &whdr, sizeof (whdr));
    SETIOV (iov + 1, buf, nbytes);

    // fill in the io_write_t at the beginning
    whdr.type = _IO_WRITE;
    whdr.nbytes = nbytes;

    // send the message to the server
    return (MsgSendv (coid, iov, 2, iov, 1));
}
```

First of all, notice there's no *malloc()* and no *memcpy()*. Next, notice the use of the `iov_t` type. This is a structure that contains an address and length pair, and we've allocated two of them (named *iov*).

The `iov_t` type definition is automatically included by `<sys/neutrino.h>`, and is defined as:

```
typedef struct iovec
{
    void     *iov_base;
    size_t    iov_len;
} iov_t;
```

Given this structure, we fill the address and length pairs with the write header (for the first part) and the data from the client (in the second part). There's a convenience macro called *SETIOV()* that does the assignments for us. It's formally defined as:

```
#include <sys/neutrino.h>

#define SETIOV(_iov, _addr, _len) \
              ((_iov)->iov_base = (void *)(_addr), \
               (_iov)->iov_len = (_len))
```

SETIOV() accepts an **iov_t**, and the address and length data to be stuffed into the IOV.

Also notice that since we're creating an IOV to point to the header, we can allocate the header on the stack without using *malloc()*. This can be a blessing and a curse — it's a blessing when the header is quite small, because you avoid the headaches of dynamic memory allocation, but it can be a curse when the header is huge, because it can consume a fair chunk of stack space. Generally, the headers are quite small.

In any event, the important work is done by *MsgSendv()*, which takes almost the same arguments as the *MsgSend()* function that we used in the previous example:

```
#include <sys/neutrino.h>

int MsgSendv (int coid,
              const iov_t *siov,
              int sparts,
              const iov_t *riov,
              int rparts);
```

Let's examine the arguments:

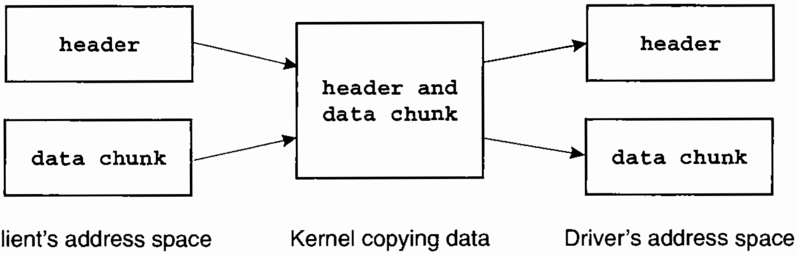
coid The connection ID that we're sending to, just as with *MsgSend()*.

sparts and *rparts*

The number of send and receive parts specified by the `iov_t` parameters. In our example, we set *sparts* to 2 indicating that we're sending a 2-part message, and *rparts* to 1 indicating that we're receiving a 1-part reply.

siov and *riov* The `iov_t` arrays indicate the address and length pairs that we wish to send. In the above example, we set up the 2 part *siov* to point to the header and the client data, and the 1 part *riov* to point to just the header.

This is how the kernel views the data:



How the kernel sees a multipart message.

The kernel just copies the data seamlessly from each part of the IOV in the client's space into the server's space (and back, for the reply). Effectively, the kernel is performing a gather-scatter operation.

A few points to keep in mind:

- The number of parts is "limited" to 512k; however, our example of 2 is typical.

- The kernel simply copies the data specified in one IOV from one address space into another.
- *The source and the target IOVs don't have to be identical.*

Why is the last point so important? To answer that, let's take a look at the big picture. On the client side, let's say we issued:

```
write (fd, buf, 12000);
```

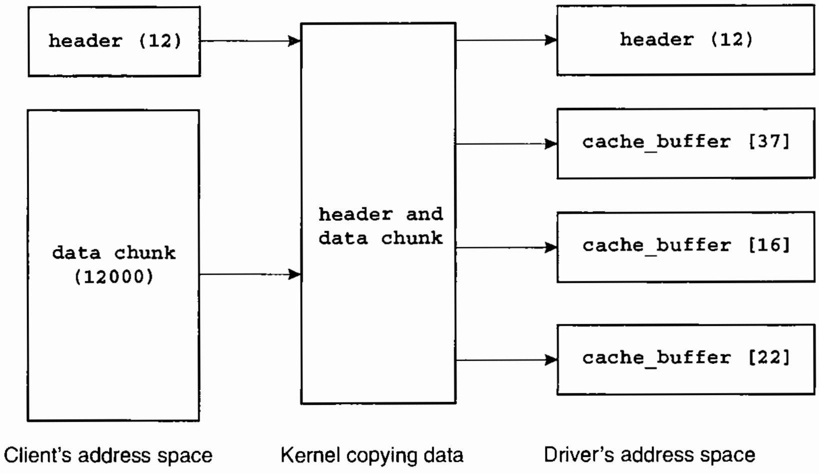
which generated a two-part IOV of:

- header (12 bytes)
- data (12000 bytes)

On the server side, (let's say it's the filesystem, **fs-qnx4**), we have a number of 4k cache blocks, and we'd like to efficiently receive the message directly into the cache blocks. Ideally, we'd like to write some code like this:

```
// set up the IOV structure to receive into:
SETIOV (iov + 0, &header, sizeof (header.io_write));
SETIOV (iov + 1, &cache_buffer [37], 4096);
SETIOV (iov + 2, &cache_buffer [16], 4096);
SETIOV (iov + 3, &cache_buffer [22], 4096);
rcvid = MsgReceivev (chid, iov, 4, NULL);
```

This code does pretty much what you'd expect: it sets up a 4-part IOV structure, sets the first part of the structure to point to the header, and the next three parts to point to cache blocks 37, 16, and 22. (These numbers represent cache blocks that just happened to be available at that particular time.) Here's a graphical representation:



Converting contiguous data to separate buffers.

Then the *MsgReceivev()* function is called, indicating that we'll receive a message from the specified channel (the *chid* parameter) and that we're supplying a 4-part IOV structure. This also shows the IOV structure itself.

(Apart from its IOV functionality, *MsgReceivev()* operates just like *MsgReceive()*.)

Oops! We made the same mistake as we did before, when we introduced the *MsgReceive()* function. How do we know what kind of message we're receiving, and how much data is associated with it, until we actually receive the message?

We can solve this the same way as before:

```
rcvid = MsgReceive (chid, &header, sizeof (header), NULL);
switch (header.message_type) {
...
case    _IO_WRITE:
    number_of_bytes = header.io_write.nbytes;
    // allocate / find cache buffer entries
    // fill 3-part IOV with cache buffers
    MsgReadv (rcvid, iov, 3, sizeof (header.io_write));
```

This does the initial *MsgReceive()* (note that we didn't use the IOV form for this — there's really no need to do that with a one-part message), figures out what kind of message it is, and then continues reading the data out of the client's address space (starting at offset `sizeof (header.io_write)`) into the cache buffers specified by the 3-part IOV.

Notice that we switched from using a 4-part IOV (in the first example) to a 3-part IOV. That's because in the first example, the first part of the 4-part IOV was the header, which we read directly using *MsgReceive()*, and the last three parts of the 4-part IOV are the same as the 3-part IOV — they specify where we'd like the data to go.

You can imagine how we'd perform the reply for a read request:

1 Find the cache entries that correspond to the requested data.

2 Fill an IOV structure with those entries.

3 Use *MsgWritev()* (or *MsgReplyv()*) to transfer the data to the client.

Note that if the data doesn't start right at the beginning of a cache block (or other data structure), this isn't a problem. Simply offset the first IOV to point to where the data does start, and modify the size.

What about the other versions?

All the message-passing functions except the *MsgSend*()* family have the same general form: if the function has a "**v**" at the end of it, it takes an IOV and a number-of-parts; otherwise, it takes a pointer and a length.

The *MsgSend*()* family has four major variations in terms of the source and destinations for the message buffers, combined with two variations of the kernel call itself.

Look at the following table:

Function	Send buffer	Receive buffer
MsgSend()	linear	linear
MsgSendnc()	linear	linear
MsgSendsv()	linear	IOV
MsgSendsvnc()	linear	IOV
MsgSendvs()	IOV	linear
MsgSendvsnc()	IOV	linear
MsgSendv()	IOV	IOV
MsgSendvnc()	IOV	IOV

By "linear," I mean a single buffer of type `void *` is passed, along with its length. The easy way to remember this is that the "**v**" stands for "vector," and is in the same place as the appropriate parameter — first or second, referring to "send" or "receive," respectively.

Hmmm... looks like the *MsgSendsv()* and *MsgSendsvnc()* functions are identical, doesn't it? Well, yes, as far as their parameters go, they indeed are. The difference lies in whether or not they are cancellation points. The "**nc**" versions are not cancellation points, whereas the non-"**nc**" versions are. (For more information about cancellation points and cancelability in general, please consult the *C Library Reference,* under *pthread_cancel()*.)

Implementation

You've probably already suspected that all the variants of the *MsgRead()*, *MsgReceive()*, *MsgSend()*, and *MsgWrite()* functions are closely related. (The only exception is *MsgReceivePulse()* — we'll look at this one shortly.)

Which ones should you use? Well, that's a bit of a philosophical debate. My own personal preference is to mix and match.

If I'm sending or receiving only one-part messages, why bother with the complexity of setting up IOVs? The tiny amount of CPU overhead in setting them up is basically the same regardless of whether you set it up yourself or let the kernel/library do it. The single-part message approach saves the kernel from having to do address space manipulations and is a little bit faster.

Should you use the IOV functions? Absolutely! Use them any time you find yourself dealing with multipart messages. *Never* copy the data when you can use a multipart message transfer with only a few lines of code. This keeps the system screaming along by minimizing the number of times data gets copied around the system; passing the pointers is much faster than copying the data into a new buffer.

Pulses

All the messaging we've talked about so far blocks the client. It's nap time for the client as soon as it calls *MsgSend()*. The client sleeps until the server gets around to replying.

However, there are instances where the sender of a message can't afford to block. We'll look at some examples in the Interrupts and Clocks, Timers, and Getting a Kick Every So Often chapters, but for now we should understand the concept.

The mechanism that implements a non-blocking send is called a *pulse*. A pulse is a tiny message that:

- can carry 40 bits of payload (an 8-bit code and 32 bits of data)
- is non-blocking for the sender
- can be received just like any other message
- is queued if the receiver isn't blocked waiting for it.

Receiving a pulse message

Receiving a pulse is very simple: a tiny, well-defined message is presented to the *MsgReceive()*, *as if a thread had sent a normal message*. The only difference is that you can't *MsgReply()* to this message — after all, the whole idea of a pulse is that it's asynchronous. In this section, we'll take a look at another function, *MsgReceivePulse()*, that's useful for dealing with pulses.

The only "funny" thing about a pulse is that the receive ID that comes back from the *MsgReceive()* function is zero. That's your indication that this is a pulse, rather than a regular message from a client. You'll often see code in servers that looks like this:

```
#include <sys/neutrino.h>

    rcvid = MsgReceive (chid, ...);
    if (rcvid == 0) {   // it's a pulse
        // determine the type of pulse

        // handle it
    } else {            // it's a regular message
        // determine the type of message

        // handle it
    }
```

What's in a pulse?

Okay, so you receive this message with a receive ID of zero. What does it actually look like? From the **<sys/neutrino.h>** header file:

```
struct _pulse {
    _uint16         type;
    _uint16         subtype;
    _int8           code;
    _uint8          zero [3];
    union sigval    value;
    _int32          scoid;
};
```

Both the *type* and *subtype* members are zero (a further indication that this is a pulse). The *code* and *value* members are set to whatever the sender of the pulse determined. Generally, the *code* will be an indication of why the pulse was sent; the *value* will be a 32-bit data value associated with the pulse. Those two fields are where the "40 bits" of content comes from; the other fields aren't user adjustable.

The kernel reserves negative values of *code*, leaving 127 values for programmers to use as they see fit.

The *value* member is actually a union:

```
union sigval {
    int     sival_int;
    void    *sival_ptr;
};
```

Therefore (expanding on the server example above), you often see code like:

```
#include <sys/neutrino.h>

    rcvid = MsgReceive (chid, ...

    if (rcvid == 0) {   // it's a pulse

        // determine the type of pulse
        switch (msg.pulse.code) {

        case    MY_PULSE_TIMER:
            // One of your timers went off, do something
            // about it...

            break;

        case    MY_PULSE_HWINT:
            // A hardware interrupt service routine sent
            // you a pulse.  There's a value in the "value"
            // member that you need to examine:

            val = msg.pulse.value.sival_int;

            // Do something about it...

            break;

        case    _PULSE_CODE_UNBLOCK:
            // A pulse from the kernel, indicating a client
            // unblock was received, do something about it...
            break;

        // etc...

    } else {            // it's a regular message

        // determine the type of message
        // handle it

    }
```

This code assumes, of course, that you've set up your *msg* structure to contain a **`struct _pulse pulse;`** member, and that the manifest constants MY_PULSE_TIMER and MY_PULSE_HWINT are defined. The pulse code _PULSE_CODE_UNBLOCK is one of those negative-numbered kernel pulses mentioned above. You can find a complete list of them in **`<sys/neutrino.h>`** along with a brief description of the value field.

The *MsgReceivePulse()* function

The *MsgReceive()* and *MsgReceivev()* functions will receive either a "regular" message or a pulse. There may be situations where you want to receive only pulses. The best example of this is in a server where you've received a request from a client to do something, but can't complete the request just yet (perhaps you have to do a long hardware operation). In such a design, you'd generally set up the hardware (or a timer, or whatever) to send you a pulse whenever a significant event occurs.

If you write your server using the classic "wait in an infinite loop for messages" design, you might run into a situation where one client sends you a request, and then, while you're waiting for the pulse to come in (to signal completion of the request), another client sends you another request. Generally, this is *exactly* what you want — after all, you want to be able to service multiple clients at the same time. However, there might be good reasons why this is not acceptable — servicing a client might be so resource-intensive that you want to limit the number of clients.

In that case, you now need to be able to "selectively" receive only a pulse, and *not* a regular message. This is where *MsgReceivePulse()* comes into play:

```
#include <sys/neutrino.h>

int MsgReceivePulse (int chid,
                     void *rmsg,
                     int rbytes,
                     struct _msg_info *info);
```

As you can see, you use the same parameters as *MsgReceive()*; the channel ID, the buffer (and its size), as well as the *info* parameter. (We discussed the *info* parameter above, in "Who sent the message?".) Note that the *info* parameter is not used in the case of a pulse; you might ask why it's present in the parameter list. Simple answer: it was easier to do it that way in the implementation. Just pass a NULL!

The *MsgReceivePulse()* function will receive *nothing but* pulses. So, if you had a channel with a number of threads blocked on it via *MsgReceivePulse()*, (and *no* threads blocked on it via *MsgReceive()*), and a client attempted to send your server a message, the client would remain SEND-blocked until a thread issued the *MsgReceive()* call. Pulses would be transfered via the *MsgReceivePulse()* functions in the meantime.

The only thing you can guarantee if you mix both *MsgReceivePulse()* and *MsgReceive()* is that the *MsgReceivePulse()* will get pulses only. The *MsgReceive()* could get pulses *or* messages! This is because, generally, the use of the *MsgReceivePulse()* function is reserved for the cases where you want to *exclude* regular message delivery to the server.

This does introduce a bit of confusion. Since the *MsgReceive()* function can receive *both* a message and a pulse, but the *MsgReceivePulse()* function can receive only a pulse, how do you deal with a server that makes use of both functions? Generally, the answer here is that you'd have a pool of threads that are performing *MsgReceive()*. This pool of threads (one or more threads; the number depends on how many clients you're prepared to service concurrently) is responsible for handling client calls (requests for service). Since you're trying to control the number of "service-providing threads," and since some of these threads may need to block, waiting for a pulse to arrive (for example, from some hardware or from another thread), you'd typically block the service-providing thread using *MsgReceivePulse()*. This ensures that a client request won't "sneak in" while you're waiting for the pulse (since *MsgReceivePulse()* will receive *only* a pulse).

The *MsgDeliverEvent()* function

As mentioned above in "The send-hierarchy," there are cases when you need to break the natural flow of sends.

Such a case might occur if you had a client that sent a message to the server, the result might not be available for a while, and the client didn't want to block. Of course, you could also partly solve this with threads, by having the client simply "use up" a thread on the blocking server call, but this may not scale well for larger systems (where you'd be using up lots of threads to wait for many different servers). Let's say you didn't want to use a thread, but instead wanted the server to reply immediately to the client, "I'll get around to your request shortly." At this point, since the server replied, the client is now free to continue processing. Once the server has completed whatever task the client gave it, the server now needs some way to tell the client, "Hey, wakeup, I'm done." Obviously, as we saw in the send-hierarchy discussion above, you can't have the server send a message to the client, because this might cause deadlock if the client sent a message to the server at that exact same instant. So, how does the server "send" a message to a client *without* violating the send hierarchy?

It's actually a multi-step operation. Here's how it works:

1. The client creates a `struct sigevent` structure, and fills it in.

2. The client sends a message to the server, effectively stating, "Perform this specific task for me, reply right away, and by the way, here's a `struct sigevent` that you should use to notify me when the work is completed."

3 The server receives the message (which includes the **struct sigevent**), stores the **struct sigevent** and the receive ID away, and replies immediately to the client.

4 The client is now running, as is the server.

5 When the server completes the work, the server uses *MsgDeliverEvent()* to inform the client that the work is now complete.

We'll take a look in detail at the **struct sigevent** in the Clocks, Timers, and Getting a Kick Every So Often chapter, under "How to fill in the **struct sigevent**." For now, just think of the **struct sigevent** as a "black box" that somehow contains the event that the server uses to notify the client.

Since the server stored the **struct sigevent** and the receive ID from the client, the server can now call *MsgDeliverEvent()* to deliver the event, *as selected by the client*, to the client:

```
int
MsgDeliverEvent (int rcvid,
                 const struct sigevent *event);
```

Notice that the *MsgDeliverEvent()* function takes two parameters, the receive ID (in *rcvid*) and the event to deliver in *event*. The server *does not modify or examine the event in any way!* This point is important, because it allows the server to deliver *whatever* kind of event the client chose, without any specific processing on the server's part. (The server can, however, *verify* that the event is valid by using the *MsgVerifyEvent()* function.)

The *rcvid* is a receive ID that the server got from the client. Note that this is indeed a special case. Generally, after the server has replied to a client, the receive ID ceases to have any meaning (the reasoning being that the client is unblocked, and the server couldn't unblock it *again*, or read or write data from/to the client, etc.). But in this case, the receive ID contains just enough information for the kernel to be able to decide which client the event should be delivered to. When the server calls the *MsgDeliverEvent()* function, the server doesn't block — this is a non-blocking call for the server. The client has the event delivered to it (by the kernel), and may then perform whatever actions are appropriate.

Channel flags

When we introduced the server (in "The server"), we mentioned that the *ChannelCreate()* function takes a *flags* parameter and that we'd just leave it as zero.

Now it's time to explain the *flags*. We'll examine only a few of the possible *flags* values:

_NTO_CHF_FIXED_PRIORITY

The receiving thread will *not* change priority based on the priority of the sender. (We talk more about priority issues in the "Priority inheritance" section, below). Ordinarily (i.e., if you don't specify this flag), the receiving thread's priority is changed to that of the sender.

_NTO_CHF_UNBLOCK

The kernel delivers a pulse whenever a client thread attempts to unblock. The server *must* reply to the client in order to allow the client to unblock. We'll discuss this one below, because it has some very interesting consequences, for both the client and the server.

_NTO_CHF_THREAD_DEATH

The kernel delivers a pulse whenever a thread blocked on this channel dies. This is useful for servers that want to maintain a fixed "pool of threads" available to service requests at all times.

_NTO_CHF_DISCONNECT

The kernel delivers a pulse whenever *all* connections from a single client have been disconnected from the server.

_NTO_CHF_SENDER_LEN

The kernel delivers the client's message size as part of the information given to the server (the *srcmsglen* member of the `struct _msg_info` structure).

_NTO_CHF_REPLY_LEN

The kernel delivers the client's reply message buffer size as part of the information given to the server (the *dstmsglen* member of the `struct _msg_info` structure).

_NTO_CHF_COID_DISCONNECT

The kernel delivers a pulse whenever any connection owned by this process is terminated due to the channel on the other end going away.

_NTO_CHF_UNBLOCK

Let's look at the _NTO_CHF_UNBLOCK flag; it has a few interesting wrinkles for both the client and the server.

Normally (i.e., where the server does *not* specify the _NTO_CHF_UNBLOCK flag) when a client wishes to unblock from a *MsgSend()* (and related *MsgSendv()*, *MsgSendvs()*, etc. family of functions), the client simply unblocks. The client could wish to unblock due to receiving a signal or a kernel timeout (see the *TimerTimeout()* function in the C Library Reference, and the Clocks, Timers, and Getting a Kick Every So Often chapter). The unfortunate aspect to this is that the server has *no idea* that the client has unblocked and is no longer waiting for a reply. Note that it isn't possible to write a reliable server with this flag off, except in very special situations which require cooperation between the server and all its clients.

Let's assume that you have a server with multiple threads, all blocked on the server's *MsgReceive()* function. The client sends a message to the server, and one of the server's threads receives it. At this point, the client is blocked, and a thread in the server is actively processing the request. Now, before the server thread has a chance to reply to the client, the client unblocks from the *MsgSend()* (let's assume it was because of a signal).

Remember, a server thread is *still* processing the request on behalf of the client. But since the client is now unblocked (the client's *MsgSend()* would have returned with EINTR), the client is free to send *another* request to the server. Thanks to the architecture of Neutrino servers, another thread would receive another message from the client, with the *exact same receive ID*! The server has no way to tell these two requests apart! When the first thread completes and replies to the client, it's really replying to the *second* message that the client sent, not the first message (as the thread actually believes that it's doing). So, the server's first thread replies to the client's second message.

This is bad enough; but let's take this one step further. Now the server's second thread completes the request and tries to reply to the client. But since the server's first thread *already* replied to the client, the client is now unblocked and the server's second thread gets an error from its reply.

This problem is limited to multithreaded servers, because in a singlethreaded server, the server thread would still be busy working on the client's first request. This means that even though the client is now unblocked and sends again to the server, the client would now go into the SEND-blocked state (instead of the REPLY-blocked state), allowing the server to finish the processing, reply to the client (which would result in an error, because the client isn't REPLY-blocked any more), and *then* the server would receive the second message from the client. The real problem here is that the server is performing useless processing on behalf of the client (the client's first request). The processing is useless because the client is no longer waiting for the results of that work.

The solution (in the multithreaded server case) is to have the server specify the _NTO_CHF_UNBLOCK flag to its *ChannelCreate()* call. This says to the kernel, "Tell me when a client *tries* to unblock from me (by sending me a pulse), but *don't let the client unblock*! I'll unblock the client myself."

The key thing to keep in mind is that this server flag changes the behaviour of the client by *not* allowing the client to unblock until the *server* says it's okay to do so.
In a single-threaded server, the following happens:

Action	**Client**	**Server**
client sends to server	blocked	processing
client gets hit with signal	blocked	processing
kernel sends pulse to server	blocked	processing (1st message)
server completes 1st request, replies to client	unblocked with correct data	processing (pulse)

This didn't help the client unblock when it should have, but it *did* ensure that the server didn't get confused. In this kind of example, the server would most likely simply ignore the pulse that it got from the kernel. This is okay to do — the assumption being made here is that it's safe to let the client block until the server is ready with the data.

If you want the server to act on the pulse that the kernel sent, there are two ways to do this:

- Create another thread in the server that listens for messages (specifically, listening for the pulse from the kernel). This second thread would be responsible for canceling the operation that's under way in the first thread. One of the two threads would reply to the client.
- Don't do the client's work in the thread itself, but rather queue up the work. This is typically done in applications where the server is going to store the client's work on a queue and the server is event driven. Usually, one of the messages arriving at the server indicates that the client's work is now complete, and that the server should reply. In this case, when the kernel pulse arrives, the server cancels the work being performed on behalf of the client and replies.

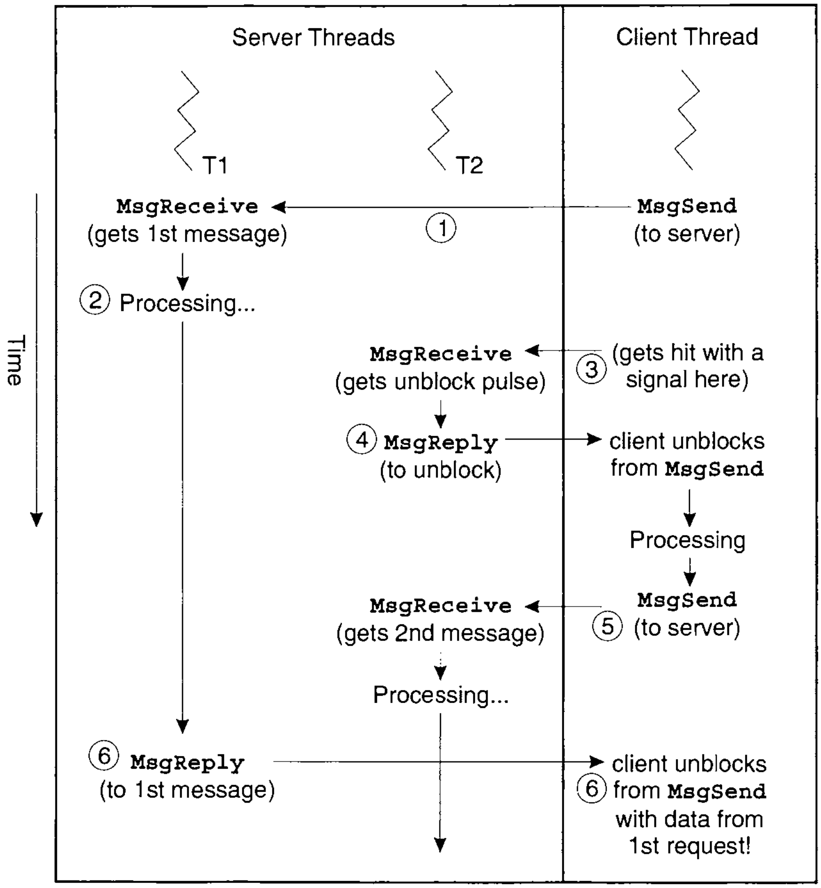
Which method you choose depends on the type of work the server does. In the first case, the server is actively performing the work on behalf of the client, so you really don't have a choice — you'll have to have a second thread that listens for unblock-pulses from the kernel (or you could poll periodically within the thread to see if a pulse has arrived, but polling is generally discouraged).

In the second case, the server has something else doing the work — perhaps a piece of hardware has been commanded to "go and collect data." In that case, the server's thread will be blocked on the *MsgReceive()* function anyway, waiting for an indication from the hardware that the command has completed.

In either case, the server *must* reply to the client, otherwise the client will remain blocked.

Synchronization problem

Even if you use the _NTO_CHF_UNBLOCK flag as described above, there's still one more synchronization problem to deal with. Suppose that you have multiple server threads blocked on the *MsgReceive()* function, waiting for messages or pulses, and the client sends you a message. One thread goes off and begins the client's work. While that's happening, the client wishes to unblock, so the kernel generates the unblock pulse. Another thread in the server receives this pulse. At this point, there's a race condition — the first thread could be *just about* ready to reply to the client. If the second thread (that got the pulse) does the reply, then there's a chance that the client would unblock and send another message to the server, with the server's first thread now getting a chance to run and replying to the client's second request with the first request's data:



Confusion in a multithreaded server.

Or, if the thread that got the pulse is *just about* to reply to the client, and the first thread does the reply, then you have the same situation — the first thread unblocks the client, who sends another request, and the second thread (that got the pulse) now unblocks the client's second request.

The situation is that you have two parallel flows of execution (one caused by the message, and one caused by the pulse). Ordinarily, we'd immediately recognize this as a situation that requires a mutex.

Unfortunately, this causes a problem — the mutex would have to be acquired immediately after the *MsgReceive()* and released before the *MsgReply()*. While this will indeed work, it defeats the whole purpose of the unblock pulse! (The server would either get the message and ignore the unblock pulse until after it had replied to the client, or the server would get the unblock pulse and cancel the client's second operation.)

A solution that looks promising (but is ultimately doomed to failure) would be to have a fine-grained mutex. What I mean by that is a mutex that gets locked and unlocked only around small portions of the control flow (the way that you're supposed to use a mutex, instead of blocking the entire processing section, as proposed above). You'd set up a "Have we replied yet?" flag in the server, and this flag would be cleared when you received a message and set when you replied to a message. Just before you replied to the message, you'd check the flag. If the flag indicates that the message has already been replied to, you'd skip the reply. The mutex would be locked and unlocked around the checking and setting of the flag.

Unfortunately, this won't work because we're not *always* dealing with two parallel flows of execution — the client won't always get hit with a signal during processing (causing an unblock pulse). Here's the scenario where it breaks:

- The client sends a message to the server; the client is now blocked, the server is now running.
- Since the server received a request from the client, the flag is reset to 0, indicating that we still need to reply to the client.
- The server replies normally to the client (because the flag was set to 0) and sets the flag to 1 indicating that, if an unblock-pulse arrives, it should be ignored.
- *(Problems begin here.)* The client sends a second message to the server, and almost immediately after sending it gets hit with a signal; the kernel sends an unblock-pulse to the server.

- The server thread that receives the message was about to acquire the mutex in order to check the flag, but didn't quite get there (it got preempted).
- Another server thread now gets the pulse and, because the flag is still set to a 1 from the last time, ignores the pulse.
- Now the server's first thread gets the mutex and clears the flag.
- At this point, the unblock event has been lost.

If you refine the flag to indicate more states (such as pulse received, pulse replied to, message received, message replied to), you'll still run into a synchronization race condition because there's no way for you to create an atomic binding between the flag and the receive and reply function calls. (Fundamentally, that's where the problem lies — the small timing windows after a *MsgReceive()* and before the flag is adjusted, and after the flag is adjusted just before the *MsgReply()*.) The only way to get around this is to have the kernel keep track of the flag for you.

Using the _NTO_MI_UNBLOCK_REQ

Luckily, the kernel keeps track of the flag for you as a single bit in the message info structure (the `struct _msg_info` that you pass as the last parameter to *MsgReceive()*, or that you can fetch later, given the receive ID, by calling *MsgInfo()*).

This flag is called _NTO_MI_UNBLOCK_REQ and is set if the client wishes to unblock (for example, after receiving a signal).

This means that in a multithreaded server, you'd typically have a "worker" thread that's performing the client's work, and another thread that's going to receive the unblock message (or some other message; we'll just focus on the unblock message for now). When you get the unblock message from the client, you'd set a flag to yourself, letting your program know that the thread wishes to unblock.

There are two cases to consider:

- the "worker" thread is blocked; or
- the "worker" thread is running.

If the worker thread is blocked, you'll need to have the thread that got the unblock message awaken it. It might be blocked if it's waiting for a resource, for example. When the worker thread wakes up, it should examine the _NTO_MI_UNBLOCK_REQ flag, and, if set, reply with an abort status. If the flag isn't set, then the thread can do whatever normal processing it does when it wakes up.

Alternatively, if the worker thread is running, it should periodically check the "flag to self" that the unblock thread may have set, and if the flag is set, it should reply to the client with an abort status. Note that this is just an optimization: in the unoptimized case, the worker thread would constantly call "MsgInfo" on the receive ID and check the _NTO_MI_UNBLOCK_REQ bit itself.

Message passing over a network

To keep things clear, I've avoided talking about how you'd use message passing over a network, even though this is a crucial part of Neutrino's flexibility!

Everything you've learned so far applies to message passing over the network.

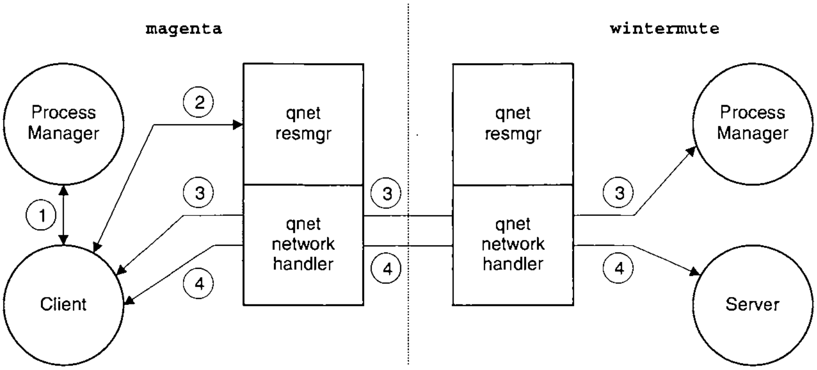
Earlier in this chapter, I showed you an example:

```
#include <fcntl.h>
#include <unistd.h>

int
main (void)
{
    int     fd;
    fd = open ("/net/wintermute/home/rk/filename", O_WRONLY);
    write (fd, "This is message passing\n", 24);
    close (fd);

    return (EXIT_SUCCESS);
}
```

At the time, I said that this was an example of "using message passing over a network." The client creates a connection to a ND/PID/CHID (which just happens to be on a different node), and the server performs a *MsgReceive()* on its channel. The client and server are identical in this case to the local, single-node case. You could stop reading right here — there really isn't anything "tricky" about message passing over the network. But for those readers who are curious about the *how* of this, read on!

Now that we've seen some of the details of local message passing, we can discuss in a little more depth how message passing over a network works. While this discussion may seem complicated, it really boils down to two phases: name resolution, and once that's been taken care of, simple message passing.

Here's a diagram that illustrates the steps we'll be talking about:



Message passing over a network. Notice that `qnet` *is divided into two sections.*

In the diagram, our node is called **magenta**, and, as implied by the example, the target node is called **wintermute**.

Let's analyze the interactions that occur when a client program uses qnet to access a server over the network:

1 The client's *open()* function was told to open a filename that happened to have /net in front of it. (The name /net is the default name manifested by qnet — consult the documentation that came with your Neutrino development system under npm-qnet for further details.) This client has no idea who is responsible for that particular pathname, so it connects to the process manager (step 1) in order to find out who actually owns the resource. This is done regardless of whether we're passing messages over a network and happens automatically. Since the native Neutrino network manager, qnet, "owns" all pathnames that begin with /net, the process manager returns information to the client telling it to ask qnet about the pathname.

2 The client now sends a message to qnet's resource manager thread, hoping that qnet will be able to handle the request. However, qnet on this node isn't responsible for providing the ultimate service that the client wants, so it tells the client that it should actually contact the process manager on node **wintermute**. (The way this is done is via a "redirect" response, which gives the client the ND/PID/CHID of a server that it should contact instead.) This redirect response is also handled automatically by the client's library.

3 The client now connects to the process manager on **wintermute**. This involves sending an off-node message through qnet's network-handler thread. The qnet process on the client's node gets the message and transports it over the medium to the remote qnet, which delivers it to the process manager on **wintermute**. The process manager there resolves the rest of the pathname (in our example, that would be the "**/home/rk/filename**" part) and sends a redirect message back. This redirect message follows the reverse path (from the

server's qnet over the medium to the qnet on the client's node, and finally back to the client). This redirect message now contains the location of the server that the client wanted to contact in the first place, that is, the ND/PID/CHID of the server that's going to service the client's requests. (In our example, the server was a filesystem.)

4 The client now sends the request to that server. The path followed here is identical to the path followed in step 3 above, except that the server is contacted directly instead of going through the process manager.

Once steps 1 through 3 have been established, step 4 is the model for all future communications. In our client example above, the *open()*, *read()*, and *close()* messages all take path number 4. Note that the client's *open()* is what triggered this sequence of events to happen in the first place — but the actual open *message* flows as described (through path number 4).

☞ For the *really* interested reader: I've left out one step. During step 2, when the client asks qnet about **wintermute**, qnet needs to figure out who **wintermute** is. This may result in qnet performing one more network transaction to resolve the nodename. The diagram presented above is correct if we assume that qnet already knew about **wintermute**.

We'll come back to the messages used for the *open()*, *read()*, and *close()* (and others) in the Resource Managers chapter.

Networked message passing differences

So, once the connection is established, all further messaging flows using step 4 in the diagram above. This may lead you to the erroneous belief that message passing over a network is identical to message passing in the local case. Unfortunately, this is *not true*. Here are the differences:

- longer delays

- *ConnectAttach()* returns success regardless of whether the node is alive or not — the real error indication happens on the first message pass
- *MsgDeliverEvent()* isn't guaranteed reliable
- *MsgReply()*, *MsgRead()*, *MsgWrite()* are now blocking calls, whereas in the local case they are not
- *MsgReceive()* won't receive all the data sent by the client; the server will need to call *MsgRead()* to get the rest.

Longer delays

Since message passing is now being done over some medium, rather than a direct kernel-controlled memory-to-memory copy, you can expect that the amount of time taken to transfer messages will be significantly higher (100 MBit Ethernet versus 100MHz 64-bit wide DRAM is going to be an order of magnitude or two slower). Plus, on top of this will be protocol overhead (minimal) and retries on lossy networks.

Impact on *ConnectAttach()*

When you call *ConnectAttach()*, you're specifying an ND, a PID, and a CHID. All that happens in Neutrino is that the kernel returns a connection ID to the `qnet` "network handler" thread pictured in the diagram above. Since no message has been sent, you're not informed as to whether the node that you've just attached to is still alive or not. In normal use, this isn't a problem, because most clients won't be doing their own *ConnectAttach()* — rather, they'll be using the services of the library call *open()*, which does the *ConnectAttach()* and then almost immediately sends out an "open" message. This has the effect of indicating almost immediately if the remote node is alive or not.

Impact on *MsgDeliverEvent()*

When a server calls *MsgDeliverEvent()* locally, it's the kernel's responsibility to deliver the event to the target thread. With the network, the server still calls *MsgDeliverEvent()*, but the kernel delivers a "proxy" of that event to `qnet`, and it's up to `qnet` to deliver the proxy to the other (client-side) `qnet`, who'll then deliver the actual event to the client. Things can get screwed up on the server side, because the *MsgDeliverEvent()* function call is non-blocking — this means that once the server has called *MsgDeliverEvent()* it's running. It's too late to turn around and say, "I hate to tell you this, but you know that *MsgDeliverEvent()* that I said succeeded? Well, it didn't!"

Impact on *MsgReply()*, *MsgRead()*, and *MsgWrite()*

To prevent the problem I just mentioned with *MsgDeliverEvent()* from happening with *MsgReply()*, *MsgRead()*, and *MsgWrite()*, these functions were transformed into blocking calls when used over the network. Locally they'd simply transfer the data and unblock immediately. On the network, we have to (in the case of *MsgReply()*) ensure that the data has been delivered to the client or (in the case of the other two) to actually transfer the data to or from the client over the network.

Impact on *MsgReceive()*

Finally, *MsgReceive()* is affected as well (in the networked case). Not all the client's data may have been transferred over the network by `qnet` when the server's *MsgReceive()* unblocks. This is done for performance reasons.

There are two flags in the `struct _msg_info` that's passed as the last parameter to *MsgReceive()* (we've seen this structure in detail in "Who sent the message?" above):

msglen indicates how much data was actually transfered by the *MsgReceive()* (`qnet` likes to transfer 8k).

srcmsglen indicates how much data the client wanted to transfer (determined by the client).

So, if the client wanted to transfer 1 megabyte of data over the network, the server's *MsgReceive()* would unblock and *msglen* would be set to 8192 (indicating that 8192 bytes were available in the buffer), while *srcmsglen* would be set to 1048576 (indicating that the client tried to send 1 megabyte).

The server then uses *MsgRead()* to get the rest of the data from the client's address space.

Some notes on NDs

The other "funny" thing that we haven't yet talked about when it comes to message passing is this whole business of a "node descriptor" or just "ND" for short.

Recall that we used symbolic node names, like `/net/wintermute` in our examples. Under QNX 4 (the previous version of the OS before Neutrino), native networking was based on the concept of a node ID, a small integer that was unique on the network. Thus, we'd talk about "node 61," or "node 1," and this was reflected in the function calls.

Under Neutrino, all nodes are internally referred to by a 32-bit quantity, but it's *not* network unique! What I mean by that is that `wintermute` might think of `spud` as node descriptor number "7," while `spud` might think of `magenta` as node descriptor number "7" as well. Let me expand that to give you a better picture. This table shows some sample node descriptors that might be used by three nodes, `wintermute`, `spud`, and `foobar`:

Node	`wintermute`	`spud`	`foobar`
`wintermute`	0	7	4
`spud`	4	0	6
`foobar`	5	7	0

Notice how each node's node descriptor for itself is zero. Also notice how `wintermute`'s node descriptor for `spud` is "7," as is `foobar`'s node descriptor for `spud`. But `wintermute`'s node descriptor for `foobar` is "4" while `spud`'s node descriptor for `foobar` is "6." As I said, they're not unique across the network, although they are unique on each node. You can effectively think of them as file descriptors — two processes might have the same file descriptor if they access the same file, but they might not; it just depends on who opened which file when.

Fortunately, you don't have to worry about node descriptors, for a number of reasons:

1 Most of the off-node message passing you'll typically be doing will be through higher-level function calls (like *open()*, as shown in the example above).

2 Node descriptors are not to be cached — if you get one, you're supposed to use it immediately and then forget about it.

3 There are library calls to convert a pathname (like `/net/magenta`) to a node descriptor.

To work with node descriptors, you'll want to include the file `<sys/netmgr.h>` because it includes a bunch of *netmgr_*()* functions.

You'd use the function *netmgr_strtond()* to convert a string into a node descriptor. Once you have this node descriptor, you'd use it immediately in the *ConnectAttach()* function call. Specifically, you shouldn't ever cache it in a data structure! The reason is that the native networking manager may decide to reuse it once all connections to that particular node are disconnected. So, if you got a node descriptor of "7" for `/net/magenta`, and you connected to it, sent a message, and then disconnected, there's a possibility that the native networking manager will return a node descriptor of "7" again for a *different* node.

Since node descriptors aren't unique per network, the question that arises is, "How do you pass these things around the network?" Obviously, `magenta`'s view of what node descriptor "7" is will be radically different from `wintermute`'s. There are two solutions here:

- Don't pass around node descriptors; use the symbolic names (e.g., `/net/wintermute`) instead.
- Use the *netmgr_remote_nd()* function.

The first is a good general-purpose solution. The second solution is reasonably simple to use:

```
int
netmgr_remote_nd (int remote_nd, int local_nd);
```

This function takes two parameters: the *remote_nd* is the node descriptor of the target machine, and *local_nd* is the node descriptor (from the local machine's point of view) to be translated to the remote machine's point of view. The result is the node descriptor that is valid from the remote machine's point of view.

For example, let's say **`wintermute`** is our local machine. We have a node descriptor of "7" that is valid on our local machine and points to **`magenta`**. What we'd like to find out is what node descriptor **`magenta`** uses to talk to us:

```
int     remote_nd;
int     magenta_nd;

magenta_nd = netmgr_strtond ("/net/magenta", NULL);
printf ("Magenta's ND is %d\n", magenta_nd);
remote_nd = netmgr_remote_nd (magenta_nd, ND_LOCAL_NODE);
printf ("From magenta's point of view, we're ND %d\n",
        remote_nd);
```

This might print something similar to:

```
Magenta's ND is 7
From magenta's point of view, we're ND 4
```

This says that *on* **`magenta`**, the node descriptor "4" refers to our node. (Notice the use of the special constant ND_LOCAL_NODE, which is really zero, to indicate "this node.")

Now, recall that we said (in "Who sent the message?") that the **`struct _msg_info`** contains, among other things, two node descriptors:

```
struct _msg_info
{
    int     nd;
    int     srcnd;
    ...
};
```

We stated in the description for those two fields that:

- *nd* is the receiving node's node descriptor for the transmitting node

- *srcnd* is the transmitting node's node descriptor for the receiving node

So, for our example above, where **`wintermute`** is the local node and **`magenta`** is the remote node, when **`magenta`** sends a message to us (**`wintermute`**), we'd expect that:

- *nd* would contain 7
- *srcnd* would contain 4.

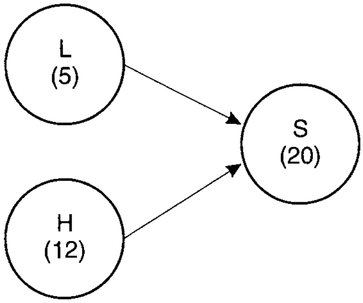
Priority inheritance

One of the interesting issues in a realtime operating system is a phenomenon known as *priority inversion.*

Priority inversion manifests itself as, for example, a low-priority thread consuming all available CPU time, even though a higher-priority thread is ready to run.

Now you're probably thinking, "Wait a minute! You said that a higher-priority thread will *always* preempt a lower-priority thread! How can this be?"

This is true — a higher-priority thread will *always* preempt a lower-priority thread. But something interesting can happen. Let's look at a scenario where we have three threads (in three different processes, just to keep things simple), "L" is our low-priority thread, "H" is our high-priority thread, and "S" is a server. This diagram shows the three threads and their priorities:



Three threads at different priorities.

Currently, H is running. S, a higher-priority server thread, doesn't have anything to do right now so it's waiting for a message and is blocked in *MsgReceive()*. L would like to run but is at a lower priority than H, which is running. Everything is as you'd expect, right?

Now H has decided that it would like to go to sleep for 100 milliseconds — perhaps it needs to wait for some slow hardware. At this point, L is running.

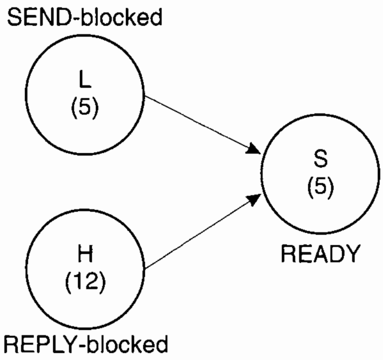
This is where things get interesting.

As part of its normal operation, L sends a message to the server thread S, causing S to go READY and (because it's the highest-priority thread that's READY) to start running. Unfortunately, the message that L sent to S was "Compute pi to 50 decimal places."

Obviously, this takes more than 100 milliseconds. Therefore, when H's 100 milliseconds are up and H goes READY, guess what? It won't run, because S is READY and at a higher priority!

What happened is that a low-priority thread prevented a higher-priority thread from running by leveraging the CPU via an even higher-priority thread. This is *priority inversion.*

To fix it, we need to talk about *priority inheritance.* A simple fix is to have the server, S, *inherit* the priority of the client thread:



Blocked threads.

In this scenario, when H's 100 millisecond sleep has completed, it goes READY and, because it's the highest-priority READY thread, runs.

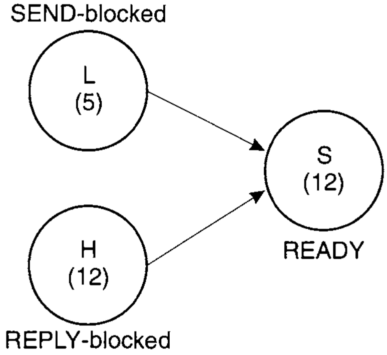
Not bad, but there's one more "gotcha."

Suppose that H now decides that it too would like a computation performed. It wants to compute the 5,034th prime number, so it sends a message to S and blocks.

However, S is still computing pi, at a priority of 5! In our example system, there are lots of other threads running at priorities higher than 5 that are making use of the CPU, effectively ensuring that S *isn't* getting much time to calculate pi.

This is another form of priority inversion. In this case, a lower-priority thread has prevented a higher-priority thread from getting access to a resource. Contrast this with the first form of priority inversion, where the lower-priority thread was effectively *consuming* CPU — in this case it's only *preventing* a higher-priority thread from getting CPU — it's not consuming any CPU itself.

Luckily, the solution is fairly simple here too. Boost the server's priority to be the highest of all blocked clients:



Boosting the server's priority.

This way we take a minor hit by letting L's job run at a priority higher than L, but we do ensure that H gets a fair crack at the CPU.

So what's the trick?

There's no trick! Neutrino does this automatically for you. (You can turn off priority inheritence if you don't want it; see the _NTO_CHF_FIXED_PRIORITY flag in the *ChannelCreate()* function's documentation.)

☞ Neutrino only does this one level deep — if a client sent to a server, and that server sent to another server, the second server would inherit the *normal* priority of the first server's thread, not the priority that the first server's thread inherited. This means that if a higher-priority thread blocked on the first server, only the first server's priority would be boosted (but since it's blocked anyway on the second server, this doesn't do much good, because the second server's priority does *not* get boosted). Beware!

There's a minor design issue here, however. How do you revert the priority to what it was before it got changed?

Your server is running along, servicing requests from clients, adjusting its priority automagically when it unblocks from the

MsgReceive() call. But when should it adjust its priority *back* to what it was before the *MsgReceive()* call changed it?

There are two cases to consider:

- The server performs some additional processing *after* it properly services the client. This should be done at the *server's* priority, not the client's.
- The server immediately does another *MsgReceive()* to handle the next client request.

In the first case, it would be incorrect for the server to run at the client's priority when it's no longer doing work for that client! The solution is fairly simple. Use the *pthread_setschedparam()* function (discussed in the Processes and Threads chapter) to revert the priority back to what it should be.

What about the other case? The answer is subtly simple: Who cares?

Think about it. What difference does it make if the server becomes RECEIVE-blocked when it was priority 29 versus when it was priority 2? The fact of the matter is it's RECEIVE-blocked! It isn't getting any CPU time, so its priority is irrelevant. As soon as the *MsgReceive()* function unblocks the server, the (new) client's priority is inherited by the server and everything works as expected.

Summary

Message passing is an extremely powerful concept and is one of the main features on which Neutrino (and indeed, all past QSSL operating systems) is built.

With message passing, a client and a server exchange messages (thread-to-thread in the same process, thread-to-thread in different processes on the same node, or thread-to-thread in different processes on different nodes in a network). The client sends a message and blocks until the server receives the message, processes it, and replies to the client.

The main advantages of message passing are:

- The content of a message doesn't change based on the location of the destination (local versus networked).
- A message provides a "clean" decoupling point for clients and servers.
- Implicit synchronization and serialization helps simplify the design of your applications.

Chapter 3

Clocks, Timers, and Getting a Kick Every So Often

In this chapter...

Clocks and timers

Using timers

Advanced topics

Clocks and timers

It's time to take a look at everything related to time in Neutrino. We'll see how and why you'd use timers and the theory behind them. Then we'll take a look at getting and setting the realtime clock.

Let's look at a typical system, say a car. In this car, we have a bunch of programs, most of which are running at different priorities. Some of these need to respond to actual external events (like the brakes or the radio tuner), while others need to operate periodically (such as the diagnostics system).

Operating periodically

So how does the diagnostics system "operate periodically?" You can imagine some process in the car's CPU that does something similar to the following:

```
// Diagnostics Process

int
main (void)     // ignore arguments here
{
    for (;;) {
        perform_diagnostics ();
        sleep (15);
    }

    // You'll never get here.
    return (EXIT_SUCCESS);
}
```

Here we see that the diagnostics process runs forever. It performs one round of diagnostics and then goes to sleep for 15 seconds, wakes up, goes through the loop again, and again, ...

Way back in the dim, dark days of single-tasking, where one CPU was dedicated to one user, these sorts of programs were implemented by having the **sleep (15);** code do a busy-wait loop. You'd calculate how fast your CPU was and then write your own *sleep()* function:

```
void
sleep (int nseconds)
{
    long    i;

    while (nseconds--) {
        for (i = 0; i < CALIBRATED_VALUE; i++) ;
    }
}
```

In those days, since nothing else was running on the machine, this didn't present much of a problem, because no other process cared that you were hogging 100% of the CPU in the *sleep()* function.

☞ Even today, we sometimes hog 100% of the CPU to do timing functions. Notably, the *nanospin()* function is used to obtain very fine-grained timing, but it does so at the expense of burning CPU at its priority. Use with caution!

If you *did* have to perform some form of "multitasking," it was usually done via an interrupt routine that would hang off the hardware timer or be performed within the "busy-wait" period, somewhat affecting the calibration of the timing. This usually wasn't a concern.

Luckily we've progressed far beyond that point. Recall from "Scheduling and the real world," in the Processes and Threads chapter, what causes the kernel to reschedule threads:

- a hardware interrupt
- a kernel call
- a fault (exception)

In this chapter, we're concerned with the first two items on the list: the hardware interrupt and the kernel call.

When a thread calls *sleep()*, the C library contains code that eventually makes a kernel call. This call tells the kernel, "Put this thread on hold for a fixed amount of time." The call removes the thread from the running queue and starts a timer.

Meanwhile, the kernel has been receiving regular hardware interrupts from the computer's clock hardware. Let's say, for argument's sake, that these hardware interrupts occur at *exactly* 10-millisecond intervals.

Let's restate: every time one of these interrupts is handled by the kernel's clock interrupt service routine (ISR), it means that 10 ms have gone by. The kernel keeps track of the time of day by incrementing its time-of-day variable by an amount corresponding to 10 ms every time the ISR runs.

So when the kernel implements a 15-second timer, all it's really doing is:

1. Setting a variable to the current time plus 15 seconds.
2. In the clock ISR, comparing this variable against the time of day.
3. When the time of day is the same as (or greater than) the variable, putting the thread back onto the READY queue.

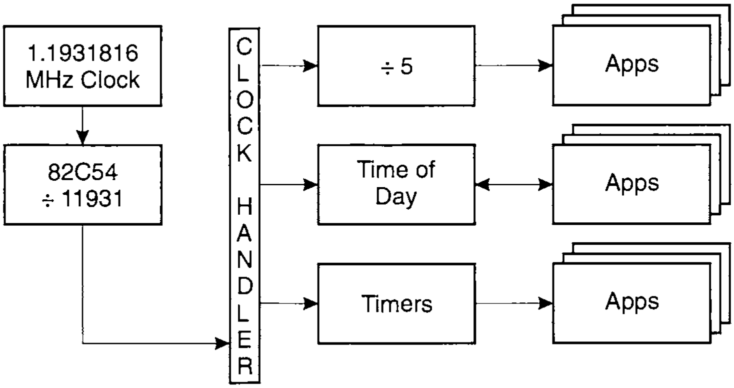
When multiple timers are outstanding, as would be the case if several threads all needed to be woken at different times, the kernel would simply queue the requests, sorting them by time order — the nearest one would be at the head of the queue, and so on. The variable that the ISR looks at is the one at the head of this queue.

That's the end of the timer five-cent tour.

Actually, there's a little bit more to it than first meets the eye.

Clock interrupt sources

So where does the clock interrupt come from? Here's a diagram that shows the hardware components (and some typical values for a PC) responsible for generating these clock interrupts:



PC clock interrupt sources.

As you can see, there's a high-speed (MHz range) clock produced by the circuitry in the PC. This high-speed clock is then divided by a hardware counter (the 82C54 component in the diagram), which reduces the clock rate to the kHz or hundreds of Hz range (i.e., something that an ISR can actually handle). The clock ISR is a component of the kernel and interfaces directly with the data structures and code of the kernel itself. On non-x86 architectures (MIPS, PowerPC), a similar sequence of events occurs; some chips have clocks built into the processor.

Note that the high-speed clock is being divided by an *integer* divisor. This means the rate isn't going to be *exactly* 10 ms, because the high-speed clock's rate *isn't* an integer multiple of 10 ms. Therefore, the kernel's ISR in our example above might actually be interrupted after 9.9999296004 ms.

Big deal, right? Well, sure, it's fine for our 15-second counter. 15 seconds is 1500 timer ticks — doing the math shows that it's approximately 106 μs off the mark:

$$
\begin{aligned}
&15\text{ s} - 1500 \times 9.9999296004\text{ ms}\\
&\quad = 15000\text{ ms} - 14999.8944006\text{ ms}\\
&\quad = 0.1055994\text{ ms}
\end{aligned}
$$

= 105.5994 µs

Unfortunately, continuing with the math, that amounts to 608 ms per day, or about 18.5 seconds per month, or almost 3.7 minutes per year!

You can imagine that with other divisors, the error could be greater or smaller, depending on the rounding error introduced. Luckily, the kernel knows about this and corrects for it.

The point of this story is that regardless of the nice round value shown, the *real* value is selected to be the next *faster* value.

Base timing resolution

Let's say that the timer tick is operating at just slightly faster than 10 ms. Can I reliably sleep for 3 milliseconds?

Nope.

Consider what happens in the kernel. You issue the C-library *delay()* call to go to sleep for 3 milliseconds. The kernel has to set the variable in the ISR to some value. If it sets it to the current time, this means the timer has already expired and that you should wake up immediately. If it sets it to one tick more than the current time, this means that you should wake up on the next tick (*up to* 10 milliseconds away).

The moral of this story is: "Don't expect timing resolution any better than the input timer tick rate."

Getting more precision

Under Neutrino, a program can adjust the value of the hardware divisor component in conjunction with the kernel (so that the kernel knows what rate the timer tick ISR is being called at). We'll look at this below in the "Getting and setting the realtime clock" section.

Timing jitter

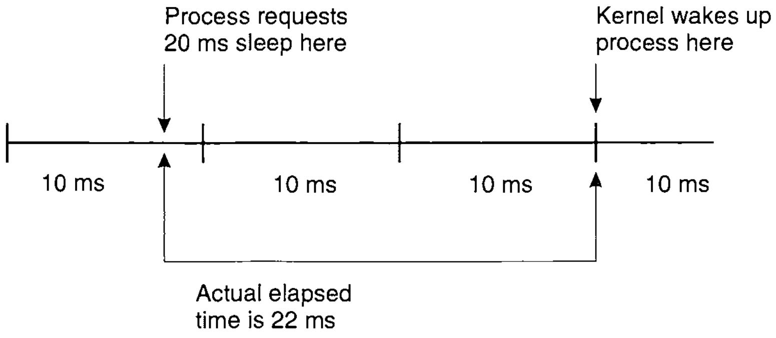
There's one more thing you have to worry about. Let's say the timing resolution is 10 ms and you want a 20 ms timeout.

Are you always going to get exactly 20 milliseconds worth of delay from the time that you issue the *delay()* call to the time that the function call returns?

Absolutely not.

There are two good reasons why. The first is fairly simple: when you block, you're taken off the running queue. This means that another thread at your priority may now be using the CPU. When your 20 milliseconds have expired, you'll be placed at the *end* of the READY queue for that priority so you'll be at the mercy of whatever thread happens to be running. This also applies to interrupt handlers running or higher-priority threads running — just because you are READY doesn't mean that you're consuming the CPU.

The second reason is a bit more subtle. The following diagram will help explain why:



Clock jitter.

The problem is that your request is *asynchronous* to the clock source. You have no way to synchronize the hardware clock with your request. Therefore, you'll get from just over 20 milliseconds to just under 30 milliseconds worth of delay, depending on where in the hardware's clock period you started your request.

☞ This is a key point. Clock jitter is a sad fact of life. The way to get around it is to increase the system's timing resolution so your timing is within tolerance. (We'll see how to do this in the "Getting and setting the realtime clock" section, below.) Keep in mind that jitter takes place only on the first tick — a 100-second delay with a 10-millisecond clock will delay for greater than 100 seconds and less than 100.01 seconds.

Types of timers

The type of timer that I showed you above is a *relative timer*. The timeout period selected is relative to the current time. If you want the timer to delay your thread until January 20, 2005 at 12:04:33 EDT, you'd have to calculate the number of seconds from "now" until then, and set up a relative timer for that number of seconds. Because this is a fairly common function, Neutrino implements an *absolute timer* that will delay *until* the specified time (instead of *for* the specified time, like a relative timer).

What if you want to *do* something while you're waiting for that date to come around? Or, what if you want to do something and get a "kick" every 27 seconds? You certainly couldn't afford to be asleep!

As we discussed in the Processes and Threads chapter, you could simply start up another thread to do the work, and your thread could take the delay. However, since we're talking about timers, we'll look at another way of doing this.

You can do this with a periodic or one-shot timer, depending on your objectives. A *periodic timer* is one that goes off periodically, notifying the thread (over and over again) that a certain time interval has elapsed. A *one-shot timer* is one that goes off just once.

The implementation in the kernel is still based on the same principle as the delay timer that we used in our first example. The kernel takes the absolute time (if you specified it that way) and stores it. In the clock ISR, the stored time is compared against the time of day in the usual manner.

However, instead of your thread being removed from the running queue when you call the kernel, your thread continues to run. When the time of day reaches the stored time, the kernel notifies your thread that the designated time has been reached.

Notification schemes

How do you receive a timeout notification? With the delay timer, you received notification by virtue of being made READY again.

With periodic and one-shot timers, you have a choice:

- send a pulse
- send a signal
- create a thread

We've talked about pulses in the Message Passing chapter; signals are a standard UNIX-style mechanism, and we'll see the thread creation notification type shortly.

How to fill in the `struct sigevent`

Let's take a quick look at how you fill in the **`struct sigevent`** structure.

Regardless of the notification scheme you choose, you'll need to fill in a **`struct sigevent`** structure:

```
struct sigevent {
    int                 sigev_notify;

    union {
        int             sigev_signo;
        int             sigev_coid;
        int             sigev_id;
        void          (*sigev_notify_function) (union sigval);
    };

    union sigval        sigev_value;

    union {
        struct {
            short       sigev_code;
            short       sigev_priority;
        };
        pthread_attr_t *sigev_notify_attributes;
    };
};
```

☞ Note that the above definition uses anonymous unions and structures. Careful examination of the header file will show you how this trick is implemented on compilers that don't support these features. Basically, there's a **#define** that uses a named union and structure to make it look like it's an anonymous union. Check out **<sys/siginfo.h>** for details.

The first field you have to fill in is the *sigev_notify* member. This determines the notification type you've selected:

SIGEV_PULSE

A pulse will be sent.

SIGEV_SIGNAL, SIGEV_SIGNAL_CODE, or SIGEV_SIGNAL_THREAD

A signal will be sent.

SIGEV_UNBLOCK

Not used in this case; used with kernel timeouts (see "Kernel timeouts" below).

SIGEV_INTR

Not used in this case; used with interrupts (see the Interrupts chapter).

SIGEV_THREAD

Creates a thread.

Since we're going to be using the **struct sigevent** with timers, we're concerned only with the SIGEV_PULSE, SIGEV_SIGNAL* and SIGEV_THREAD values for *sigev_notify*; we'll see the other types as mentioned in the list above.

Pulse notification

To send a pulse when the timer fires, set the *sigev_notify* field to SIGEV_PULSE and provide some extra information:

Field	Value and meaning
sigev_coid	Send the pulse to the channel associated with this connection ID.
sigev_value	A 32-bit value that gets sent to the connection identified in the *sigev_coid* field.
sigev_code	An 8-bit value that gets sent to the connection identified in the *sigev_coid* field.
sigev_priority	The pulse's delivery priority. The value zero is not allowed (too many people were getting bitten by running at priority zero when they got a pulse — priority zero is what the idle task runs at, so effectively they were competing with Neutrino's IDLE process and not getting much CPU time `:-)`).

Note that the *sigev_coid* could be a connection to *any* channel (usually, though not necessarily, the channel associated with the process that's initiating the event).

Signal notification

To send a signal, set the *sigev_notify* field to one of:

SIGEV_SIGNAL

Send a regular signal to the process.

SIGEV_SIGNAL_CODE

Send a signal containing an 8-bit code to the process.

SIGEV_SIGNAL_THREAD

Send a signal containing an 8-bit code to a specific thread.

For SIGEV_SIGNAL*, the additional fields you'll have to fill are:

Field	Value and meaning
sigev_signo	Signal number to send (from `<signal.h>`, e.g., SIGALRM).
sigev_code	An 8-bit code (if using SIGEV_SIGNAL_CODE or SIGEV_SIGNAL_THREAD).

Thread notification

To create a thread whenever the timer fires, set the *sigev_notify* field to SIGEV_THREAD and fill these fields:

Field	Value and meaning
sigev_notify_function	Address of `void *` function that accepts a `void *` to be called when the event triggers.
sigev_value	Value passed as the parameter to the *sigev_notify_function()* function.
sigev_notify_attributes	Thread attributes structure (see the Processes and Threads chapter, under "The thread attributes structure" for details).

☞ This notification type is a little scary! You could have a whole slew of threads created if the timer fires often enough and, if there are higher priority threads waiting to run, this could chew up all available resources on the system! Use with caution!

General tricks for notification

There are some convenience macros in `<sys/siginfo.h>` to make filling in the notification structures easier:

SIGEV_SIGNAL_INIT (eventp, signo)

Fill *eventp* with SIGEV_SIGNAL, and the appropriate signal number *signo.*

SIGEV_SIGNAL_CODE_INIT (eventp, signo, value, code)

Fill *eventp* with SIGEV_SIGNAL_CODE, the signal number *signo*, as well as the *value* and *code.*

SIGEV_SIGNAL_THREAD_INIT (eventp, signo, value, code)

Fill *eventp* with SIGEV_SIGNAL_THREAD, the signal number *signo*, as well as the *value* and *code.*

SIGEV_PULSE_INIT (eventp, coid, priority, code, value)

Fill *eventp* with SIGEV_SIGNAL_PULSE, the connection to the channel in *coid* and a *priority*, *code*, and *value*. Note that there is a special value for *priority* of SIGEV_PULSE_PRIO_INHERIT that *prevents* the receiving thread's priority from changing.

SIGEV_UNBLOCK_INIT (eventp)

Fill *eventp* with SIGEV_UNBLOCK.

SIGEV_INTR_INIT (eventp)

Fill *eventp* with SIGEV_INTR.

SIGEV_THREAD_INIT (eventp, func, val, attributes)

Fill *eventp* with the thread function (*func*) and the attributes structure (*attributes*). The value in *val* is passed to the function in *func* when the thread is executed.

Pulse notification

Suppose you're designing a server that spent most of its life RECEIVE blocked, waiting for a message. Wouldn't it be ideal to receive a special message, one that told you that the time you had been waiting for finally arrived?

This scenario is *exactly* where you should use pulses as the notification scheme. In the "Using timers" section below, I'll show you some sample code that can be used to get periodic pulse messages.

Signal notification

Suppose that, on the other hand, you're performing some kind of work, but don't want that work to go on forever. For example, you may be waiting for some function call to return, but you can't predict how long it takes.

In this case, using a signal as the notification scheme, with perhaps a signal handler, is a good choice (another choice we'll discuss later is to use kernel timeouts; see _NTO_CHF_UNBLOCK in the Message Passing chapter as well). In the "Using timers" section below, we'll see a sample that uses signals.

Alternatively, a signal with *sigwait()* is cheaper than creating a channel to receive a pulse on, if you're not going to be receiving messages in your application anyway.

Using timers

Having looked at all this wonderful theory, let's turn our attention to some specific code samples to see what you can do with timers.

To work with a timer, you must:

1 Create the timer object.

2 Decide how you wish to be notified (signal, pulse, or thread creation), and create the notification structure (the **struct sigevent**).

3 Decide what kind of timer you wish to have (relative versus absolute, and one-shot versus periodic).

4 Start it.

Let's look at these in order.

Creating a timer

The first step is to create the timer with *timer_create()*:

```
#include <time.h>
#include <sys/siginfo.h>

int
timer_create (clockid_t clock_id,
              struct sigevent *event,
              timer_t *timerid);
```

The *clock_id* argument tells the *timer_create()* function *which* time base you're creating this timer for. This is a POSIX thing — POSIX says that on different platforms you can have multiple time bases, but that every platform must support at least the CLOCK_REALTIME time base. Under Neutrino, there are *three* time bases to choose from:

- CLOCK_REALTIME
- CLOCK_SOFTTIME
- CLOCK_MONOTONIC

For now, we'll ignore CLOCK_SOFTTIME and CLOCK_MONOTONIC but we will come back to them in the "Other clock sources" section, below.

Signal, pulse, or thread?

The second parameter is a pointer to a `struct sigevent` data structure. This data structure is used to inform the kernel about what kind of event the timer should deliver whenever it "fires." We discussed how to fill in the `struct sigevent` above in the discussion of signals versus pulses versus thread creation.

So, you'd call *timer_create()* with CLOCK_REALTIME and a pointer to your `struct sigevent` data structure, and the kernel would create a timer object for you (which gets returned in the last argument). This timer object is just a small integer that acts as an index into the kernel's timer tables; think of it as a "handle."

At this point, nothing else is going to happen. You've only just *created* the timer; you haven't triggered it yet.

What kind of timer?

Having created the timer, you now have to decide what *kind* of timer it is. This is done by a combination of arguments to *timer_settime()*, the function used to actually start the timer:

```
#include <time.h>

int
timer_settime (timer_t timerid,
               int flags,
               struct itimerspec *value,
               struct itimerspec *oldvalue);
```

The *timerid* argument is the value that you got back from the *timer_create()* function call — you can create a bunch of timers, and then call *timer_settime()* on them individually to set and start them at your convenience.

The *flags* argument is where you specify absolute versus relative.

If you pass the constant TIMER_ABSTIME, then it's absolute, pretty much as you'd expect. You then pass the actual date and time when you want the timer to go off.

If you pass a zero, then the timer is considered relative to the current time.

Let's look at how you specify the times. Here are key portions of two data structures (in **`<time.h>`**):

```
struct timespec {
    long    tv_sec,
            tv_nsec;
};

struct itimerspec {
    struct timespec it_value,
                    it_interval;
};
```

There are two members in **`struct itimerspec`**:

it_value	the one-shot value
it_interval	the reload value

The *it_value* specifies either how long from now the timer should go off (in the case of a relative timer), or when the timer should go off (in the case of an absolute timer). Once the timer fires, the *it_interval* value specifies a relative value to reload the timer with so that it can trigger again. Note that specifying a value of zero for the *it_interval* makes it into a one-shot timer. You might expect that to create a "pure" periodic timer, you'd just set the *it_interval* to the reload value, and set *it_value* to zero. Unfortunately, the last part of that statement is false — setting the *it_value* to zero *disables* the timer. If you want to create a pure periodic timer, set *it_value* equal to *it_interval* and create the timer as a relative timer. This will fire once (for the *it_value* delay) and then keep reloading with the *it_interval* delay.

Both the *it_value* and *it_interval* members are actually structures of type **`struct timespec`**, another POSIX thing. The structure lets you specify sub-second resolutions. The first member, *tv_sec*, is the number of seconds; the second member, *tv_nsec*, is the number of nanoseconds in the current second. (What this means is that you should never set *tv_nsec* past the value 1 billion — this would imply more than a one-second offset.)

Here are some examples:

```
it_value.tv_sec = 5;
it_value.tv_nsec = 500000000;
it_interval.tv_sec = 0;
it_interval.tv_nsec = 0;
```

This creates a one-shot timer that goes off in 5.5 seconds. (We got the ".5" because of the 500,000,000 nanoseconds value.)

We're assuming that this is used as a relative timer, because if it weren't, then that time would have elapsed long ago (5.5 seconds past January 1, 1970, 00:00 GMT).

Here's another example:

```
it_value.tv_sec = 987654321;
it_value.tv_nsec = 0;
it_interval.tv_sec = 0;
it_interval.tv_nsec = 0;
```

This creates a one-shot timer that goes off Thursday, April 19, 2001 at 00:25:21 EDT. (There are a bunch of functions that help you convert between the human-readable date and the "number of seconds since January 1, 1970, 00:00:00 GMT" representation. Take a look in the C library at *time()*, *asctime()*, *ctime()*, *mktime()*, *strftime()*, etc.)

For this example, we're assuming that it's an absolute timer, because of the huge number of seconds that we'd be waiting if it were relative (987654321 seconds is about 31.3 years).

Note that in both examples, I've said, "We're assuming that..." There's nothing in the *code* for *timer_settime()* that checks those assumptions and does the "right" thing! *You* have to specify whether the timer is absolute or relative yourself. The kernel will happily schedule something 31.3 years into the future.

One last example:

```
it_value.tv_sec = 1;
it_value.tv_nsec = 0;
it_interval.tv_sec = 0;
it_interval.tv_nsec = 500000000;
```

Assuming it's relative, this timer will go off in one second, and then again every half second after that. There's absolutely no requirement that the reload values look anything like the one-shot values.

A server with periodic pulses

The first thing we should look at is a server that wants to get periodic messages. The most typical uses for this are:

- server-maintained timeouts on client requests
- periodic server maintenance cycles

Of course there are other, specialized uses for these things, such as network "keep alive" messages that need to be sent periodically, retry requests, etc.

Server-maintained timeouts

In this scenario, a server is providing some kind of service to a client, and the client has the ability to specify a timeout. There are lots of places where this is used. For example, you may wish to tell a server, "Get me 15 second's worth of data," or "Let me know when 10 seconds are up," or "Wait for data to show up, but if it doesn't show up within 2 minutes, time out."

These are all examples of server-maintained timeouts. The client sends a message to the server, and blocks. The server receives periodic messages from a timer (perhaps once per second, perhaps more or less often), and counts how many of those messages it's received. When the number of timeout messages exceeds the timeout specified by the client, the server replies to the client with some kind of timeout indication or perhaps with the data accumulated so far — it really depends on how the client/server relationship is structured.

Here's a complete example of a server that accepts one of two messages from clients and a timeout message from a pulse. The first client message type says, "Let me know if there's any data available, but don't block me for more than 5 seconds." The second client message type says, "Here's some data." The server should allow multiple clients to be blocked on it, waiting for data, and must therefore associate a timeout with the clients. This is where the pulse message comes in; it says, "One second has elapsed."

In order to keep the code sample from being one overwhelming mass, I've included some text before each of the major sections. In the online source code that you can get from the PARSE FTP site (visit **`ftp://ftp.parse.com/pub/book_v3.tar.gz`**), this example is kept together in one file, **`time1.c`**.

Declarations

The first section of code here sets up the various manifest constants that we'll be using, the data structures, and includes all the header files required. We'll present this without comment. `:-)`

```
/*
 *  time1.c
 *
 *  Example of a server that receives periodic messages from
 *  a timer, and regular messages from a client.
 *
 *  Illustrates using the timer functions with a pulse.
*/

#include <stdio.h>
#include <stdlib.h>
#include <time.h>
#include <signal.h>
#include <errno.h>
#include <unistd.h>
#include <sys/siginfo.h>
#include <sys/neutrino.h>

// message send definitions

// messages
#define MT_WAIT_DATA        2       // message from client
#define MT_SEND_DATA        3       // message from client

// pulses
#define CODE_TIMER          1       // pulse from timer

// message reply definitions
#define MT_OK               0       // message to client
#define MT_TIMEDOUT         1       // message to client

// message structure
typedef struct
{
    // contains both message to and from client
    int messageType;
    // optional data, depending upon message
    int messageData;
} ClientMessageT;

typedef union
{
    // a message can be either from a client, or a pulse
    ClientMessageT  msg;
    struct _pulse   pulse;
} MessageT;

// client table
#define MAX_CLIENT 16       // max # of simultaneous clients

struct
{
    int in_use;             // is this client entry in use?
    int rcvid;              // receive ID of client
    int timeout;            // timeout left for client
}   clients [MAX_CLIENT];   // client table

int     chid;               // channel ID (global)
int     debug = 1;          // set debug value, 1=on, 0=off
char    *progname = "time1.c";

// forward prototypes
static  void setupPulseAndTimer (void);
static  void gotAPulse (void);
static  void gotAMessage (int rcvid, ClientMessageT *msg);
```

main() This next section of code is the mainline. It's responsible for:

- creating the channel (via *ChannelCreate()*),
- calling the *setupPulseAndTimer()* routine (to set up a once-per-second timer, with a pulse as the event delivery method), and then
- sitting in a "do-forever" loop waiting for pulses or messages and processing them.

Notice the check against the return value from *MsgReceive()* — a zero indicates it's a pulse (and we don't do any strong checking to ensure that it's *our* pulse), a non-zero indicates it's a message. The processing of the pulse or message is done by *gotAPulse()* and *gotAMessage()*.

```
int
main (void)                     // ignore command-line arguments
{
    int rcvid;                  // process ID of the sender
    MessageT msg;               // the message itself

    if ((chid = ChannelCreate (0)) == -1) {
        fprintf (stderr, "%s:  couldn't create channel!\n",
                 progname);
        perror (NULL);
        exit (EXIT_FAILURE);
    }

    // set up the pulse and timer
    setupPulseAndTimer ();

    // receive messages
    for (;;) {
        rcvid = MsgReceive (chid, &msg, sizeof (msg), NULL);

        // determine who the message came from
        if (rcvid == 0) {
            // production code should check "code" field...
            gotAPulse ();
        } else {
            gotAMessage (rcvid, &msg.msg);
        }
    }

    // you'll never get here
    return (EXIT_SUCCESS);
}
```

setupPulseAndTimer()

In *setupPulseAndTimer()* you see the code where we define the type of timer and notification scheme. When we talked about the timer function calls in the text above, I said that the timer could deliver a signal, a pulse, or cause a thread to be created. That decision is made here (in *setupPulseAndTimer()*). Notice that we used the macro *SIGEV_PULSE_INIT()*. By using this macro, we're effectively assigning the value SIGEV_PULSE to the *sigev_notify* member. (Had we used one of the *SIGEV_SIGNAL*_INIT()* macros instead, it would have delivered the specified signal.) Notice that, for the pulse, we set the connection back to ourselves via the *ConnectAttach()* call, and give it a code that uniquely identifies it (we chose the manifest constant CODE_TIMER; something that *we* defined). The final parameter in the initialization of the event structure is the priority of the pulse; we chose SIGEV_PULSE_PRIO_INHERIT (the constant -1). This tells the kernel not to change the priority of the receiving thread when the pulse arrives.

Near the bottom of this function, we call *timer_create()* to create a timer object within the kernel, and then we fill it in with data saying that it should go off in one second (the *it_value* member) and that it should reload with one-second repeats (the *it_interval* member). Note that the timer is activated only when we call *timer_settime()*, *not* when we create it.

☞ The SIGEV_PULSE notification scheme is a Neutrino extension — POSIX has no concept of pulses.

```
/*
 *  setupPulseAndTimer
 *
 *  This routine is responsible for setting up a pulse so it
 *  sends a message with code MT_TIMER.  It then sets up a
 *  periodic timer that fires once per second.
*/

void
setupPulseAndTimer (void)
{
    timer_t             timerid;    // timer ID for timer
    struct sigevent     event;      // event to deliver
    struct itimerspec   timer;      // the timer data struct
    int                 coid;       // connection back to us

    // create a connection back to ourselves
    coid = ConnectAttach (0, 0, chid, 0, 0);
    if (coid == -1) {
        fprintf (stderr, "%s:  couldn't ConnectAttach!\n",
                 progname);
        perror (NULL);
        exit (EXIT_FAILURE);
    }

    // set up the kind of event that we want -- a pulse
    SIGEV_PULSE_INIT (&event, coid,
                      SIGEV_PULSE_PRIO_INHERIT, CODE_TIMER, 0);

    // create the timer, binding it to the event
    if (timer_create (CLOCK_REALTIME, &event, &timerid) == -1) {
        fprintf (stderr, "%s:  can't timer_create, errno %d\n",
                 progname, errno);
        perror (NULL);
        exit (EXIT_FAILURE);
    }

    // setup the timer (1s delay, 1s reload)
    timer.it_value.tv_sec = 1;
    timer.it_value.tv_nsec = 0;
    timer.it_interval.tv_sec = 1;
    timer.it_interval.tv_nsec = 0;

    // and start it!
    timer_settime (timerid, 0, &timer, NULL);
}
```

gotAPulse()

In *gotAPulse()*, you can see how we've implemented the server's ability to timeout a client. We walk down the list of clients, and since we know that the pulse is being triggered once per second, we simply decrement the number of seconds that the client has left before a timeout. If this value reaches zero, we reply back to that client with a message saying, "Sorry, timed out" (the MT_TIMEDOUT message type). You'll notice that we prepare this message ahead of time (outside the `for` loop), and then send it as needed. This is just a style/usage issue — if you expect to be doing a lot of replies, then it might make sense to incur the setup overhead once. If you don't expect to do a lot of replies, then it might make more sense to set it up as needed.

If the timeout value hasn't yet reached zero, we don't do anything about it — the client is still blocked, waiting for a message to show up.

```
/*
 *  gotAPulse
 *
 *  This routine is responsible for handling the fact that a
 *  timeout has occurred.  It runs through the list of clients
 *  to see which client has timed-out, and replies to it with
 *  a timed-out response.
 */

void
gotAPulse (void)
{
    ClientMessageT  msg;
    int             i;

    if (debug) {
        time_t  now;

        time (&now);
        printf ("Got a Pulse at %s", ctime (&now));
    }

    // prepare a response message
    msg.messageType = MT_TIMEDOUT;

    // walk down list of clients
    for (i = 0; i < MAX_CLIENT; i++) {

        // is this entry in use?
        if (clients [i].in_use) {

            // is it about to time out?
            if (--clients [i].timeout == 0) {

                // send a reply
                MsgReply (clients [i].rcvid, EOK, &msg,
                          sizeof (msg));

                // entry no longer used
                clients [i].in_use = 0;
            }
        }
    }
}
```

gotAMessage()

In *gotAMessage()*, you see the other half of the functionality, where we add a client to the list of clients waiting for data (if it's a MT_WAIT_DATA message), or we match up a client with the message that just arrived (if it's a MT_SEND_DATA message). Note that for simplicity we didn't add a queue of clients that are waiting to send data, but for which no receiver is yet available — that's a queue management issue left as an exercise for the reader!

```
/*
 *  gotAMessage
 *
 *  This routine is called whenever a message arrives.  We
 *  look at the type of message (either a "wait for data"
 *  message, or a "here's some data" message), and act
 *  accordingly.  For simplicity, we'll assume that there is
 *  never any data waiting.  See the text for more discussion
 *  about this.
*/

void
gotAMessage (int rcvid, ClientMessageT *msg)
{
    int i;

    // determine the kind of message that it is
    switch (msg -> messageType) {

    // client wants to wait for data
    case    MT_WAIT_DATA:

        // see if we can find a blank spot in the client table
        for (i = 0; i < MAX_CLIENT; i++) {

            if (!clients [i].in_use) {

                // found, mark in use, save rcvid, set timeout
                clients [i].in_use = 1;
                clients [i].rcvid = rcvid;
                clients [i].timeout = 5;
                return;
            }
        }

        fprintf (stderr, "Table full, message %d ignored, "
                         "client blocked\n", rcvid);
        break;

    // client with data
    case    MT_SEND_DATA:

        // see if we can find another client to reply to with
        // this client's data
        for (i = 0; i < MAX_CLIENT; i++) {

            if (clients [i].in_use) {

                // found one -- reuse the incoming message
                // as an outgoing message
```

```
                    msg -> messageType = MT_OK;

                    // reply to BOTH CLIENTS!
                    MsgReply (clients [i].rcvid, EOK, msg,
                              sizeof (*msg));
                    MsgReply (rcvid, EOK, msg, sizeof (*msg));

                    clients [i].in_use = 0;
                    return;
                }
            }

            fprintf (stderr, "Table empty, message %d ignored, "
                             "client blocked\n", rcvid);
            break;
        }
    }
```

Notes Some general notes about the code:

- If there's no one waiting and a data message arrives, or there's no room in the list for a new waiter client, we print a message to standard error, but never reply to the client. This means that some clients could be sitting there, REPLY-blocked forever — we've lost their receive ID, so we have no way to reply to them later.

  This is intentional in the design. You could modify this to add MT_NO_WAITERS and MT_NO_SPACE messages, respectively, which can be returned whenever these errors were detected.

- When a waiter client is waiting, and a data-supplying client sends to it, we reply to *both* clients. This is crucial, because we want *both* clients to unblock.

- We reused the data-supplying client's buffer for both replies. This again is a style issue — in a larger application you'd probably have to have multiple types of return values, in which case you may not want to reuse the same buffer.

- The implementation shown here uses a "cheesy" fixed-length array with an "in use" flag (**`clients[i].in_use`**). Since my goal here isn't to demonstrate owner-list tricks and techniques for singly linked list management, I've shown the version that's the easiest to understand. Of course, in your production code, you'd probably use a linked list of dynamically managed storage blocks.

- When the message arrives in the *MsgReceive()*, our decision as to whether it was in fact "our" pulse is done on weak checking — we assume (as per the comments) that *all* pulses are the CODE_TIMER pulse. Again, in your production code you'd want to check the pulse's code value and report on any anomalies.

Note that the example above shows just *one* way of implementing timeouts for clients. Later in this chapter (in "Kernel timeouts"), we'll talk about kernel timeouts, which are another way of implementing almost the exact same thing, except that it's driven by the client, rather than a timer.

Periodic server maintenance cycles

Here we have a slightly different use for the periodic timeout messages. The messages are purely for the internal use of the server and generally have nothing to do with the client at all.

For example, some hardware might require that the server poll it periodically, as might be the case with a network connection — the server should see if the connection is still "up," regardless of any instructions from clients.

Another case could occur if the hardware has some kind of "inactivity shutdown" timer. For example, since keeping a piece of hardware powered up for long periods of time may waste power, if no one has used that hardware for, say, 10 seconds, the hardware could be powered down. Again, this has nothing to do with the client (except that a client request will cancel this inactivity powerdown) — it's just something that the server has to be able to provide for its hardware.

Code-wise, this would be very similar to the example above, except that instead of having a list of clients that are waiting, you'd have only one timeout variable. Whenever a timer event arrives, this variable would be decremented; if zero, it would cause the hardware to shut down (or whatever other activity you wish to perform at that point). If it's still greater than zero, nothing would happen.

The only "twist" in the design would be that whenever a message comes in from a client that uses the hardware, you'd have to reset that timeout variable back to its full value — having someone use that resource resets the "countdown." Conversely, the hardware may take a certain "warm-up" time in order to recover from being powered down. In this case, once the hardware has been powered down, you would have to set a different timer once a request arrived from a client. The purpose of this timer would be to delay the client's request from going to the hardware until the hardware has been powered up again.

Timers delivering signals

So far, we've seen just about all there is to see with timers, except for one small thing. We've been delivering messages (via a pulse), but you can also deliver POSIX signals. Let's see how this is done:

```
timer_create (CLOCK_REALTIME, NULL, &timerid);
```

This is the simplest way to create a timer that sends you a signal. This method raises SIGALRM when the timer fires. If we had actually supplied a **struct sigevent**, we could specify which signal we actually want to get:

```
struct sigevent event;

SIGEV_SIGNAL_INIT (&event, SIGUSR1);
timer_create (CLOCK_REALTIME, &event, &timerid);
```

This hits us with SIGUSR1 instead of SIGALRM.

You catch timer signals with normal signal handlers, there's nothing special about them.

Timers creating threads

If you'd like to create a new thread every time a timer fires, then you can do so with the **struct sigevent** and all the other timer stuff we just discussed:

```
struct sigevent event;

SIGEV_THREAD_INIT (&event, maintenance_func, NULL);
```

You'll want to be particularly careful with this one, because if you specify too short an interval, you'll be flooded with new threads! This could eat up all your CPU and memory resources!

Getting and setting the realtime clock and more

Apart from using timers, you can also get and set the current realtime clock, and adjust it gradually. The following functions can be used for these purposes:

Function	**Type?**	**Description**
ClockAdjust()	Neutrino	Gradually adjust the time
ClockCycles()	Neutrino	High-resolution snapshot
clock_getres()	POSIX	Fetch base timing resolution
clock_gettime()	POSIX	Get current time of day
ClockPeriod()	Neutrino	Get/set base timing resolution
clock_settime()	POSIX	Set current time of day
ClockTime()	Neutrino	Get/set current time of day

Getting and setting

The functions *clock_gettime()* and *clock_settime()* are the POSIX functions based on the kernel function *ClockTime()*. These functions can be used to get or set the current time of day. Unfortunately, setting this is a "hard" adjustment, meaning that whatever time you specify in the buffer is immediately taken as the *current* time. This can have startling consequences, especially when time appears to move "backwards" because the time was ahead of the "real" time. Generally, setting a clock using this method should be done only during power up or when the time is very much out of synchronization with the real time.

That said, to effect a gradual change in the current time, the function *ClockAdjust()* can be used:

```
int
ClockAdjust (clockid_t id,
             const struct _clockadjust *new,
             const struct _clockadjust *old);
```

The parameters are the clock source (always use CLOCK_REALTIME), and a *new* and *old* parameter. Both the *new* and *old* parameters are optional, and can be NULL. The *old* parameter simply returns the current adjustment. The operation of the clock adjustment is controlled through the *new* parameter, which is a pointer to a structure that contains two elements, *tick_nsec_inc* and *tick_count*. Basically, the operation of *ClockAdjust()* is very simple. Over the next *tick_count* clock ticks, the adjustment contained in *tick_nsec_inc* is added to the current system clock. This means that to move the time forward (to "catch up" with the real time), you'd specify a positive value for *tick_nsec_inc*. Note that you'd never move the time backwards! Instead, if your clock was too fast, you'd specify a small negative number to *tick_nsec_inc*, which would cause the current time to not advance as fast as it would. So effectively, you've slowed down the clock until it matches reality. A rule of thumb is that you shouldn't adjust the clock by more than 10% of the base timing resolution of your system (as indicated by the functions we'll talk about next, *ClockPeriod()* and friends).

Adjusting the timebase

As we've been saying throughout this chapter, the timing resolution of everything in the system is going to be *no more accurate than* the base timing resolution coming into the system. So the obvious question is, how do you set the base timing resolution? You can use the following function for this:

```
int
ClockPeriod (clockid_t id,
             const struct _clockperiod *new,
             struct _clockperiod *old,
             int reserved);
```

As with the *ClockAdjust()* function described above, the *new* and the *old* parameters are how you get and/or set the values of the base timing resolution. The *new* and *old* parameters are pointers to structures of **`struct _clockperiod`**, which contains two members, *nsec* and *fract*. Currently, the *fract* member must be set to zero (it's the number of femtoseconds; we probably won't use this kind of resolution for a little while yet!) The *nsec* member indicates how many nanoseconds elapse between ticks of the base timing clock. The default is 10 milliseconds (1 millisecond on machines with CPU speeds of greater than 40 MHz), so the *nsec* member (if you use the "get" form of the call by specifying the *old* parameter) will show approximately 10 million nanoseconds. (As we discussed above, in "Clock interrupt sources," it's not going to be *exactly* 10 millisecond.)

While you can certainly feel free to try to set the base timing resolution on your system to something ridiculously small, the kernel will step in and prevent you from doing that. Generally, you can set most systems in the 1 millisecond to hundreds of microseconds range.

An accurate timestamp

There is one timebase that might be available on your processor that doesn't obey the rules of "base timing resolution" we just described. Some processors have a high-frequency (high-accuracy) counter built right into them, which Neutrino can let you have access to via the *ClockCycles()* call. For example, on a Pentium processor running at 200 MHz, this counter increments at 200 MHz as well, so it can give you timing samples right down to 5 nanoseconds. This is particularly useful if you want to figure out exactly how long a piece of code takes to execute (assuming of course, that you don't get preempted). You'd call *ClockCycles()* before your code and after your code, and then compute the delta. See the C Library reference for more details.

☞ Note that on an SMP system, you may run into a little problem. If your thread gets a *ClockCycles()* value from one CPU and then eventually runs on another CPU, you may get inconsistent results. This stems from the fact that the counters used by *ClockCycles()* are stored in the CPU chips themselves, and are not synchronized between CPUs. The solution to this is to use thread affinity to force the thread to run on a particular CPU.

Advanced topics

Now that we've seen the basics of timers, we'll look at a few advanced topics:

1 the CLOCK_SOFTTIME and CLOCK_MONOTONIC timer types, and

2 kernel timeouts.

Other clock sources

We've seen the clock source CLOCK_REALTIME, and mentioned that a POSIX conforming implementation may supply as many different clock sources as it feels like, provided that it at least provides CLOCK_REALTIME.

What is a clock source? Simply put, it's an abstract source of timing information. If you want to put it into real life concepts, your personal watch is a clock source; it measures how fast time goes by. Your watch will have a different level of accuracy than someone else's watch. You may forget to wind your watch, or get it new batteries, and time may seem to "freeze" for a while. Or, you may adjust your watch, and all of a sudden time seems to "jump." These are all characteristics of a clock source.

Under Neutrino, CLOCK_REALTIME is based off of the "current time of day" clock that Neutrino provides. (In the examples below, we refer to this as "Neutrino Time.") This means that if the system is running, and suddenly someone adjusts the time forward by 5 seconds, the change may or may not adversely affect your programs (depending on what you're doing). Let's look at a `sleep (30);` call:

Real Time	**Neutrino Time**	**Activity**
11:22:05	11:22:00	`sleep (30);`
11:22:15	11:22:15	clock gets adjusted to 11:22:15; it was 5 seconds too slow!
11:22:35	11:22:35	`sleep (30);` wakes up

Beautiful! The thread did exactly what you expected: at 11:22:00 it went to sleep for thirty seconds, and at 11:22:35 (thirty elapsed seconds later) it woke up. Notice how the *sleep()* "appeared" to sleep for 35 seconds, instead of 30; in real, elapsed time, though, only 30 seconds went by because Neutrino's clock got adjusted ahead by five seconds (at 11:22:15).

The kernel knows that the *sleep()* call is a relative timer, so it takes care to ensure that the specified amount of "real time" elapses.

Now, what if, on the other hand, we had used an absolute timer, and at 11:22:00 in "Neutrino time" told the kernel to wake us up at 11:22:30?

Real Time	**Neutrino Time**	**Activity**
11:22:05	11:22:00	wake up at 11:22:30
11:22:15	11:22:15	clock gets adjusted as before
11:22:30	11:22:30	wakes up

This too is just like what you'd expect — you wanted to be woken up at 11:22:30, and (in spite of adjusting the time) you were.

However, there's a small twist here. If you take a look at the *pthread_mutex_timedlock()* function, for example, you'll notice that it takes an *absolute* timeout value, as opposed to a relative one:

```
int
pthread_mutex_timedlock (pthread_mutex_t *mutex,
                         const struct timespec *abs_timeout);
```

As you can imagine, there could be a problem if we try to implement a mutex that times out in 30 seconds. Let's go through the steps. At 11:22:00 (Neutrino time) we decide that we're going to try and lock a mutex, but we only want to block for a maximum of 30 seconds. Since the *pthread_mutex_timedlock()* function takes an absolute time, we perform a calculation: we add 30 seconds to the current time, giving us 11:22:30. If we follow the example above, we would wake up at 11:22:30, which means that we would have only locked the mutex for 25 seconds, instead of the full 30.

CLOCK_MONOTONIC

The POSIX people thought about this, and the solution they came up with was to make the *pthread_mutex_timedlock()* function be based on CLOCK_MONOTONIC instead of CLOCK_REALTIME. This is built in to the *pthread_mutex_timedlock()* function and isn't something that you can change.

They way CLOCK_MONOTONIC works is that its timebase is *never* adjusted. The impact of that is that regardless of what time it is in the real world, if you base a timer in CLOCK_MONOTONIC and add 30 seconds to it (and then do whatever adjustments you want to the time), the timer will expire in 30 elapsed seconds.

The clock source CLOCK_MONOTONIC has the following characteristics:

- always increasing count
- based on *real* time
- starts at zero

☞ The important thing about the clock starting at zero is that this is a different "epoch" (or "base") than CLOCK_REALTIME's epoch of Jan 1 1970, 00:00:00 GMT. So, even though both clocks run at the same rate, their values are *not* interchangeable.

So what does CLOCK_SOFTTIME do?

If we wanted to sort our clock sources by "hardness" we'd have the following ordering. You can think of CLOCK_MONOTONIC as being a freight train — it doesn't stop for anyone. Next on the list is CLOCK_REALTIME, it can be pushed around a bit (as we saw with the time adjustment). Finally, we have CLOCK_SOFTTIME, which we can push around a *lot*.

The main use of CLOCK_SOFTTIME is for things that are "soft" — things that aren't going to cause a critical failure if they don't get done. CLOCK_SOFTTIME is "active" only when the CPU is running. (Yes, this does sound obvious `:-)` but wait!) When the CPU is powered down due to Power Management detecting that nothing is going to happen for a little while, CLOCK_SOFTTIME gets powered down as well!

Here's a timing chart showing the three clock sources:

Real Time	Neutrino Time	Activity
11:22:05	11:22:00	wake up at "now" + 00:00:30 (see below)
11:22:15	11:22:15	clock gets adjusted as before
11:22:20	11:22:20	power management turns off CPU
11:22:30	11:22:30	CLOCK_REALTIME wakes up
11:22:35	11:22:35	CLOCK_MONOTONIC wakes up

continued...

Real Time	Neutrino Time	Activity
11:45:07	11:45:07	power management turns on CPU, and CLOCK_SOFTTIME wakes up

There are a few things to note here:

- we precomputed our wakeup time as "now" plus 30 seconds and used an absolute timer to wake us up at the computed time. This is *different* than waking up *in* 30 seconds using a relative timer.
- Note that for convenience of putting the example on one time-line, we've lied a little bit. If the CLOCK_REALTIME thread did indeed wake up, (and later the same for CLOCK_MONOTONIC) it would have caused us to exit out of power management mode at that time, which would then cause CLOCK_SOFTTIME to wake up.

When CLOCK_SOFTTIME "over-sleeps," it wakes up as soon as it's able — it doesn't stop "timing" while the CPU is powered down, it's just not in a position to wake up until *after* the CPU powers up. Other than that, CLOCK_SOFTTIME is just like CLOCK_REALTIME.

Using different clock sources

To specify one of the different clock source, use a POSIX timing function that accepts a clock ID. For example:

```
#include <time.h>

int
clock_nanosleep (clockid_t clock_id,
                 int flags,
                 const struct timespec *rqtp,
                 struct timespec *rmtp);
```

The *clock_nanosleep()* function accepts the *clock_id* parameter (telling it which clock source to use), a *flag* (which determines if the time is relative or absolute), a "requested sleep time" parameter (*rqtp*), as well as a pointer to an area where the function can fill in the amount of time remaining (in the *rmtp* parameter, which can be NULL if you don't care).

Kernel timeouts

Neutrino lets you have a timeout associated with all kernel blocking states. We talked about the blocking states in the Processes and Threads chapter, in the section "Kernel states." Most often, you'll want to use this with message passing; a client will send a message to a server, but the client won't want to wait "forever" for the server to respond. In that case, a kernel timeout is suitable. Kernel timeouts are also useful with the *pthread_join()* function. You might want to wait for a thread to finish, but you might not want to wait too long.

Here's the definition for the *TimerTimeout()* function call, which is the kernel function responsible for kernel timeouts:

```
#include <sys/neutrino.h>

int
TimerTimeout (clockid_t id,
              int flags,
              const struct sigevent *notify,
              const uint64_t *ntime,
              uint64_t *otime);
```

This says that *TimerTimeout()* returns an integer (a pass/fail indication, with -1 meaning the call failed and set *errno*, and zero indicating success). The time source (CLOCK_REALTIME, etc.) is passed in *id*, and the *flags* parameter gives the relevant kernel state or states. The *notify* should always be a notification event of type SIGEV_UNBLOCK, and the *ntime* is the relative time when the kernel call should timeout. The *otime* parameter indicates the previous value of the timeout — it's not used in the vast majority of cases (you can pass NULL).

☞ It's important to note that the timeout is *armed* by *TimerTimeout()*, and *triggered* on entry into one of the kernel states specified by *flags*. It is *cleared* upon return from any kernel call. This means that you must re-arm the timeout before *each and every* kernel call that you want to be timeout-aware. You don't have to clear the timeout *after* the kernel call; this is done automagically.

Kernel timeouts with *pthread_join()*

The simplest case to consider is a kernel timeout used with the *pthread_join()* call. Here's how you'd set it up:

```
/*
 * part of tt1.c
*/

#include <sys/neutrino.h>

// 1 billion nanoseconds in a second
#define SEC_NSEC 1000000000LL

int
main (void) // ignore arguments
{
    uint64_t        timeout;
    struct sigevent event;
    int             rval;

    ...
    // set up the event -- this can be done once

    // This or event.sigev_notify = SIGEV_UNBLOCK:
    SIGEV_UNBLOCK_INIT (&event);

    // set up for 10 second timeout
    timeout = 10LL * SEC_NSEC;

    TimerTimeout (CLOCK_REALTIME, _NTO_TIMEOUT_JOIN,
                  &event, &timeout, NULL);

    rval = pthread_join (thread_id, NULL);
    if (rval == ETIMEDOUT) {
        printf ("Thread %d still running after 10 seconds!\n",
                thread_id);
    }
    ...
```

We used the *SIGEV_UNBLOCK_INIT()* macro to initialize the event structure, but we could have set the *sigev_notify* member to SIGEV_UNBLOCK ourselves. Even more elegantly, we could pass NULL as the **`struct sigevent`** — *TimerTimeout()* understands this to mean that it should use a SIGEV_UNBLOCK.

If the thread (specified in *thread_id*) is still running after 10 seconds, then the kernel call will be timed out — *pthread_join()* will return with an *errno* of ETIMEDOUT.

You can use another shortcut — by specifying a NULL for the timeout value (*ntime* in the formal declaration above), this tells the kernel not to block in the given state. This can be used for polling. (While polling is generally discouraged, you could use it quite effectively in the case of the *pthread_join()* — you'd periodically poll to see if the thread you're interested in was finished yet. If not, you could perform other work.)

Here's a code sample showing a non-blocking *pthread_join()*:

```
int
pthread_join_nb (int tid, void **rval)
{
    TimerTimeout (CLOCK_REALTIME, _NTO_TIMEOUT_JOIN,
                  NULL, NULL, NULL);
    return (pthread_join (tid, rval));
}
```

Kernel timeouts with message passing

Things get a little trickier when you're using kernel timeouts with message passing. Recall from the Message Passing chapter (in the "Message passing and client/server" part) that the server may or may not be waiting for a message when the client sends it. This means that the client could be blocked in either the SEND-blocked state (if the server hasn't received the message yet), or the REPLY-blocked state (if the server has received the message, and hasn't yet replied). The implication here is that you should specify *both* blocking states for the *flags* argument to *TimerTimeout()*, because the client might get blocked in either state.

To specify multiple states, you simply OR them together:

```
TimerTimeout (... _NTO_TIMEOUT_SEND | _NTO_TIMEOUT_REPLY, ...);
```

This causes the timeout to be active whenever the kernel enters either the SEND-blocked state or the REPLY-blocked state. There's nothing special about entering the SEND-blocked state and timing out — the server hasn't received the message yet, so the server isn't actively doing anything on behalf of the client. This means that if the kernel times out a SEND-blocked client, the server doesn't have to be informed. The client's *MsgSend()* function returns an ETIMEDOUT indication, and processing has completed for the timeout.

However, as was mentioned in the Message Passing chapter (under "_NTO_CHF_UNBLOCK"), if the server has already received the client's message, and the client wishes to unblock, there are two choices for the server. If the server has *not* specified _NTO_CHF_UNBLOCK on the channel it received the message on, then the client will be unblocked immediately, and the server won't receive any indication that an unblock has occurred. Most of the servers I've seen *always* have the _NTO_CHF_UNBLOCK flag enabled. In that case, the kernel delivers a pulse to the server, *but the client remains blocked until the server replies!* As mentioned in the above-referenced section of the Message Passing chapter, this is done so that the server has an indication that it should *do* something about the client's unblock request.

Summary

We've looked at Neutrino's time-based functions, including timers and how they can be used, as well as kernel timeouts. Relative timers provide some form of event "in a certain number of seconds," while absolute timers provide this event "at a certain time." Timers (and, generally speaking, the `struct sigevent`) can cause the delivery of a pulse, a signal, or a thread to start.

The kernel implements timers by storing the absolute time that represents the next "event" on a sorted queue, and comparing the current time (as derived by the timer tick interrupt service routine) against the head of the sorted queue. When the current time is greater than or equal to the first member of the queue, the queue is processed (for all matching entries) and the kernel dispatches events or threads (depending on the type of queue entry) and (possibly) reschedules.

To provide support for power-saving features, you should disable periodic timers when they're not needed — otherwise, the power-saving feature won't implement power saving, because it believes that there's something to "do" periodically. You could also use the CLOCK_SOFTTIME clock source, unless of course you actually *wanted* the timer to defeat the power saving feature.

Given the different types of clock sources, you have flexibility in determining the basis of your clocks and timer; from "real, elapsed" time through to time sources that are based on power management activities.

Chapter 4

Interrupts

In this chapter...

Neutrino and interrupts

Writing interrupt handlers

Summary

Neutrino and interrupts

In this section, we'll take a look at interrupts, how we deal with them under Neutrino, their impact on scheduling and realtime, and some interrupt-management strategies.

The first thing we need to ask is, "What's an interrupt?"

An interrupt is exactly what it sounds like — an interruption of whatever was going on and a diversion to another task.

For example, suppose you're sitting at your desk working on job "A." Suddenly, the phone rings. A Very Important Customer (VIC) needs you to immediately answer some skill-testing question. When you've answered the question, you may go back to working on job "A," or the VIC may have changed your priorities so that you push job "A" off to the side and immediately start on job "B."

Now let's put that into perspective under Neutrino.

At any moment in time, the processor is busy processing the work for the highest-priority READY thread (this will be a thread that's in the RUNNING state). To cause an interrupt, a piece of hardware on the computer's bus asserts an interrupt line (in our analogy, this was the phone ringing).

As soon as the interrupt line is asserted, the kernel jumps to a piece of code that sets up the environment to run an *interrupt service routine* (ISR), a piece of software that determines what should happen when that interrupt is detected.

The amount of time that elapses between the time that the interrupt line is asserted by the hardware and the first instruction of the ISR being executed is called the *interrupt latency*. Interrupt latency is measured in microseconds. Different processors have different interrupt latency times; it's a function of the processor speed, cache architecture, memory speed, and, of course, the efficiency of the operating system.

In our analogy, if you're listening to some music in your headphones and ignoring the ringing phone, it will take you longer to notice this phone "interrupt." Under Neutrino, the same thing can happen; there's a processor instruction that disables interrupts (`cli` on the x86, for example). The processor won't notice any interrupts until it reenables interrupts (on the x86, this is the `sti` opcode).

☞ To avoid CPU-specific assembly language calls, Neutrino provides four calls: *InterruptEnable()* and *InterruptDisable()*, and *InterruptLock()* and *InterruptUnlock()*. These take care of all the low-level details on all supported platforms.

The ISR usually performs the minimum amount of work possible, and then ends (in our analogy, this was the conversation on the telephone with the VIC — we usually don't put the customer on hold and do several hours of work; we just tell the customer, "Okay, I'll get right on that!"). When the ISR ends, it can tell the kernel either that nothing should happen (meaning the ISR has completely handled the event and nothing else needs to be done about it) or that the kernel should perform some action that might cause a thread to become READY.

In our analogy, telling the kernel that the interrupt was handled would be like telling the customer the answer — we can return back to whatever we were doing, knowing that the customer has had their question answered.

Telling the kernel that some action needs to be performed is like telling the customer that you'll get back to them — the telephone has been hung up, but it could ring again.

Interrupt service routine

The ISR is a piece of code that's responsible for clearing the source of the interrupt.

This is a key point, especially in conjunction with this fact: the interrupt runs at a priority *higher than any software priority*. This means that the amount of time spent in the ISR can have a serious impact on thread scheduling. You should spend as little time as possible in the ISR. Let's examine this in a little more depth.

Clearing the interrupt source

The hardware device that generated the interrupt will keep the interrupt line asserted until it's sure the software handled the interrupt. Since the hardware can't read minds, the software must tell it when it has responded to the cause of the interrupt. Generally, this is done by reading a status register from a specific hardware port or a block of data from a specific memory location.

In any event, there's usually some form of positive acknowledgement between the hardware and the software to "de-assert" the interrupt line. (Sometimes there isn't an acknowledgement; for example, a piece of hardware may generate an interrupt and assume that the software will handle it.)

Because the interrupt runs at a higher priority than any software thread, we should spend as little time as possible in the ISR itself to minimize the impact on scheduling. If we clear the source of the interrupt simply by reading a register, and perhaps stuffing that value into a global variable, then our job is simple.

This is the kind of processing done by the ISR for the serial port. The serial port hardware generates an interrupt when a character has arrived. The ISR handler reads a status register containing the character, and stuffs that character into a circular buffer. Done. Total processing time: a few microseconds. And, it *must* be fast. Consider what would happen if you were receiving characters at 115k baud (a character about every 100 μs); if you spent anywhere near 100 μs *handling* the interrupt, you wouldn't have time to do anything else!

☞ Don't let me mislead you though — the serial port's interrupt service routine could take longer to complete. This is because there's a tail-end poll that looks to see if more characters are waiting in the device.

Clearly, minimizing the amount of time spent in the interrupt can be perceived as "Good customer service" in our analogy — by keeping the amount of time that we're on the phone to a minimum, we avoid giving other customers a busy signal.

What if the handler needs to do a significant amount of work? Here are a couple of possibilities:

- The amount of time required to clear the source of the interrupt is short, but the amount of work required to talk to the hardware is long (the customer asked us a short question that takes a long time to answer).
- The amount of time required to clear the source of the interrupt is long (the customer's description of the problem is long and involved).

In the first case, we'd like to clear the source of the interrupt as fast as possible and then tell the kernel to have a thread do the actual work of talking to the slow hardware. The advantage here is that the ISR spends just a tiny amount of time at the super-high priority, and then the rest of the work is done based on regular thread priorities. This is similar to your answering the phone (the super-high priority), and delegating the real work to one of your assistants. We'll look at how the ISR tells the kernel to schedule someone else later in this chapter.

In the second case, things get ugly. If an ISR doesn't clear the source of the interrupt when it exits, the kernel will immediately be re-interrupted by the Programmable Interrupt Controller (PIC — on the x86, this is the 8259 or equivalent) chip.

☞ For PIC fans: we'll talk about edge-sensitive and level-sensitive interrupts shortly.

We'll continuously be running the ISR, without ever getting a chance to run the thread-level code we need to properly handle the interrupt.

What kind of brain-damaged hardware requires a long time to clear the source of the interrupt? Your basic PC floppy disk controller keeps the interrupt asserted until you've read a number of status register values. Unfortunately, the data in the registers isn't available immediately, and you have to poll for this status data. This could take milliseconds (a long time in computer terms)!

The solution to this is to temporarily *mask interrupts* — literally tell the PIC to ignore interrupts from this particular source until you tell it otherwise. In this case, even though the interrupt line is asserted from the hardware, the PIC ignores it and doesn't tell the processor about it. This lets your ISR schedule a thread to handle this hardware outside the ISR. When your thread is finished transferring data from the hardware, it can tell the PIC to *unmask* that interrupt. This lets interrupts from that piece of hardware be recognized again. In our analogy, this is like transferring the VIC's call to your assistant.

Telling a thread to do something

How does an ISR tell the kernel that it should now schedule a thread to do some work? (And conversely, how does it tell the kernel that it *shouldn't* do that?)

Here's some pseudo-code for a typical ISR:

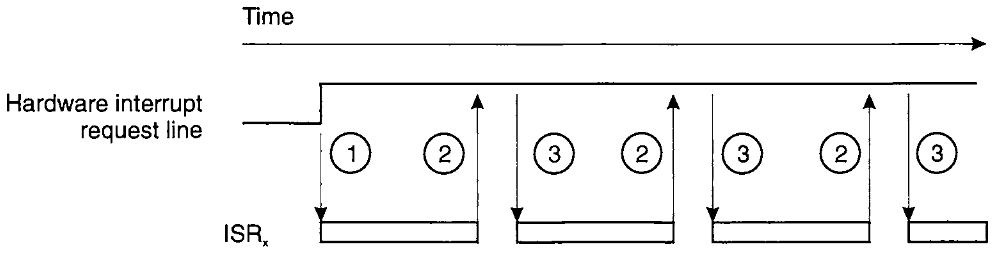
```
FUNCTION ISR BEGIN
    determine source of interrupt
    clear source of interrupt
    IF thread required to do some work THEN
        RETURN (event);
    ELSE
        RETURN (NULL);
    ENDIF
END
```

The trick is to return an event (of type `struct sigevent`, which we talked about in the Clocks, Timers, and Getting a Kick Every So Often chapter) instead of NULL. Note that the event that you return *must* be persistent after the stack frame of the ISR has been destroyed. This means that the event must be declared outside of the ISR, or be passed in from a persistent data area using the *area* parameter to the ISR, or declared as a `static` within the ISR itself. Your choice. If you return an event, the kernel delivers it to a thread when your ISR returns. Because the event "alerts" a thread (via a pulse, as we talked about in the Message Passing chapter, or via a signal), this can cause the kernel to reschedule the thread that gets the CPU next. If you return NULL from the ISR, then the kernel knows that nothing special needs to be done at thread time, so it won't reschedule any threads — the thread that was running at the time that the ISR preempted it resumes running.

Level-sensitivity versus edge-sensitivity

There's one more piece of the puzzle we've been missing. Most PICs can be programmed to operate in *level-sensitive* or *edge-sensitive* mode.

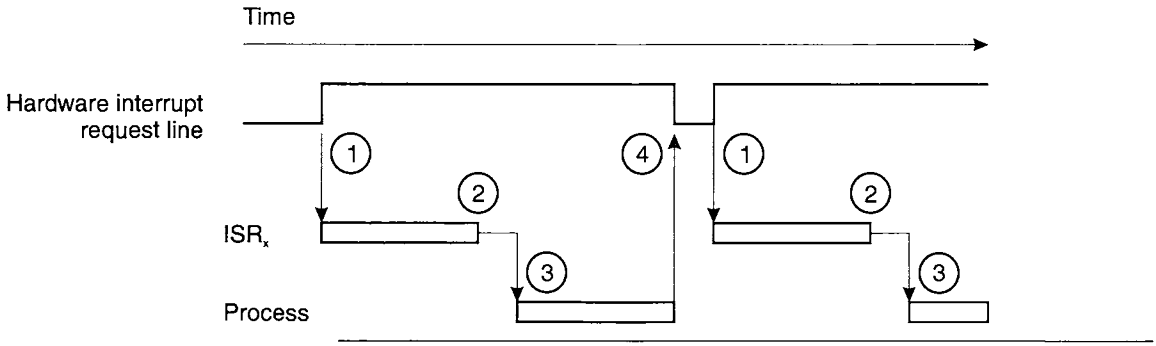
In level-sensitive mode, the interrupt line is deemed to be asserted by the PIC while it's in the "on" state. (This corresponds to label "1" in the diagram below.)



Level-sensitive interrupt assertion.

We can see that this would cause the problem described above with the floppy controller example. Whenever the ISR finishes, the kernel tells the PIC, "Okay, I've handled this interrupt. Tell me the next time that it gets activated" (step 2 in the diagram). In technical terms, the kernel sends an *End Of Interrupt* (EOI) to the PIC. The PIC looks at the interrupt line and if it's still active would immediately re-interrupt the kernel (step 3).

We could get around this by programming the PIC into edge-sensitive mode. In this mode, the interrupt is noticed by the PIC only *on an active-going edge.*



Edge-sensitive interrupt assertion.

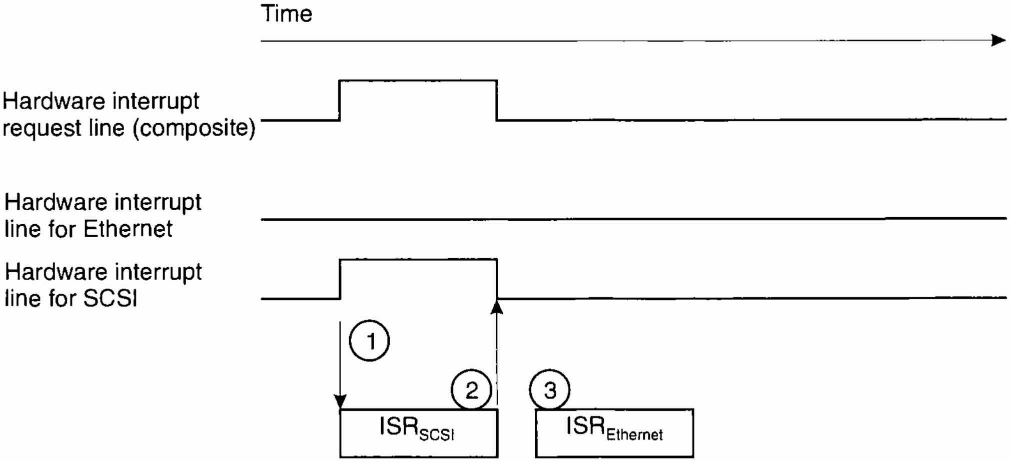
Even if the ISR fails to clear the source of the interrupt, when the kernel sends the EOI to the PIC (step 2 in the diagram), the PIC wouldn't re-interrupt the kernel, because there isn't another active-going edge transition after the EOI. In order to recognize another interrupt on that line, the line must first go inactive (step 4), and then active (step 1).

Well, it seems all our problems have been solved! Simply use edge-sensitive for all interrupts.

Unfortunately, edge-sensitive mode has a problem of its own.

Suppose your ISR fails to clear the cause of the interrupt. The hardware would still have the interrupt line asserted when the kernel issues the EOI to the PIC. However, because the PIC is operating in edge-sensitive mode, it never sees another interrupt from that device.

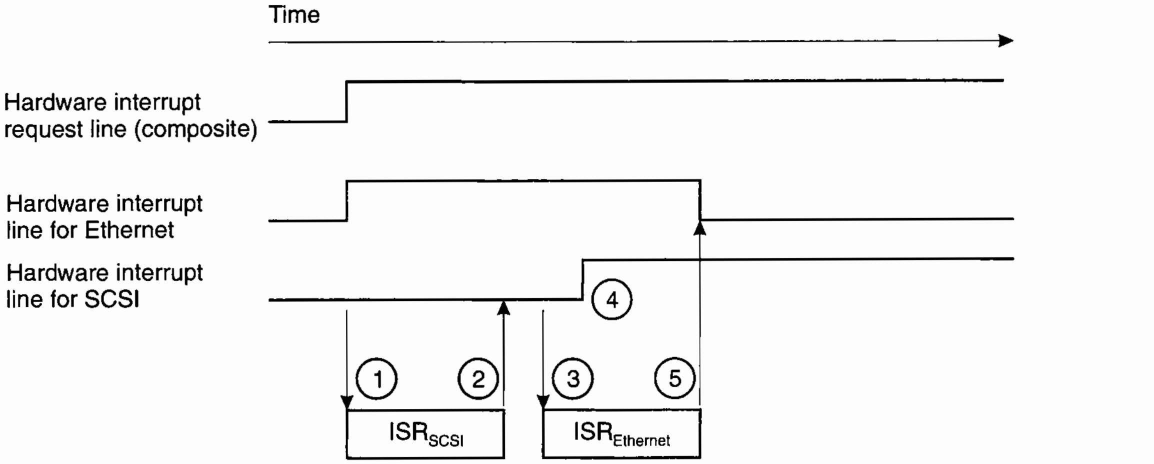
Now what kind of bozo would write an ISR that forgot to clear the source of the interrupt? Unfortunately it isn't that cut-and-dried. Consider a case where two devices (let's say a SCSI bus adapter and an Ethernet card) are sharing the same interrupt line, on a hardware bus architecture that allows that. (Now you're asking, "Who'd set up a machine like that?!?" Well, it happens, especially if the number of interrupt sources on the PIC is in short supply!) In this case, the two ISR routines would be attached to the same interrupt vector (this is legal, by the way), and the kernel would call them in turn whenever it got an interrupt from the PIC for that hardware interrupt level.


Time
Hardware interrupt request line (composite)
Hardware interrupt line for Ethernet
Hardware interrupt line for SCSI
1
2
3
ISR$_{SCSI}$
ISR$_{Ethernet}$

Sharing interrupts — one at a time.

In this case, because only one of the hardware devices was active when its associated ISR ran (the SCSI device), it correctly cleared the source of the interrupt (step 2). Note that the kernel runs the ISR for the Ethernet device (in step 3) regardless — it doesn't know whether the Ethernet hardware requires servicing or not as well, so it *always* runs the whole chain.

But consider this case:


Time
Hardware interrupt request line (composite)
Hardware interrupt line for Ethernet
Hardware interrupt line for SCSI
1
2
3
4
5
ISR$_{SCSI}$
ISR$_{Ethernet}$

Sharing interrupts — several at once.

Here's where the problem lies.

The Ethernet device interrupted first. This caused the interrupt line to be asserted (active-going edge was noted by the PIC), and the kernel called the first interrupt handler in the chain (the SCSI disk driver; step 1 in the diagram). The SCSI disk driver's ISR looked at its hardware and said, "Nope, wasn't me. Oh well, ignore it" (step 2). Then the kernel called the next ISR in the chain, the Ethernet ISR (step 3). The Ethernet ISR looked at the hardware and said, "Hey! That's my hardware that triggered the interrupt. I'm going to clear it." Unfortunately, while it was clearing it, the SCSI device generated an interrupt (step 4).

When the Ethernet ISR finished clearing the source of the interrupt (step 5), the interrupt line is *still asserted*, thanks to the SCSI hardware device. However, the PIC, being programmed in edge-sensitive mode, is looking for an inactive-to-active transition (on the composite line) before recognizing another interrupt. That isn't going to happen because the kernel has already called both interrupt service routines and is now waiting for another interrupt from the PIC.

In this case, a level-sensitive solution would be appropriate because when the Ethernet ISR finishes and the kernel issues the EOI to the PIC, the PIC would pick up the fact that an interrupt is still active on the bus and re-interrupt the kernel. The kernel would then run through the chain of ISRs, and this time the SCSI driver would get a chance to run and clear the source of the interrupt.

The selection of edge-sensitive versus level-sensitive is something that will depend on the hardware and the startup code. Some hardware will support only one or the other; hardware that supports either mode will be programmed by the startup code to one or the other. You'll have to consult the BSP (Board Support Package) documentation that came with your system to get a definitive answer.

Writing interrupt handlers

Let's see how to set up interrupt handlers — the calls, the characteristics, and some strategies.

Attaching an interrupt handler

To attach to an interrupt source, you'd use either *InterruptAttach()* or *InterruptAttachEvent()*.

```
#include <sys/neutrino.h>

int
InterruptAttachEvent (int intr,
                      const struct sigevent *event,
                      unsigned flags);

int
InterruptAttach (int intr,
                 const struct sigevent *
                     (*handler) (void *area, int id),
                 const void *area,
                 int size,
                 unsigned flags);
```

The *intr* argument specifies *which* interrupt you wish to attach the specified handler to. The values passed are defined by the startup code that initialized the PIC (amongst other things) just before Neutrino was started. (There's more information on the startup code in your Neutrino documentation; look in the *Utilities Reference* under **`startup-*`**; e.g., **`startup-p5064`**.)

At this point, the two functions *InterruptAttach()* and *InterruptAttachEvent()* differ. Let's look at *InterruptAttachEvent()* as it's simpler, first. Then we'll come back to *InterruptAttach()*.

Attaching with *InterruptAttachEvent()*

The *InterruptAttachEvent()* function takes two additional arguments: the argument *event*, which is a pointer to the **`struct sigevent`** that should be delivered, and a *flags* parameter. *InterruptAttachEvent()* tells the kernel that the *event* should be returned whenever the interrupt is detected, and that the interrupt level should be masked off. Note that it's the kernel that interprets the event and figures out which thread should be made READY.

Attaching with *InterruptAttach()*

With *InterruptAttach()*, we're specifying a different set of parameters. The *handler* parameter is the address of a function to call. As you can see from the prototype, *handler()* returns a **`struct sigevent`**, which indicates what kind of an event to return, and takes two parameters. The first passed parameter is the *area*, which is simply the *area* parameter that's passed to *InterruptAttach()* to begin with. The second parameter, *id*, is the identification of the interrupt, which is also the return value from *InterruptAttach()*. This is used to identify the interrupt and to mask, unmask, lock, or unlock the interrupt. The fourth parameter to *InterruptAttach()* is the *size*, which indicates how big (in bytes) the data area that you passed in *area* is. Finally, the *flags* parameter is the same as that passed for the *InterruptAttachEvent()*; we'll discuss that shortly.

Now that you've attached an interrupt

At this point, you've called either *InterruptAttachEvent()* or *InterruptAttach()*.

☞ Since attaching an interrupt isn't something you want everyone to be able to do, Neutrino allows only threads that have "I/O privity" enabled to do it (see the *ThreadCtl()* function in your Neutrino C Library Reference). Only threads running from the **root** account or that are *setuid()* to **root** can obtain "I/O privity"; hence we're effectively limiting this ability to **root**.

Here's a code snippet that attaches an ISR to the hardware interrupt vector, which we've identified in our code sample by the constant HW_SERIAL_IRQ:

```
#include <sys/neutrino.h>

int interruptID;

const struct sigevent *
intHandler (void *arg, int id)
{
    ...
}

int
main (int argc, char **argv)
{
    ...
    interruptID = InterruptAttach (HW_SERIAL_IRQ,
                                   intHandler,
                                   &event,
                                   sizeof (event),
                                   0);
    if (interruptID == -1) {
        fprintf (stderr, "%s:  can't attach to IRQ %d\n",
                 progname, HW_SERIAL_IRQ);
        perror (NULL);
        exit (EXIT_FAILURE);
    }
    ...
    return (EXIT_SUCCESS);
}
```

This creates the association between the ISR (the routine called *intHandler()*; see below for details) and the hardware interrupt vector HW_SERIAL_IRQ.

At this point, if an interrupt occurs on that interrupt vector, our ISR will be dispatched. When we call *InterruptAttach()*, the kernel unmasks the interrupt source at the PIC level (unless it's already unmasked, which would be the case if multiple ISRs were sharing the same interrupt).

Detaching an interrupt handler

When done with the ISR, we *may* wish to break the association between the ISR and the interrupt vector:

```
int
InterruptDetach (int id);
```

I said "may" because threads that handle interrupts are generally found in servers, and servers generally hang around forever. It's therefore conceivable that a well-constructed server wouldn't ever issue the *InterruptDetach()* function call. Also, the OS will remove any interrupt handlers that a thread or process may have associated with it when the thread or process dies. So, simply falling off the end of *main()*, calling *exit()*, or exiting due to a SIGSEGV, will dissociate your ISR from the interrupt vector, automagically. (Of course, you'll probably want to handle this a little better, and stop your device from generating interrupts. If another device is sharing the interrupt, then there are no two ways about it — you *must* clean up, otherwise you won't get any more interrupts if running edge-sensitive mode, or you'll get a constant flood of ISR dispatches if running in level-sensitive mode.)

Continuing the above example, if we want to detach, we'd use the following code:

```
void
terminateInterrupts (void)
{
    InterruptDetach (interruptID);
}
```

If this was the last ISR associated with that interrupt vector, the kernel would automatically mask the interrupt source at the PIC level so that it doesn't generate interrupts.

The *flags* parameter

The last parameter, *flags*, controls all kinds of things:

_NTO_INTR_FLAGS_END

Indicates that this handler should go *after* other handlers that may be attached to the same interrupt source.

_NTO_INTR_FLAGS_PROCESS

Indicates that this handler is associated with the process rather than the thread. What this boils down to is that if you specify this flag, the interrupt handler will be automatically dissociated from the interrupt source when the process exits. If you don't specify this thread, the interrupt handler will be dissociated from the interrupt source when the thread that created the association in the first place exits.

_NTO_INTR_FLAGS_TRK_MSK

Indicates that the kernel should track the number of times the interrupt has been masked. This causes a little more work for the kernel, but is required to ensure an orderly unmasking of the interrupt source should the process or thread exit.

The interrupt service routine

Let's look at the ISR itself. In the first example, we'll look at using the *InterruptAttach()* function. Then, we'll see the exact same thing, except with *InterruptAttachEvent()*.

Using *InterruptAttach()*

Continuing our example, here's the ISR *intHandler()*. It looks at the 8250 serial port chip that we assume is attached to HW_SERIAL_IRQ:

```
/*
 * part of int1.c
*/

volatile int serial_msr; // saved contents of Modem Status Reg
volatile int serial_rx;  // saved contents of RX register
volatile int serial_lsr; // saved contents of Line Status Reg

const struct sigevent *
intHandler (void *arg, int id)
{
```

```
int  iir;
struct sigevent *event = (struct sigevent *)arg;

/*
 * determine the source of the interrupt
 * by reading the Interrupt Identification Register
*/

iir = in8 (base_reg + REG_II) & IIR_MASK;

/* no interrupt? */
if (iir & 1) {
    /* then no event */
    return (NULL);
}

/*
 * figure out which interrupt source caused the interrupt,
 * and see if a thread needs to do something about it.
 * (The constants are based on the 8250 serial port's
 * interrupt identification register.)
*/

switch (iir) {
case    IIR_MSR:
    serial_msr = in8 (base_reg + REG_MS);

    /* wake up thread */
    return (event);
    break;

case    IIR_THE:
    /* do nothing */
    break;

case    IIR_RX:
    /* note the character */
    serial_rx = in8 (base_reg + REG_RX);
    break;

case    IIR_LSR:
    /* note the line status reg. */
    serial_lsr = in8 (base_reg + REG_LS);
    break;

default:
    break;
}

/* don't bother anyone */
```

```
    return (NULL);
}
```

The first thing we notice is that any variable that the ISR touches must be declared `volatile`. On a single-processor box, this isn't for the ISR's benefit, but rather for the benefit of the thread-level code, which can be interrupted at any point by the ISR. Of course, on an SMP box, we *could* have the ISR running concurrently with the thread-level code, in which case we have to be *very* careful about these sorts of things.

With the `volatile` keyword, we're telling the compiler not to cache the value of any of these variables, because they can change at any point during execution.

The next thing we notice is the prototype for the interrupt service routine itself. It's marked as `const struct sigevent *`. This says that the routine `intHandler` returns a `struct sigevent` pointer. This is standard for all interrupt service routines.

Finally, notice that the ISR decides if the thread will or won't be sent an event. Only in the case of a Modem Status Register (MSR) interrupt do we want the event to be delivered (the event is identified by the variable *event*, which was conveniently passed to the ISR when we attached it). In all other cases, we ignore the interrupt (and update some global variables). In *all* cases, however, we clear the source of the interrupt. This is done by reading the I/O port via *in8()*.

Using *InterruptAttachEvent()*

If we were to recode the example above to use *InterruptAttachEvent()*, it would look like this:

```
/*
 * part of int2.c
*/

int
main (int argc, char **argv)
{
    int  intId;         // interrupt id
    int  iir;           // interrupt identification register
    int  serial_msr;    // saved contents of Modem Status Reg
int  serial_rx;     // saved contents of RX register
int  serial_lsr;    // saved contents of Line Status Reg

// usual main() setup stuff...

// set up the event
intId = InterruptAttachEvent (HW_SERIAL_IRQ, &event, 0);

for (;;) {

    // wait for an interrupt event
    // (could use MsgReceive instead)
    InterruptWait (0, NULL);

    /*
     * determine the source of the interrupt (and clear
     * it) by reading the Interrupt Identification
     * Register
    */

    iir = in8 (base_reg + REG_II) & IIR_MASK;

    // unmask the interrupt, so we can get the next event
    InterruptUnmask (HW_SERIAL_IRQ, intId);

    /* no interrupt? */
    if (iir & 1) {
        /* then wait again for next */
        continue;
    }

    /*
     * figure out which interrupt source caused the
     * interrupt, and determine if we need to do
     * something about it
    */

    switch (iir) {
    case    IIR_MSR:
        serial_msr = in8 (base_reg + REG_MS);

        /*
         * perform whatever processing you would've done
         * in the other example...
        */
        break;

    case    IIR_THE:
        /* do nothing */
        break;
        case    IIR_RX:
            /* note the character */
            serial_rx = in8 (base_reg + REG_RX);
            break;

        case    IIR_LSR:
            /* note the line status reg. */
            serial_lsr = in8 (base_reg + REG_LS);
            break;
        }
    }

    /* You won't get here. */
    return (0);
}
```

Notice that the *InterruptAttachEvent()* function returns an interrupt identifier (a small integer). We've saved this into the variable *intId* so that we can use it later when we go to unmask the interrupt.

After we've attached the interrupt, we then need to wait for the interrupt to hit. Since we're using *InterruptAttachEvent()*, we'll get the event that we created earlier dropped on us *for every interrupt*. Contrast this with what happened when we used *InterruptAttach()* — in that case, our ISR determined whether or not to drop an event on us. With *InterruptAttachEvent()*, the kernel has no idea whether or not the hardware event that caused the interrupt was "significant" for us, so it drops the event on us every time it occurs, masks the interrupt, and lets us decide if the interrupt was significant or not.

We handled the decision in the code example for *InterruptAttach()* (above) by returning either a `struct sigevent` to indicate that something should happen, or by returning the constant NULL. Notice the changes that we did to our code when we modified it for *InterruptAttachEvent()*:

- The "ISR" work is now done at thread time in *main()*.
- We must *always* unmask the interrupt source after receiving our event (because the kernel masks it for us).

- If the interrupt is not significant to us, we don't do anything and simply loop around again in the `for` statement, waiting for another interrupt.
- If the interrupt *is* significant to us, we handle it directly (in the `case IIR_MSR` part).

Where you decide to clear the source of the interrupt depends on your hardware and the notification scheme you've chosen. With the combination of SIGEV_INTR and *InterruptWait()*, the kernel doesn't "queue" more than one notification; with SIGEV_PULSE and *MsgReceive()*, the kernel will queue all the notifications. If you're using signals (and SIGEV_SIGNAL, for example), you define whether the signals are queued or not. With some hardware schemes, you may need to clear the source of the interrupt *before* you can read more data out of the device; with other pieces of hardware, you don't have to and can read data while the interrupt is asserted.

☞ An ISR returning SIGEV_THREAD is one scenario that fills me with absolute fear! I'd recommend avoiding this "feature" if at all possible.

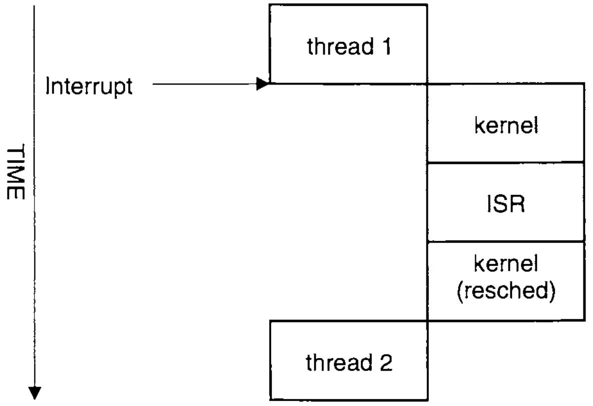
In the serial port example above, we've decided to use *InterruptWait()*, which will queue one entry. The serial port hardware may assert another interrupt immediately after we've read the interrupt identification register, but that's fine, because at most one SIGEV_INTR will get queued. We'll pick up this notification on our next iteration of the `for` loop.

InterruptAttach() versus *InterruptAttachEvent()*

This naturally brings us to the question, "Why would I use one over the other?"

The most obvious advantage of *InterruptAttachEvent()* is that it's simpler to use than *InterruptAttach()* — there's no ISR routine (hence no need to debug it). Another advantage is that since there's nothing running in kernel space (as an ISR routine would be) there's no danger of crashing the entire system. If you do encounter a programming error, then the process will crash, rather than the whole system. However, it may be more or less efficient than *InterruptAttach()* depending on what you're trying to achieve. This issue is complex enough that reducing it to a few words (like "faster" or "better") probably won't suffice. We'll need to look at a few pictures and scenarios.

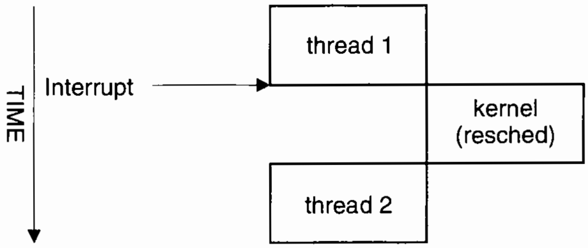
Here's what happens when we use *InterruptAttach()*:



Control flow with InterruptAttach().

The thread that's currently running ("thread1") gets interrupted, and we go into the kernel. The kernel saves the context of "thread1." The kernel then does a lookup to see who's responsible for handling the interrupt and decides that "ISR1" is responsible. At this point, the kernel sets up the context for "ISR1" and transfers control. "ISR1" looks at the hardware and decides to return a `struct sigevent`. The kernel notices the return value, figures out who needs to handle it, and makes them READY. This may cause the kernel to schedule a different thread to run, "thread2."

Now, let's contrast that with what happens when we use *InterruptAttachEvent()*:



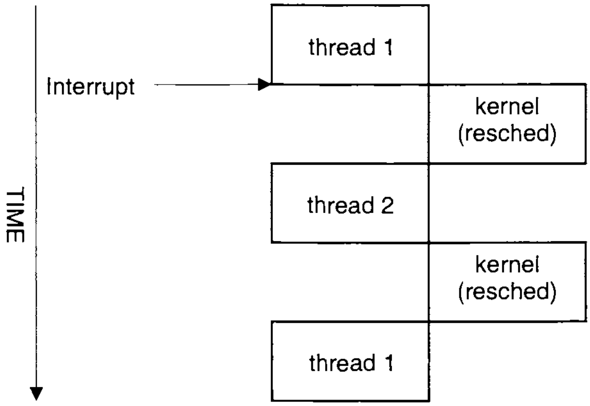
Control flow with InterruptAttachEvent().

In this case, the servicing path is much shorter. We made one context switch from the currently running thread ("thread1") into the kernel. Instead of doing another context switch into the ISR, the kernel simply "pretended" that the ISR returned a `struct sigevent` and acted on it, rescheduling "thread2" to run.

Now you're thinking, "Great! I'm going to forget all about *InterruptAttach()* and just use the easier *InterruptAttachEvent()*."

That's not such a great idea, because you may not *need* to wake up for every interrupt that the hardware generates! Go back and look at the source example above — it returned an event only when the modem status register on the serial port changed state, not when a character arrived, not when a line status register changed, and not when the transmit holding buffer was empty.

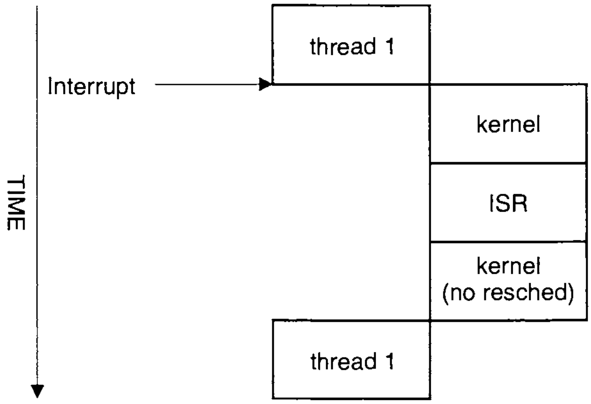
In that case, especially if the serial port was receiving characters (that you wanted to ignore), you'd be wasting a lot of time rescheduling your thread to run, only to have it look at the serial port and decide that it didn't want to do anything about it anyway. In that case, things would look like this:



Control flow with InterruptAttachEvent() and unnecessary rescheduling.

All that happens is that you incur a thread-to-thread context switch to get into "thread2" which looks at the hardware and decides that it doesn't need to do anything about it, costing you another thread-to-thread context switch to get back to "thread1."

Here's how things would look if you used *InterruptAttach()* but *didn't* want to schedule a different thread (i.e., you returned):



Control flow with InterruptAttach() with no thread rescheduling.

The kernel knows that “thread1” was running, and the ISR didn’t tell it to do anything, so it can just go right ahead and let “thread1” continue after the interrupt.

Just for reference, here’s what the *InterruptAttachEvent()* function call does (note that this isn’t the real source, because *InterruptAttachEvent()* actually binds a data structure to the kernel — it *isn’t* implemented as a discrete function that gets called!):

```
// the "internal" handler
static const struct sigevent *
internalHandler (void *arg, int id)
{
    struct sigevent *event = arg;

    InterruptMask (intr, id);
    return (arg);
}

int
InterruptAttachEvent (int intr,
    const struct sigevent *event, unsigned flags)
{
    static struct sigevent static_event;

    memcpy (&static_event, event, sizeof (static_event));

    return (InterruptAttach (intr, internalHandler,
            &static_event, sizeof (*event), flags));
}
```

The tradeoffs

So, which function should you use? For low-frequency interrupts, you can almost always get away with *InterruptAttachEvent()*. Since the interrupts occur infrequently, there won’t be a significant impact on overall system performance, even if you do schedule threads unnecessarily. The only time that this can come back to haunt you is if another device is chained off the same interrupt — in this case, because *InterruptAttachEvent()* masks the source of the interrupt, it’ll effectively disable interrupts from the other device until the interrupt source is unmasked. This is a concern only if the first device takes a long time to be serviced. In the bigger picture, this is a hardware system design issue — you shouldn't chain slow-to-respond devices on the same line as high-speed devices.

For higher-frequency interrupts, it's a toss up, and there are many factors:

- Unnecessary interrupts — if there will be a significant number of these, you're better off using *InterruptAttach()* and filtering them out in the ISR. For example, consider the case of a serial device. A thread may issue a command saying "Get me 64 bytes." If the ISR is programmed with the knowledge that nothing useful will happen until 64 bytes are received from the hardware, the ISR has effectively filtered the interrupts. The ISR will then return an event only *after* 64 bytes have been accumulated.
- Latency — if your hardware is sensitive to the amount of time that passes between asserting the interrupt request and the execution of the ISR, you should use *InterruptAttach()* to minimize this interrupt latency. This is because the kernel is very fast at dispatching the ISR.
- Buffering — if your hardware has buffering in it, you may be able to get away with *InterruptAttachEvent()* and a single-entry queueing mechanism like SIGEV_INTR and *InterruptWait()*. This method lets the hardware interrupt as often as it wants, while letting your thread pick the values out of the hardware's buffer when it can. Since the hardware is buffering the data, there's no problem with interrupt latencies.

ISR functions

The next issue we should tackle is the list of functions an ISR is allowed to call.

Let me digress just a little at this point. Historically, the reason that ISRs were so difficult to write (and still are in most other operating systems) is that the ISR runs in a special environment.

One particular thing that complicates writing ISRs is that the ISR isn't actually a "proper" thread as far as the kernel is concerned. It's this weird "hardware" thread, if you want to call it that. This means that the ISR isn't allowed to do any "thread-level" things, like messaging, synchronization, kernel calls, disk I/O, etc.

But doesn't that make it much *harder* to write ISR routines? Yes it does. The solution, therefore, is to do as little work as possible in the ISR, and do the rest of the work at thread-level, where you have access to all the services.

Your goals in the ISR should be:

- Fetch information that is transitory.
- Clear the source of the ISR.
- Optionally dispatch a thread to get the "real" work done.

This "architecture" hinges on the fact that Neutrino has very fast context-switch times. You know that you can get into your ISR quickly to do the time-critical work. You also know that when the ISR returns an event to trigger thread-level work, that thread will start quickly as well. It's this "don't do anything in the ISR" philosophy that makes Neutrino ISRs so simple!

So, what calls can you use in the ISR? Here's the official list:

- *atomic_*()* functions (such as *atomic_set()*)
- *mem*()* functions (such as *memcpy()*)
- most *str*()* functions (such as *strcmp()*). Beware, though, that not all these are safe, such as *strdup()* — it calls *malloc()*, which uses a mutex, and that's not allowed. For the string functions, you should really consult the individual C Library References before using.
- *InterruptMask()*
- *InterruptUnmask()*
- *InterruptLock()*
- *InterruptUnlock()*

- *InterruptDisable()*
- *InterruptEnable()*
- *in*()* and *out*()*

Basically, the rule of thumb is, "Don't use anything that's going to take a huge amount of stack space or time, and don't use anything that issues kernel calls." The stack space requirement stems from the fact that ISRs have very limited stacks.

The list of interrupt-safe functions makes sense — you might want to move some memory around, in which case the *mem*()* and *str*()* functions are a good choice. You'll most likely want to read data registers from the hardware (in order to save transitory data variables and/or clear the source of the interrupt), so you'll want to use the *in*()* and *out*()* functions.

What about the bewildering choice of *Interrupt*()* functions? Let's examine them in pairs:

InterruptMask() and *InterruptUnmask()*

> These functions are responsible for masking the interrupt source at the PIC level; this keeps them from being passed on to the CPU. Generally, you'd use this if you want to perform further work in the thread and can't clear the source of the interrupt in the ISR itself. In this case, the ISR would issue *InterruptMask()*, and the thread would issue *InterruptUnmask()* when it had completed whatever operation it was invoked to do.
>
> Keep in mind that *InterruptMask()* and *InterruptUnmask()* are *counting* — you must "unmask" the same number of times that you've "masked" in order for the interrupt source to be able to interrupt you again.
>
> By the way, note that the *InterruptAttachEvent()* performs the *InterruptMask()* for you (in the kernel) — therefore you must call *InterruptUnmask()* from your interrupt-handling thread.

InterruptLock() and *InterruptUnlock()*

> These functions are used to disable (*InterruptLock()*) and enable (*InterruptUnlock()*) interrupts on a single or multiprocessor system. You'd want to disable interrupts if you needed to protect the thread from the ISR (or additionally, on an SMP system, the ISR from a thread). Once you've done your critical data manipulation, you'd then enable interrupts. Note that these functions are recommended over the "old" *InterruptDisable()* and *InterruptEnable()* functions as they will operate properly on an SMP system. There's an additional cost over the "old" functions to perform the check on an SMP system, but in a single processor system it's negligible, which is why I'm recommending that you always use *InterruptLock()* and *InterruptUnlock()*.

InterruptDisable() and *InterruptEnable()*

> These functions shouldn't be used in new designs. Historically, they were used to invoke the x86 processor instructions `cli` and `sti` when Neutrino was x86-only. They've since been upgraded to handle all supported processors, but you should use *InterruptLock()* and *InterruptUnlock()* (to keep SMP systems happy).

The one thing that bears repeating is that on an SMP system, *it is possible* to have *both* the interrupt service routine *and* another thread running *at the same time.*

Summary

Keep the following things in mind when dealing with interrupts:

- Don't take too long in an ISR — perform the minimum amount of work you can get away with. This helps minimize interrupt latency and debugging.

- Use *InterruptAttach()* when you *need* to access the hardware as soon as the interrupt occurs; otherwise, avoid it.
- Use *InterruptAttachEvent()* at all other times. The kernel will schedule a thread (based on the event that you passed) to handle the interrupt.
- Protect variables used by both the interrupt service routine (if using *InterruptAttach()*) and threads by calling *InterruptLock()* and *InterruptUnlock()*.
- Declare variables that are going to be used between the thread and the ISR as `volatile` so that the compiler isn't caching "stale" values that have been changed by the ISR.

Chapter 5

Resource Managers

In this chapter...

What is a resource manager?

The client's view

The resource manager's view

The resource manager library

Writing a resource manager

Handler routines

Examples

Advanced topics

Summary

What is a resource manager?

In this chapter, we'll take a look at what you need to understand in order to write a *resource manager*.

A resource manager is simply a program with some well-defined characteristics. This program is called different things on different operating systems — some call them "device drivers," "I/O managers," "filesystems," "drivers," "devices," and so on. In all cases, however, the goal of this program (which we'll just call a resource manager) is to present an abstract view of some service.

Also, since Neutrino is a POSIX-conforming operating system, it turns out that the abstraction is based on the POSIX specification.

Examples of resource managers

Before we get carried away, let's take a look at a couple of examples and see how they "abstract" some "service." We'll look at an actual piece of hardware (a serial port) and something much more abstract (a filesystem).

Serial port

On a typical system, there usually exists some way for a program to transmit output and receive input from a serial, RS-232-style hardware interface. This hardware interface consists of a bunch of hardware devices, including a *UART* (*U*niversal *A*synchronous *R*eceiver *T*ransmitter) chip which knows how to convert the CPU's parallel data stream into a serial data stream and vice versa.

In this case, the "service" being provided by the serial resource manager is the capability for a program to send and receive characters on a serial port.

We say that an "abstraction" occurs, because the client program (the one ultimately using the service) doesn't know (nor does it care about) the details of the UART chip and its implementation. All the client program knows is that to send some characters it should call the *fprintf()* function, and to receive some characters it should call the *fgets()* function. Notice that we used standard, POSIX function calls to interact with the serial port.

Filesystem

As another example of a resource manager, let's examine the filesystem. This consists of a number of cooperating modules: the filesystem itself, the block I/O driver, and the disk driver.

The "service" being offered here is the capability for a program to read and write characters on some medium. The "abstraction" that occurs is the same as with the serial port example above — the client program can still use *the exact same function calls* (e.g., the *fprintf()* and *fgets()* functions) to interact with a storage medium instead of a serial port. In fact, the client really doesn't know or need to know which resource manager it's interacting with.

Characteristics of resource managers

As we saw in our examples (above), the key to the flexibility of the resource managers is that all the functionality of the resource manager is accessed using standard POSIX function calls — we didn't use "special" functions when talking to the serial port. But what if you *need* to do something "special," something *very* device-specific? For example, setting the baud rate on a serial port is an operation that's very specific to the serial port resource manager — it's totally meaningless to the filesystem resource manager. Likewise, setting the file position via *lseek()* is useful in a filesystem, but meaningless in a serial port. The solution POSIX chose for this is simple. Some functions, like *lseek()*, simply return an error code on a device that doesn't support them. Then there's the "catch-all" device control function, called *devctl()*, that allows device-specific functionality to be provided within a POSIX framework. Devices that don't understand the particular *devctl()* command simply return an error, just as devices that don't understand the *lseek()* command would.

Since we've mentioned *lseek()* and *devctl()* as two common commands, it's worthwhile to note that pretty much *all* file-descriptor (or `FILE *` stream) function calls are supported by resource managers.

This naturally leads us to the conclusion that resource managers will be dealing almost exclusively with file-descriptor based function calls. Since Neutrino is a message-passing operating system, it follows that the POSIX functions get translated into messages, which are then sent to resource managers. It is this "POSIX-function to message-passing" translation trick that lets us decouple clients from resource managers. All a resource manager has to do is handle certain well-defined messages. All a client has to do is generate the same well-defined messages that the resource manager is expecting to receive and handle.

☞ Since the interaction between clients and resource managers is based on message passing, it makes sense to make this "translation layer" as thin as possible. For example, when a client does an *open()* and gets back a file descriptor, the *file descriptor is in fact the connection ID*! This connection ID (file descriptor) gets used in the client's C library functions (like *read()*) where a message is created and sent to the resource manager.

The client's view

We've already seen a hint of what the client expects. It expects a file-descriptor-based interface, using standard POSIX functions.

In reality, though, there are a few more things going on "under the hood."

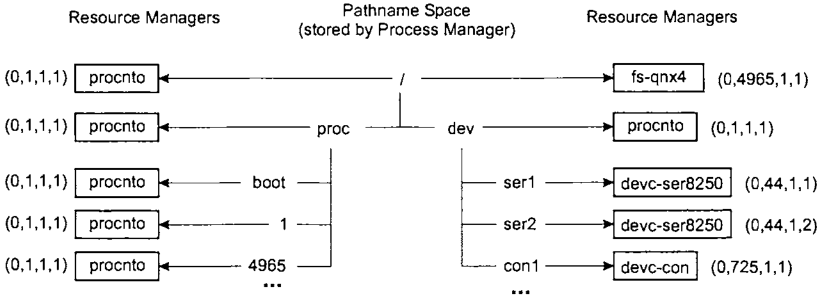
For example, how does the client actually connect to the appropriate resource manager? What happens in the case of union filesystems (where multiple filesystems are responsible for the same "namespace")? How are directories handled?

Finding the server

The first thing that a client does is call *open()* to get a file descriptor. (Note that if the client calls the higher-level function *fopen()* instead, the same discussion applies —*fopen()* eventually calls *open()*).

Inside the C library implementation of *open()*, a message is constructed, and sent to the process manager (**procnto**) component.

The process manager is responsible for maintaining information about the *pathname space*. This information consists of a tree structure that contains pathnames and node descriptor, process ID, channel ID, and handle associations:



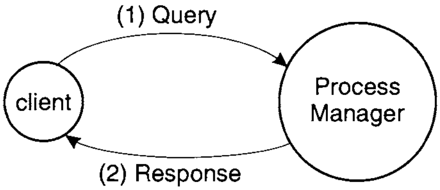
Neutrino's namespace.

Note that in the diagram above and in the descriptions that follow, I've used the designation **fs-qnx4** as the name of the resource manager that implements the QNX 4 filesystem — in reality, it's a bit more complicated, because the filesystem drivers are based on a series of DLLs that get bundled together. So, there's actually no executable called **fs-qnx4**; we're just using it as a placeholder for the filesystem component.

Let's say that the client calls *open()*:

```
fd = open ("/dev/ser1", O_WRONLY);
```

In the client's C library implementation of *open()*, a message is constructed and sent to the process manager. This message states, "I want to open **/dev/ser1**; who should I talk to?"

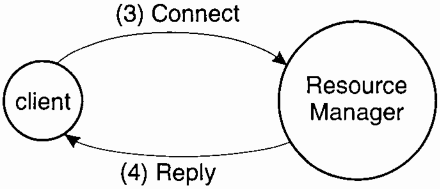


First stage of name resolution.

The process manager receives the request and looks through its tree structure to see if there's a match (let's assume for now that we need an exact match). Sure enough, the pathname "`/dev/ser1`" matches the request, and the process manager is able to reply to the client: "I found `/dev/ser1`. It's being handled by node descriptor 0, process ID 44, channel ID 1, handle 1. Send them your request!"

Remember, we're still in the client's *open()* code!

So, the *open()* function creates another message, and a connection to the specified node descriptor (0, meaning our node), process ID (44), channel ID (1), stuffing the handle into the message itself. This message is really the "connect" message — it's the message that the client's *open()* library uses to establish a connection to a resource manager (step 3 in the picture below). When the resource manager gets the connect message, it looks at it and performs validation. For example, you may have tried to open-for-write a resource manager that implements a read-only filesystem, in which case you'd get back an error (in this case, EROFS). In our example, however, the serial port resource manager looks at the request (we specified O_WRONLY; perfectly legal for a serial port) and replies back with an EOK (step 4 in the picture below).



The _IO_CONNECT message.

Finally, the client's *open()* returns to the client with a valid file descriptor.

Really, this file descriptor is the connection ID we just used to send a connect message to the resource manager! Had the resource manager *not* given us an EOK, we would have passed this error back to the client (via *errno* and a -1 return from *open()*). (It's worthwhile to note that the process manager can return the node ID, process ID and channel ID of *more than one* resource manager in response to a name resolution request. In that case, the client will try each of them in turn until one succeeds, returns an error that's not ENOSYS, ENOENT, or EROFS, or the client exhausts the list, in which case the *open()* fails. We'll discuss this further when we look at the "before" and "after" flags, later on.)

Finding the process manager

Now that we understand the basic steps used to find a particular resource manager, we need to solve the mystery of, "How did we find the process manager to begin with?" Actually, this one's easy. By definition, the process manager has a node descriptor of 0 (meaning this node), a process ID of 1, and a channel ID of 1. So, the ND/PID/CHID triplet 0/1/1 always identifies the process manager.

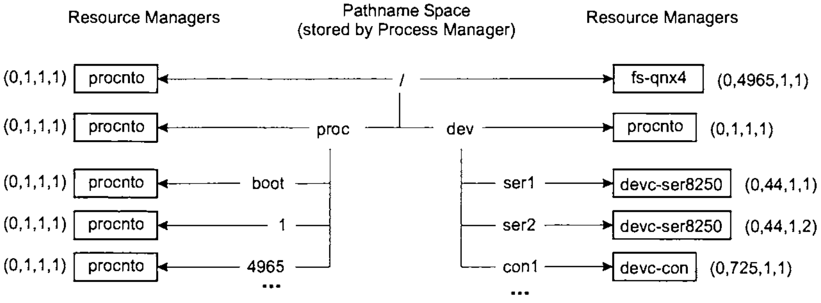
Handling directories

The example we used above was that of a serial port resource manager. We also stated an assumption: "let's assume for now that we need an exact match." The assumption is only half-true — all the pathname matching we'll be talking about in this chapter has to *completely* match a *component* of the pathname, but may not have to match the *entire* pathname. We'll clear this up shortly.

Suppose I had code that does this:

```
fp = fopen ("/etc/passwd", "r");
```

Recall that *fopen()* eventually calls *open()*, so we have *open()* asking about the pathname **/etc/passwd**. But there isn't one in the diagram:



Neutrino's namespace.

We do notice, however, that **fs-qnx4** has registered its association of ND/PID/CHID at the pathname "**/**." Although it's not shown on the diagram, **fs-qnx4** registered itself as a *directory resource manager* — it told the process manager that it'll be responsible for "**/**" *and below*. This is something that the other, "device" resource managers (e.g., the serial port resource manager) didn't do. By setting the "directory" flag, **fs-qnx4** is able to handle the request for "**/etc/passwd**" because the first part of the request is "**/**" — a matching component!

What if we tried to do the following?

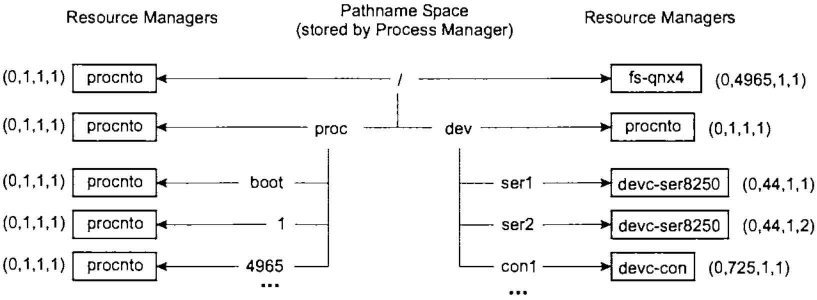
```
fd = open ("/dev/ser1/9600.8.1.n", O_WRONLY);
```

Well, since the serial port resource manager doesn't have the directory flag set, the process manager will look at it and say "Nope, sorry, the pathname **/dev/ser1** is not a directory. I'm going to have to fail this request." The request fails right then and there — the process manager doesn't even return a ND/PID/CHID/handle that the *open()* function should try.

☞ Obviously, as hinted at in my choice of parameters for the *open()* call above, it *may* be a clever idea to allow some "traditional" drivers to be opened with additional parameters past the "usual" name. However, the rule of thumb here is, "If you can get away with it in a design review meeting, knock yourself out." Some of my students, upon hearing me say that, pipe up with "But I *am* the design review committee!" To which I usually reply, "You are given a gun. Shoot yourself in the foot. `:-)` "

Union'd filesystems

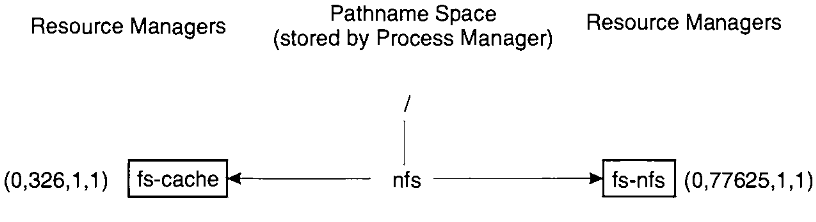
Take a closer look at the diagram we've been using:



Neutrino's namespace.

Notice how *both* **fs-qnx4** *and* the process manager have registered themselves as being responsible for "/"? This is fine, and nothing to worry about. In fact, there are times when it's a very good idea. Let's consider one such case.

Suppose you have a very slow network connection and you've mounted a networked filesystem over it. You notice that you often use certain files and wish that they were somehow magically "cached" on your system, but alas, the designers of the network filesystem didn't provide a way for you to do that. So, you write yourself a caching filesystem (called **fs-cache**) that sits on top of the network filesystem. Here's how it looks from the client's point of view:



Overlayed filesystems.

Both **fs-nfs** (the network filesystem) and your caching filesystem (**fs-cache**) have registered themselves for the same prefix, namely "**/nfs**." As we mentioned above, this is fine, normal, and legal under Neutrino.

Let's say that the system just started up and your caching filesystem doesn't have anything in it yet. A client program tries to open a file, let's say **/nfs/home/rk/abc.txt**. Your caching filesystem is "in front of" the network filesystem (I'll show you how to do that later, when we discuss resource manager implementation).

At this point, the client's *open()* code does the usual steps:

1. Message to the process manager: "Who should I talk to about the filename **/nfs/home/rk/abc.txt**?"
2. Response from the process manager: "Talk to **fs-cache** first, and then **fs-nfs**."

Notice here that the process manager returned *two* sets of ND/PID/CHID/handle; one for **fs-cache** and one for **fs-nfs**. This is critical.

Now, the client's *open()* continues:

1. Message to **fs-cache**: "I'd like to open the file **/nfs/home/rk/abc.txt** for read, please."

2 Response from `fs-cache`: "Sorry, I've never heard of this file."

At this point, the client's *open()* function is out of luck as far as the `fs-cache` resource manager is concerned. The file doesn't exist! However, the *open()* function knows that it got a list of *two* ND/PID/CHID/handle tuples, so it tries the second one next:

1 Message to `fs-nfs`: "I'd like to open the file `/nfs/home/rk/abc.txt` for read, please."

2 Response from `fs-nfs`: "Sure, no problem!"

Now that the *open()* function has an EOK (the "no problem"), it returns the file descriptor. The client then performs *all* further interactions with the `fs-nfs` resource manager.

☞ The *only* time that we "resolve" to a resource manager is during the *open()* call. This means that once we've successfully opened a particular resource manager, we will continue to use that resource manager for all file descriptor calls.

So how does our `fs-cache` caching filesystem come into play? Well, eventually, let's say that the user is done reading the file (they've loaded it into a text editor). Now they want to write it out. The same set of steps happen, with an interesting twist:

1 Message to the process manager: "Who should I talk to about the filename `/nfs/home/rk/abc.txt`?"

2 Response from the process manager: "Talk to `fs-cache` first, and then `fs-nfs`."

3 Message to `fs-cache`: "I'd like to open the file `/nfs/home/rk/abc.txt` for *write*, please."

4 Response from `fs-cache`: "Sure, no problem."

Notice that this time, in step 3, we opened the file for *write* and not *read* as we did previously. It's not surprising, therefore, that `fs-cache` allowed the operation this time (in step 4).

Even more interesting, observe what happens the *next* time we go to read the file:

1. Message to the process manager: "Who should I talk to about the filename `/nfs/home/rk/abc.txt`?"
2. Response from the process manager: "Talk to `fs-cache` first, and then `fs-nfs`."
3. Message to `fs-cache`: "I'd like to open the file `/nfs/home/rk/abc.txt` for *read*, please."
4. Response from `fs-cache`: "Sure, no problem."

Sure enough, the caching filesystem handled the request for the read this time (in step 4)!

Now, we've left out a few details, but these aren't important to getting across the basic ideas. Obviously, the caching filesystem will need some way of sending the data across the network to the "real" storage medium. It should also have some way of verifying that no one else modified the file just before it returns the file contents to the client (so that the client doesn't get stale data). The caching filesystem *could* handle the first read request itself, by loading the data from the network filesystem on the first read into its cache. And so on.

Client summary

We're done with the client side of things. The following are key points to remember:

- The client usually triggers communication with the resource manager via *open()* (or *fopen()*).
- Once the client's request has "resolved" to a particular resource manager, we never change resource managers.

- All further messages for the client's session are based on the file descriptor (or `FILE *` stream), (e.g., *read()*, *lseek()*, *fgets()*).
- The session is terminated (or "dissociated") when the client closes the file descriptor or stream (or terminates for any reason).
- All client file-descriptor-based function calls are translated into messages.

The resource manager's view

Let's look at things from the resource manager's perspective. Basically, the resource manager needs to tell the process manager that it'll be responsible for a certain part of the pathname space (it needs to *register* itself). Then, the resource manager needs to receive messages from clients and handle them. Obviously, things aren't quite *that* simple.

Let's take a quick overview look at the functions that the resource manager provides, and then we'll look at the details.

Registering a pathname

The resource manager needs to tell the process manager that one or more pathnames are now under its *domain of authority* — effectively, that this particular resource manager is prepared to handle client requests for those pathnames.

The serial port resource manager might handle (let's say) four serial ports. In this case, it would register four different pathnames with the process manager: **/dev/ser1**, **/dev/ser2**, **/dev/ser3**, and **/dev/ser4**. The impact of this is that there are now four distinct entries in the process manager's pathname tree, one for each of the serial ports. Four entries isn't too bad. But what if the serial port resource manager handled one of those fancy multiport cards, with 256 ports on it? Registering 256 *individual* pathnames (i.e., **/dev/ser1** through **/dev/ser256**) would result in 256 different entries in the process manager's pathname tree! The process manager isn't optimized for searching this tree; it assumes that there will be a few entries in the tree, not hundreds.

As a rule, you shouldn't *discretely* register more than a few dozen pathnames at each level — this is because a linear search is performed. The 256 port registration is certainly beyond that. In that case, what the multiport serial resource manager should do is register a *directory*-style pathname, for example **/dev/multiport**. This occupies only one entry in the process manager's pathname tree. When a client opens a serial port, let's say port 57:

```
fp = fopen ("/dev/multiport/57", "w");
```

The process manager resolves this to the ND/PID/CHID/handle for the multiport serial resource manager; it's up to that resource manager to decide if the rest of the pathname (in our case, the "57") is valid. In this example, assuming that the variable *path* contains the rest of the pathname past the mountpoint, this means that the resource manager could do checking in a *very* simple manner:

```
devnum = atoi (path);
if ((devnum <= 0) || (devnum >= 256)) {
    // bad device number specified
} else {
    // good device number specified
}
```

This search would certainly be faster than anything the process manager could do, because the process manager must, by design, be much more general-purpose than our resource manager.

Handling messages

Once we've registered one or more pathnames, we should then be prepared to receive messages from clients. This is done in the "usual" way, with the *MsgReceive()* function call. There are fewer than 30 well-defined message types that the resource manager handles. To simplify the discussion and implementation, however, they're broken into two groups:

connect messages
: Always contain a pathname; these are either one-shot messages or they establish a context for further I/O messages.

I/O messages
: Always based on a connect message; these perform further work.

Connect messages

Connect messages always contain a pathname. The *open()* function that we've been using throughout our discussion is a perfect example of a function that generates a connect message. In this case, the handler for the connect message establishes a context for further I/O messages. (After all, we expect to be performing things like *read()* after we've done an *open()*).

An example of a "one-shot" connect message is the message generated as a result of the *rename()* function call. No further "context" is established — the handler in the resource manager is expected to change the name of the specified file to the new name, and that's it.

I/O messages

An I/O message is expected only after a connect message and refers to the context created by that connect message. As mentioned above in the connect message discussion, *open()* followed by *read()* is a perfect example of this.

Three groups, really

Apart from connect and I/O messages, there are also "other" messages that can be received (and handled) by a resource manager. Since they aren't "resource manager" messages proper, we'll defer discussion of them until later.

The resource manager library

Before we get too far into all the issues surrounding resource managers, we have to get acquainted with QSSL's resource manager library. Note that this "library" actually consists of several distinct pieces:

- thread pool functions (which we discussed in the Processes and Threads chapter under "Pools of threads")
- dispatch interface
- resource manager functions
- POSIX library helper functions

While you certainly *could* write resource managers "from scratch" (as was done in the QNX 4 world), that's far more hassle than it's worth.

Just to show you the utility of the library approach, here's the source for a single-threaded version of "`/dev/null`":

```
/*
 *  rm1.c
 *
 *  /dev/null using the resource manager library
*/

#include <stdio.h>
#include <stdlib.h>
#include <stddef.h>
#include <sys/iofunc.h>
#include <sys/dispatch.h>

int
main (int argc, char **argv)
{
    dispatch_t              *dpp;
    resmgr_attr_t           resmgr_attr;
    resmgr_context_t        *ctp;
    resmgr_connect_funcs_t  cfuncs;
    resmgr_io_funcs_t       ifuncs;
    iofunc_attr_t           attr;

    // create the dispatch structure
    if ((dpp = dispatch_create ()) == NULL) {
        perror ("Unable to dispatch_create\n");
        exit (EXIT_FAILURE);
    }

    // initialize the attributes structure for the device
    iofunc_attr_init (&attr, S_IFNAM | 0666, 0, 0);

    // initialize the resource manager control structure
    memset (&resmgr_attr, 0, sizeof (resmgr_attr));
    resmgr_attr.nparts_max = 1;
    resmgr_attr.msg_max_size = 2048;

    // bind default functions into the outcall tables
    iofunc_func_init (_RESMGR_CONNECT_NFUNCS, &cfuncs,
                      _RESMGR_IO_NFUNCS, &ifuncs);

    // establish a name in the pathname space
    if (resmgr_attach (dpp, &resmgr_attr, "/dev/null",
                       _FTYPE_ANY, 0, &cfuncs, &ifuncs,
                       &attr) == -1) {
        perror ("Unable to resmgr_attach\n");
        exit (EXIT_FAILURE);
    }

    // allocate a resource manager context block
    ctp = resmgr_context_alloc (dpp);

    while (1) {
        // wait here for a message
        if ((ctp = resmgr_block (ctp)) == NULL) {
            perror ("Unable to resmgr_block\n");
            exit (EXIT_FAILURE);
        }
        // handle the message
        resmgr_handler (ctp);
    }

    // you'll never get here
    return (EXIT_SUCCESS);
}
```

There you have it! A complete **/dev/null** resource manager implemented in a few function calls!

If you were to write this from scratch, and have it support all the functionality that this one does (e.g., *stat()* works, *chown()* and *chmod()* work, and so on), you'd be looking at many hundreds if not thousands of lines of C code.

The library really does what we just talked about

By way of introduction to the library, let's see (briefly) what the calls do in the `/dev/null` resource manager.

dispatch_create()

Creates a dispatch structure; this will be used for blocking on the message reception.

iofunc_attr_init()

Initializes the attributes structure used by the device. We'll discuss attributes structures in more depth later, but for now, the short story is that there's one of these per device name, and they contain information about a particular device.

iofunc_func_init()

Initializes the two data structures *cfuncs* and *ifuncs*, which contain pointers to the connect and I/O functions, respectively. You might argue that this call has the most "magic" in it, as this is where the actual "worker" routines for handling all the messages got bound into a data structure. We didn't actually see any *code* to handle the connect message, or the I/O messages resulting from a client *read()* or *stat()* function etc. That's because the library is supplying default POSIX versions of those functions for us, and it's the *iofunc_func_init()* function that binds those same default handler functions into the two supplied tables.

resmgr_attach()

Creates the channel that the resource manager will use for receiving messages, and talks to the process manager to tell it that we're going to be responsible for "`/dev/null`." While there are a lot of parameters, we'll see them all in painful detail later. For now, it's important to note that this is where the dispatch handle (*dpp*), pathname (the string `/dev/null`), and the connect (*cfuncs*) and I/O (*ifuncs*) message handlers all get bound together.

resmgr_context_alloc()

Allocates a resource manager internal context block. You'll see details of this context block later; the short story is it contains information relevant to the message being processed.

resmgr_block()

This is the resource manager's blocking call; this is where we wait for a message to arrive from a client.

resmgr_handler()

Once the message arrives from the client, this function is called to process it.

Behind the scenes at the library

You've seen that your code is responsible for providing the main message receiving loop:

```
while (1) {
    // wait here for a message
    if ((ctp = resmgr_block (ctp)) == NULL) {
        perror ("Unable to resmgr_block\n");
        exit (EXIT_FAILURE);
    }
    // handle the message
    resmgr_handler (ctp);
}
```

This is very convenient, for it lets you place breakpoints on the receiving function and to intercept messages (perhaps with a debugger) during operation.

The library implements the "magic" inside of the *resmgr_handler()* function, because that's where the message is analyzed and disposed of through the connect and I/O functions tables we mentioned earlier.

In reality, the library consists of two cooperating layers: a *base layer* that provides "raw" resource manager functionality, and a *POSIX layer* that provides POSIX helper and default functions. We'll briefly define the two layers, and then in "Resource manager structure," below, we'll pick up the details.

The base layer

The bottom-most layer consists of functions that begin with *resmgr_*()* in their names. This class of function is concerned with the mechanics of making a resource manager work.

I'll just briefly mention the functions that are available and where we'd use them. I'll then refer you to QSSL's documentation for additional details on these functions.

The base layer functions consist of:

resmgr_msgreadv() and *resmgr_msgread()*

Reads data from the client's address space using message passing.

resmgr_msgwritev() and *resmgr_msgwrite()*

Writes data to the client's address space using message passing.

resmgr_open_bind()

Associates the context from a connect function, so that it can be used later by an I/O function.

resmgr_attach() Creates a channel, associates a pathname, dispatch handle, connect functions, I/O functions, and other parameters together. Sends a message to the process manager to register the pathname.

resmgr_detach() Opposite of *resmgr_attach()*; dissociates the binding of the pathname and the resource manager.

pulse_attach() Associates a pulse code with a function. Since the library implements the message receive loop, this is a convenient way of "gaining control" for handling pulses.

pulse_detach() Dissociates a pulse code from the function.

In addition to the functions listed above, there are also numerous functions dealing with the dispatch interface.

One function from the above list that deserves special mention is *resmgr_open_bind()*. It associates some form of context data when the connect message (typically as a result of the client calling *open()* or *fopen()*) arrives, so that this data block is around when the I/O messages are being handled. Why didn't we see this in the `/dev/null` handler? Because the POSIX layer default functions call this function for us. If we're handling all the messages ourselves, we'd certainly call this function.

☞ The *resmgr_open_bind()* function not only sets up the context block for further I/O messages, but *also* initializes other data structures used by the resource manager library itself.

The rest of the functions from the above list are somewhat intuitive — we'll defer their discussion until we use them.

The POSIX layer

The second layer provided by QSSL's resource manager library is the POSIX layer. As with the base layer, you *could* code a resource manager without using it, but it would be a *lot* of work! Before we can talk about the POSIX layer functions in detail, we need to look at some of the base layer data structures, the messages that arrive from the clients, and the overall structure and responsibilities of a resource manager.

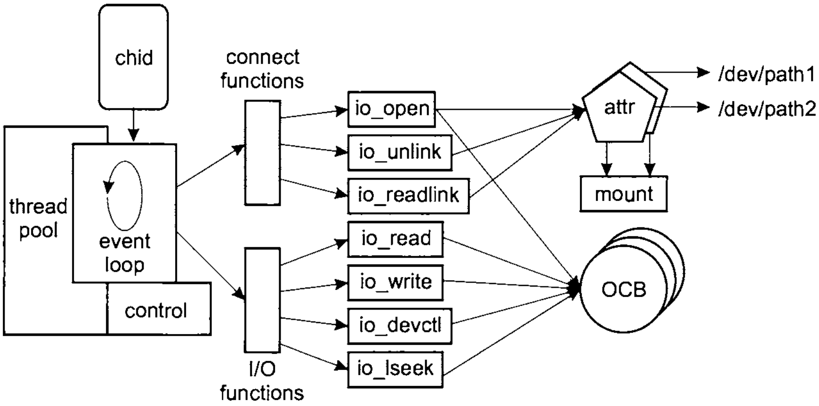
Writing a resource manager

Now that we've introduced the basics — how the client looks at the world, how the resource manager looks at the world, and an overview of the two cooperating layers in the library, it's time to focus on the details.

In this section, we'll take a look at the following topics:

- data structures
- resource manager structure
- POSIX layer data structure
- handler routines
- and of course, lots of examples

Keep in mind the following "big picture," which contains almost everything related to a resource manager:



Architecture of a resource manager — the big picture.

Data structures

The first thing we need to understand is the data structures used to control the operation of the library:

- `resmgr_attr_t` control structure
- `resmgr_connect_funcs_t` connect table
- `resmgr_io_funcs_t` I/O table

And one data structure that's used internally by the library:

- **resmgr_context_t** internal context block

Later, we'll see the OCB, attributes structure, and mount structure data types that are used with the POSIX layer libraries.

resmgr_attr_t control structure

The control structure (type **resmgr_attr_t**) is passed to the *resmgr_start()* function, which looks at the various members and handles the main receive loop of the resource manager.

The control structure (from **<sys/dispatch.h>**) has the following contents:

```
typedef struct _resmgr_attr {
    unsigned flags;
    unsigned nparts_max;
    unsigned msg_max_size;
    int      (*other_func) (resmgr_context_t *ctp, void *msg);
} resmgr_attr_t;
```

The *other_func* message handler

In general, you should avoid using this member. This member, if non-NULL, represents a routine that will get called with the current message received by the resource manager library when the library doesn't recognize the message. While you *could* use this to implement "private" or "custom" messages, this practice is discouraged (use either the _IO_DEVCTL or _IO_MSG handlers, see below). If you wish to handle pulses that come in, I recommend that you use the *pulse_attach()* function instead.

You should leave this member with the value NULL.

The data structure sizing parameters

These two parameters are used to control various sizes of messaging areas.

The *nparts_max* parameter controls the size of the dynamically allocated *iov* member in the resource manager library context block (of type `resmgr_context_t`, see below). You'd typically adjust this member if you were returning more than a one-part IOV from some of your handling functions. Note that it has no effect on the *incoming* messages — this is only used on *outgoing* messages.

The *msg_max_size* parameter controls how much buffer space the resource manager library should set aside as a receive buffer for the message. The resource manager library will set this value to be at least as big as the header for the biggest message it will be receiving. This ensures that when your handler function gets called, it will be passed the entire header of the message. Note, however, that the data (if any) beyond the current header is *not* guaranteed to be present in the buffer, even if the *msg_max_size* parameter is "large enough." An example of this is when messages are transferred over a network using `qnet`. (For more details about the buffer sizes, see "The `resmgr_context_t` internal context block," below.)

The *flags* parameter

This parameter gives additional information to the resource manager library. For our purposes, we'll just pass a 0. You can read up about the other values in the C Library reference under the *resmgr_attach()* function.

`resmgr_connect_funcs_t` connect table

When the resource manager library receives a message, it looks at the type of message and sees if it can do anything with it. In the base layer, there are two tables that affect this behavior. The `resmgr_connect_funcs_t` table, which contains a list of connect message handlers, and the `resmgr_io_funcs_t` table, which contains a similar list of I/O message handlers. We'll see the I/O version below.

When it comes time to fill in the connect and I/O tables, we recommend that you use the *iofunc_func_init()* function to load up the tables with the POSIX layer default handler routines. Then, if you need to override some of the functionality of particular message handlers, you'd simply assign your own handler function instead of the POSIX default routine. We'll see this in the section "Putting in your own functions." Right now, let's look at the connect functions table itself (this is from **<sys/resmgr.h>**):

```
typedef struct _resmgr_connect_funcs {
  unsigned nfuncs;

  int (*open)
      (ctp, io_open_t *msg, handle, void *extra);
  int (*unlink)
      (ctp, io_unlink_t *msg, handle, void *reserved);
  int (*rename)
      (ctp, io_rename_t *msg, handle, io_rename_extra_t *extra);
  int (*mknod)
      (ctp, io_mknod_t *msg, handle, void *reserved);
  int (*readlink)
      (ctp, io_readlink_t *msg, handle, void *reserved);
  int (*link)
      (ctp, io_link_t *msg, handle, io_link_extra_t *extra);
  int (*unblock)
      (ctp, io_pulse_t *msg, handle, void *reserved);
  int (*mount)
      (ctp, io_mount_t *msg, handle, io_mount_extra_t *extra);

} resmgr_connect_funcs_t;
```

Note that I've shortened the prototype down by omitting the **resmgr_context_t *** type for the first member (the *ctp*), and the **RESMGR_HANDLE_T *** type for the third member (the *handle*). For example, the full prototype for *open* is really:

```
int (*open) (resmgr_context_t *ctp,
             io_open_t *msg,
             RESMGR_HANDLE_T *handle,
             void *extra);
```

The very first member of the structure (*nfuncs*) indicates how big the structure is (how many members it contains). In the above structure, it should contain the value "8," for there are 8 members (*open* through to *mount*). This member is mainly in place to allow QSSL to upgrade this library without any ill effects on your code. For example, suppose you had compiled in a value of 8, and then QSSL upgraded the library to have 9. Because the member only had a value of 8, the library could say to itself, "Aha! The user of this library was compiled when we had only 8 functions, and now we have 9. I'll provide a useful default for the 9th function." There's a manifest constant in **`<sys/resmgr.h>`** called _RESMGR_CONNECT_NFUNCS that has the current number. Use this constant if manually filling in the connect functions table (although it's *best* to use *iofunc_func_init()*).

Notice that the function prototypes all share a common format. The first parameter, *ctp*, is a pointer to a **`resmgr_context_t`** structure. This is an internal context block used by the resource manager library, and which you should treat as read-only (except for one field, which we'll come back to).

The second parameter is always a pointer to the message. Because the functions in the table are there to handle different types of messages, the prototypes match the kind of message that each function will handle.

The third parameter is a **`RESMGR_HANDLE_T`** structure called a *handle* — it's used to identify the device that this message was targeted at. We'll see this later as well, when we look at the attributes structure.

Finally, the last parameter is either "reserved" or an "extra" parameter for functions that need some extra data. We'll show the *extra* parameter as appropriate during our discussions of the handler functions.

`resmgr_io_funcs_t` I/O table

The I/O table is very similar in spirit to the connect functions table just shown above. Here it is, from **`<sys/resmgr.h>`**:

```
typedef struct _resmgr_io_funcs {
  unsigned nfuncs;
  int (*read)       (ctp, io_read_t *msg,     ocb);
  int (*write)      (ctp, io_write_t *msg,    ocb);
  int (*close_ocb)  (ctp, void *reserved,     ocb);
  int (*stat)       (ctp, io_stat_t *msg,     ocb);
  int (*notify)     (ctp, io_notify_t *msg,   ocb);
  int (*devctl)     (ctp, io_devctl_t *msg,   ocb);
  int (*unblock)    (ctp, io_pulse_t *msg,    ocb);
  int (*pathconf)   (ctp, io_pathconf_t *msg, ocb);
  int (*lseek)      (ctp, io_lseek_t *msg,    ocb);
  int (*chmod)      (ctp, io_chmod_t *msg,    ocb);
  int (*chown)      (ctp, io_chown_t *msg,    ocb);
  int (*utime)      (ctp, io_utime_t *msg,    ocb);
  int (*openfd)     (ctp, io_openfd_t *msg,   ocb);
  int (*fdinfo)     (ctp, io_fdinfo_t *msg,   ocb);
  int (*lock)       (ctp, io_lock_t *msg,     ocb);
  int (*space)      (ctp, io_space_t *msg,    ocb);
  int (*shutdown)   (ctp, io_shutdown_t *msg, ocb);
  int (*mmap)       (ctp, io_mmap_t *msg,     ocb);
  int (*msg)        (ctp, io_msg_t *msg,      ocb);
  int (*dup)        (ctp, io_dup_t *msg,      ocb);
  int (*close_dup)  (ctp, io_close_t *msg,    ocb);
  int (*lock_ocb)   (ctp, void *reserved,     ocb);
  int (*unlock_ocb) (ctp, void *reserved,     ocb);
  int (*sync)       (ctp, io_sync_t *msg,     ocb);
} resmgr_io_funcs_t;
```

For this structure as well, I've shortened the prototype by removing the type of the *ctp* member (`resmgr_context_t *`) and the last member (*ocb*, of type `RESMGR_OCB_T *`). For example, the full prototype for *read* is really:

```
int (*read) (resmgr_context_t *ctp,
             io_read_t *msg,
             RESMGR_OCB_T *ocb);
```

The very first member of the structure (*nfuncs*) indicates how big the structure is (how many members it contains). The proper manifest constant for initialization is _RESMGR_IO_NFUNCS.

Note that the parameter list in the I/O table is also very regular. The first parameter is the *ctp*, and the second parameter is the *msg*, just as they were in the connect table handlers.

The third parameter is different, however. It's an *ocb*, which stands for "Open Context Block." It holds the context that was bound by the connect message handler (e.g., as a result of the client's *open()* call), and is available to the I/O functions.

As discussed above, when it comes time to fill in the two tables, we recommend that you use the *iofunc_func_init()* function to load up the tables with the POSIX layer default handler routines. Then, if you need to override some of the functionality of particular message handlers, you'd simply assign your own handler function instead of the POSIX default routine. We'll see this in the section "Putting in your own functions."

The `resmgr_context_t` internal context block

Finally, one data structure is used by the lowest layer of the library to keep track of information that *it* needs to know about. You should view the contents of this data structure as "read-only," (except for the *iov* member).

Here's the data structure (from `<sys/resmgr.h>`):

```
typedef struct _resmgr_context {
  int                   rcvid;
  struct _msg_info      info;
  resmgr_iomsgs_t       *msg;
  dispatch_t            *dpp;
  int                   id;
  unsigned              msg_max_size;
  int                   status;
  int                   offset;
  int                   size;
  iov_t                 iov [1];
} resmgr_context_t;
```

As with the other data structure examples, I've taken the liberty of deleting reserved fields.

Let's look at the contents:

rcvid

The receive ID from the resource manager library's *MsgReceivev()* function call. Indicates who you should reply to (if you're going to do the reply yourself).

info

Contains the information structure returned by *MsgReceivev()* in the resource manager library's receive loop. Useful for getting information about the client, including things like the node descriptor, process ID, thread ID, and so on. See the man pages for *MsgReceivev()* for more details.

msg

A pointer to a union of all possible message types. This isn't very useful to you, because each of your handler functions get passed the appropriate union member as their second parameter.

dpp

A pointer to the dispatch structure that you passed in to begin with. Again, not very useful to you, but obviously useful to the resource manager library.

id

The identifier for the mountpoint this message was meant for. When you did the *resmgr_attach()*, it returned a small integer ID. This ID is the value of the *id* member. Note that you'd most likely never use this parameter yourself, but would instead rely on the attributes structure passed to you in your *io_open()* handler.

msg_max_size

This contains the *msg_max_size* that was passed in as the *msg_max_size* member of `resmgr_attr_t` (given to the *resmgr_attach()* function) so that the *size*, *offset*, and *msg_max_size* are all contained in one handy structure/location.

status

This is where your handler function places the result of the operation. Note that you should always use the macro _RESMGR_STATUS to write this field. For example, if you're handling the connect message from an *open()*, and you're a read-only resource manager but the client wanted to open you for write, you'd return an EROFS *errno* via (typically) `_RESMGR_STATUS (ctp, EROFS)`.

offset

The current number of bytes into the client's message buffer. Only relevant to the base layer library when used with *resmgr_msgreadv()* with combine messages (see below).

size This tells you how many bytes are valid in the message area that gets passed to your handler function. This number is important because it indicates if more data needs to be read from the client (for example, if not all of the client's data was read by the resource manager base library), or if storage needs to be allocated for a reply to the client (for example, to reply to the client's *read()* request). (Note: there's a bug in the 2.00 release where this field does *not* get stuffed in the case of a non-combine connect message. All other messages operate correctly. The workaround in that case (and that case *only*) is to use the *info* structure's *msglen* parameter.)

iov The I/O Vector table where you can write your return values, if returning data. For example, when a client calls *read()* and your read-handling code is invoked, you may need to return data. This data can be set up in the *iov* array, and your read-handling code can then return something like `_RESMGR_NPARTS (2)` to indicate (in this example) that both `iov [0]` and `iov [1]` contain data to return to the client. Note that the *iov* member is defined as only having one element. However, you'll also notice that it's conveniently at the end of the structure. The actual number of elements in the *iov* array is defined by you when you set the *nparts_max* member of the control structure above (in the section "`resmgr_attr_t` control structure," above).

Resource manager structure

Now that we've seen the data structures, we can discuss interactions between the parts that you'd supply to actually make your resource manager *do* something.

We'll look at:

- The *resmgr_attach()* function and its parameters
- Putting in your own functions
- The general flow of a resource manager
- Messages that *should* be connect messages but aren't
- Combine messages

The *resmgr_attach()* function and its parameters

As you saw in the **/dev/null** example above, the first thing you'll want to do is register your chosen "mountpoint" with the process manager. This is done via *resmgr_attach()*, which has the following prototype:

```
int
resmgr_attach (void *dpp,
               resmgr_attr_t *resmgr_attr,
               const char *path,
               enum _file_type file_type,
               unsigned flags,
               const resmgr_connect_funcs_t *connect_funcs,
               const resmgr_io_funcs_t *io_funcs,
               RESMGR_HANDLE_T *handle);
```

Let's examine these arguments, in order, and see what they're used for.

dpp The dispatch handle. This lets the dispatch interface manage the message receive for your resource manager.

resmgr_attr Controls the resource manager characteristics, as discussed above.

path The mountpoint that you're registering. If you're registering a discrete mountpoint (such as would be the case, for example, with **/dev/null**, or **/dev/ser1**), then this mountpoint must be matched *exactly* by the client, with no further pathname components past the mountpoint. If you're registering a directory mountpoint (such as would be the case, for example, with a network filesystem mounted as `/nfs`), then the match must be exact as well, with the added feature that pathnames past the mountpoint are allowed; they get passed to the connect functions stripped of the mountpoint (for example, the pathname `/nfs/etc/passwd` would match the network filesystem resource manager, and it would get `etc/passwd` as the rest of the pathname).

file_type The class of resource manager. See below.

flags Additional flags to control the behavior of your resource manager. These flags are defined below.

connect_funcs and *io_funcs*

These are simply the list of connect functions and I/O functions that you wish to bind to the mountpoint.

handle This is an "extendable" data structure (*aka* "attributes structure") that identifies the resource being mounted. For example, for a serial port, you'd extend the standard POSIX-layer attributes structure by adding information about the base address of the serial port, the baud rate, etc. Note that it *does not* have to be an attributes structure — if you're providing your own "open" handler, then you can choose to interpret this field any way you wish. It's only if you're using the default *iofunc_open_default()* handler as your "open" handler that this field *must* be an attributes structure.

The *flags* member can contain any of the following flags (or the constant 0 if none are specified):

_RESMGR_FLAG_BEFORE or _RESMGR_FLAG_AFTER

These flags indicate that your resource manager wishes to be placed before or after (respectively) other resource managers with the same mountpoint. These two flags would be useful with union'd (overlayed) filesystems. We'll discuss the interactions of these flags shortly.

_RESMGR_FLAG_DIR

This flag indicates that your resource manager is taking over the specified mountpoint *and below* — it's effectively a filesystem style of resource manager, as opposed to a discretely-manifested resource manager.

_RESMGR_FLAG_OPAQUE

If set, prevents resolving to any other manager below your mount point *except* for the pathmanager. This effectively eliminates unioning on a path.

_RESMGR_FLAG_FTYPEONLY

This ensures that only requests that have the same FTYPE_* as the *file_type* passed to *resmgr_attach()* are matched.

_RESMGR_FLAG_FTYPEALL

This flag is used when a resource manager wants to catch *all* client requests, even those with a different FTYPE_* specification than the one passed to *resmgr_attach()* in the *file_type* argument. This can only be used in conjunction with a registration file type of FTYPE_ALL.

_RESMGR_FLAG_SELF

Allow this resource manager to talk to itself. This really is a "Don't try this at home, kids" kind of flag, because allowing a resource manager to talk to itself can break the send-hierarchy and lead to deadlock (as was discussed in the Message Passing chapter).

You can call *resmgr_attach()* as many times as you wish to mount different mountpoints. You can also call *resmgr_attach() from within* *the connect or I/O functions* — this is kind of a neat feature that allows you to "create" devices on the fly.

When you've decided on the mountpoint, and want to create it, you'll need to tell the process manager if this resource manager can handle requests from just anyone, or if it's limited to handling requests only from clients who identify their connect messages with special tags. For example, consider the POSIX message queue (`mqueue`) driver. It's not going to allow (and certainly wouldn't know what to do with) "regular" *open()* messages from any old client. It will allow messages only from clients that use the POSIX *mq_open()*, *mq_receive()*, and so on, function calls. To prevent the process manager from even allowing regular requests to arrive at the `mqueue` resource manager, `mqueue` specified _FTYPE_MQUEUE as the *file_type* parameter. This means that when a client requests a name resolution from the process manager, the process manager won't even bother considering the resource manager during the search unless the client has specified that it wants to talk to a resource manager that has identified itself as _FTYPE_MQUEUE.

Unless you're doing something very special, you'll use a *file_type* of _FTYPE_ANY, which means that your resource manager is prepared to handle requests from anyone. For the full list of _FTYPE_* manifest constants, take a look in `<sys/ftype.h>`.

With respect to the "before" and "after" flags, things get a little bit more interesting. You can specify only one of these flags or the constant 0.

Let's see how this works. A number of resource managers have started, in the order given in the table. We also see the flags they passed for the *flags* member. Observe the positions they're given:

Resmgr	Flag	Order
1	_RESMGR_BEFORE	1
2	_RESMGR_AFTER	1, 2
3	0	1, 3, 2
4	_RESMGR_BEFORE	1, 4, 3, 2
5	_RESMGR_AFTER	1, 4, 3, 5, 2
6	0	1, 4, 6, 3, 5, 2

As you can see, the first resource manager to actually specify a flag always ends up in that position. (From the table, resource manager number 1 was the first to specify the "before" flag; no matter who registers, resource manager 1 is always first in the list. Likewise, resource manager 2 was the first to specify the "after" flag; again, no matter who else registers, it's always last.) If no flag is specified, it effectively acts as a "middle" flag. When resource manager 3 started with a flag of zero, it got put into the middle. As with the "before" and "after" flags, there's a preferential ordering given to all the "middle" resource managers, whereby newer ones are placed in front of other, existing "middle" ones.

However, in reality, there are very few cases where you'd actually mount more than one, and even fewer cases where you'd mount more than two resource managers at the same mountpoint. Here's a design tip: expose the ability to set the flags at the command line of the resource manager so that the end-user of your resource manager is able to specify, for example, `-b` to use the "before" flag, and `-a` to use the "after" flag, with no command-line option specified to indicate that a zero should be passed as the flag.

Keep in mind that this discussion applies *only* to resource managers mounted with the same mountpoint. Mounting "`/nfs`" with a "before" flag and "`/disk2`" with an "after" flag will have no effect on each other; only if you were to *then* mount *another* "`/nfs`" or "`/disk2`" would these flags (and rules) come into play.

Finally, the *resmgr_attach()* function returns a small integer handle on success (or -1 for failure). This handle can then be used subsequently to detach the pathname from the process manager's internal pathname tables.

Putting in your own functions

When designing your very first resource manager, you'll most likely want to take an incremental design approach. It can be very frustrating to write thousands of lines of code only to run into a fundamental misunderstanding and then having to make the ugly decision of whether to try to kludge (er, I mean "fix") all that code, or scrap it and start from scratch.

The recommended approach for getting things running is to use the *iofunc_func_init()* POSIX-layer default initializer function to fill the connect and I/O tables with the POSIX-layer default functions. This means that you can literally write your initial cut of your resource manager as we did above, in a few function calls.

Which function you'll want to implement first really depends on what kind of resource manager you're writing. If it's a filesystem type of resource manager where you're taking over a mountpoint and everything below it, you'll most likely be best off starting with the *io_open()* function. On the other hand, if it's a discretely manifested resource manager that does "traditional" I/O operations (i.e., you primarily access it with client calls like *read()* and *write()*), then the best place to start would be the *io_read()* and/or *io_write()* functions. The third possibility is that it's a discretely manifested resource manager that doesn't do traditional I/O operations, but instead relies on *devctl()* or *ioctl()* client calls to perform the majority of its functionality. In that case, you'd start at the *io_devctl()* function.

Regardless of where you start, you'll want to make sure that your functions are getting called in the expected manner. The really cool thing about the POSIX-layer default functions is that they can be placed directly into the connect or I/O functions table. This means that if you simply want to gain control, perform a *printf()* to say "I'm here in the io_open!", and then "do whatever should be done," you're going to have an easy time of it. Here's a portion of a resource manager that takes over the *io_open()* function:

```
// forward reference
int io_open (resmgr_context_t *, io_open_t *,
             RESMGR_HANDLE_T *, void *);

int
main ()
{
    // everything as before, in the /dev/null example
    // except after this line:
    iofunc_func_init (_RESMGR_CONNECT_NFUNCS, &cfuncs,
                      _RESMGR_IO_NFUNCS, &ifuncs);

    // add the following to gain control:
    cfuncs.open = io_open;
```

Assuming that you've prototyped the *io_open()* function call correctly, as in the code example, you can just use the default one from within your own!

```
int
io_open (resmgr_context_t *ctp, io_open_t *msg,
         RESMGR_HANDLE_T *handle, void *extra)
{
    printf ("I'm here in the io_open!\n");
    return (iofunc_open_default (ctp, msg, handle, extra));
}
```

In this manner, you're still using the default POSIX-layer *iofunc_open_default()* handler, but you've also gained control to do a *printf()*.

Obviously, you could do this for the *io_read()*, *io_write()*, and *io_devctl()* functions as well as any others that have POSIX-layer default functions. In fact, this is a really good idea, because it shows you that the client *really is* calling your resource manager as expected.

The general flow of a resource manager

As we alluded to in the client and resource manager overview sections above, the general flow of a resource manager begins on the client side with the *open()*. This gets translated into a connect message and ends up being received by the resource manager's *io_open()* outcall connect function.

This is really key, because the *io_open()* outcall function is the "gate keeper" for your resource manager. If the message causes the gate keeper to fail the request, you *will not* get any I/O requests, because the client never got a valid file descriptor. Conversely, if the message is accepted by the gate keeper, the client now has a valid file descriptor and you should expect to get I/O messages.

But the *io_open()* outcall function plays a greater role. Not only is it responsible for verifying whether the client can or can't open the particular resource, it's also responsible for:

- initializing internal library parameters
- binding a context block to this request
- binding an attribute structure to the context block.

The first two operations are performed via the base layer function *resmgr_open_bind()*; the binding of the attribute structure is done via a simple assignment.

Once the *io_open()* outcall function has been called, it's out of the picture. The client may or may not send I/O messages, but in any case will eventually terminating the "session" with a message corresponding to the *close()* function. Note that if the client suffers an unexpected death (e.g., gets hit with SIGSEGV, or the node that it's running on crashes), the operating system will synthesize a *close()* message so that the resource manager can clean up. Therefore, you are *guaranteed* to get a *close()* message!

Messages that *should* be connect messages but aren't

Here's an interesting point you may have noticed. The client's prototype for *chown()* is:

```
int
chown (const char *path,
       uid_t owner,
       gid_t group);
```

Remember, a connect message always contains a pathname and is either a one-shot message or establishes a context for further I/O messages.

So, why isn't there a *connect* message for the client's *chown()* function? In fact, why *is* there an *I/O* message?!? There's certainly no file descriptor implied in the client's prototype!

The answer is, "to make your life simpler!"

Imagine if functions like *chown()*, *chmod()*, *stat()*, and others required the resource manager to look up the pathname and then perform some kind of work. (This is, by the way, the way it was implemented in QNX 4.) The usual problems with this are:

- Each function has to call the lookup routine.
- Where file descriptor versions of these functions exist, the driver has to provide two separate entry points; one for the pathname version, and one for the file descriptor version.

In any event, what happens under Neutrino is that the client constructs a *combine message* — really just a single message that comprises multiple resource manager messages. Without combine messages, we could simulate *chown()* with something like this:

```
int
chown (const char *path, uid_t owner, gid_t group)
{
    int fd, sts;

    if ((fd = open (path, O_RDWR)) == -1) {
        return (-1);
    }
    sts = fchown (fd, owner, group);
    close (fd);
    return (sts);
}
```

where *fchown()* is the file-descriptor-based version of *chown()*. The problem here is that we are now issuing three function calls (and three separate message passing transactions), and incurring the overhead of *open()* and *close()* on the client side.

With combine messages, under Neutrino a single message that looks like this is constructed directly by the client's *chown()* library call:

`_IO_CONNECT_COMBINE_CLOSE`	`_IO_CHOWN`

A combine message.

The message has two parts, a connect part (similar to what the client's *open()* would have generated) and an I/O part (the equivalent of the message generated by the *fchown()*). There is no equivalent of the *close()* because we implied that in our particular choice of connect messages. We used the _IO_CONNECT_COMBINE_CLOSE message, which effectively states "Open this pathname, use the file descriptor you got for handling the rest of the message, and when you run off the end or encounter an error, close the file descriptor."

The resource manager that you write doesn't have a clue that the client called *chown()* or that the client did a distinct *open()*, followed by an *fchown()*, followed by a *close()*. It's all hidden by the base-layer library.

Combine messages

As it turns out, this concept of combine messages isn't useful just for saving bandwidth (as in the *chown()* case, above). It's also critical for ensuring atomic completion of operations.

Suppose the client process has two or more threads and one file descriptor. One of the threads in the client does an *lseek()* followed by a *read()*. Everything is as we expect it. If another thread in the client does the same set of operations, *on the same file descriptor*, we'd run into problems. Since the *lseek()* and *read()* functions don't know about each other, it's possible that the first thread would do the *lseek()*, and then get preempted by the second thread. The second thread gets to do its *lseek()*, and then its *read()*, before giving up CPU. The problem is that since the two threads are sharing the *same* file descriptor, the first thread's *lseek()* offset is now at the wrong place — it's at the position given by the second thread's *read()* function! This is also a problem with file descriptors that are *dup()*'d across processes, let alone the network.

An obvious solution to this is to put the *lseek()* and *read()* functions within a mutex — when the first thread obtains the mutex, we now know that it has exclusive access to the file descriptor. The second thread has to wait until it can acquire the mutex before it can go and mess around with the position of the file descriptor.

Unfortunately, if someone forgot to obtain a mutex *for each and every file descriptor operation*, there'd be a possibility that such an "unprotected" access would cause a thread to read or write data to the wrong location.

Let's look at the C library call *readblock()* (from **<unistd.h>**):

```
int
readblock (int fd,
           size_t blksize,
           unsigned block,
           int numblks,
           void *buff);
```

(The *writeblock()* function is similar.)

You can imagine a fairly "simplistic" implementation for *readblock()*:

```
int
readblock (int fd, size_t blksize, unsigned block,
           int numblks, void *buff)
{
    lseek (fd, blksize * block, SEEK_SET); // get to the block
    read (fd, buff, blksize * numblks);
}
```

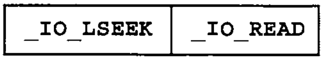
Obviously, this implementation isn't useful in a multi-threaded environment. We'd have to at least put a mutex around the calls:

```
int
readblock (int fd, size_t blksize, unsigned block,
           int numblks, void *buff)
{
    pthread_mutex_lock (&block_mutex);
    lseek (fd, blksize * block, SEEK_SET); // get to the block
    read (fd, buff, blksize * numblks);
    pthread_mutex_unlock (&block_mutex);
}
```

(We're assuming the mutex is already initialized.)

This code is still vulnerable to "unprotected" access; if some other thread in the process does a simple non-mutexed *lseek()* on the file descriptor, we've got a bug.

The solution to this is to use a combine message, as we discussed above for the *chown()* function. In this case, the C library implementation of *readblock()* puts *both* the *lseek() and* the *read()* operations into a single message and sends that off to the resource manager:



The readblock() function's combine message.

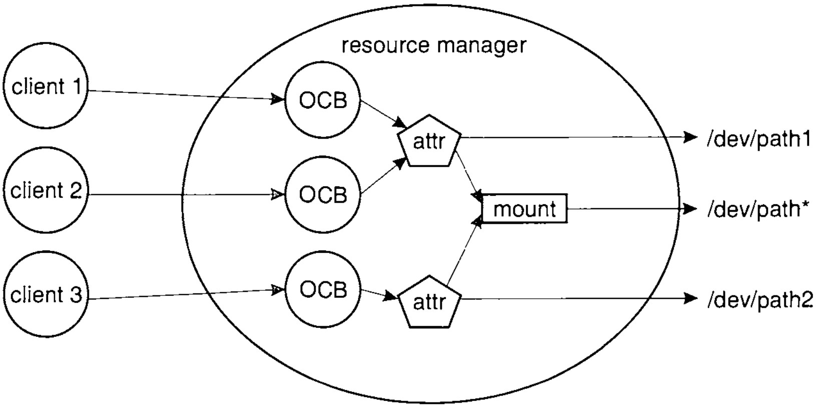
The reason that this works is because message passing is atomic. From the client's point of view, either the entire message has gone to the resource manager, or none of it has. Therefore, an intervening "unprotected" *lseek()* is irrelevant — when the *readblock()* operation is received by the resource manager, it's done in one shot. (Obviously, the damage will be to the unprotected *lseek()*, because after the *readblock()* the file descriptor's offset is at a different place than where the original *lseek()* put it.)

But what about the resource manager? How does it ensure that it *processes* the entire *readblock()* operation in one shot? We'll see this shortly, when we discuss the operations performed for each message component.

POSIX layer data structures

There are three data structures that relate to the POSIX-layer support routines. Note that as far as the *base layer* is concerned, you can use any data structures you want; it's the POSIX layer that requires you to conform to a certain content and layout. The benefits delivered by the POSIX layer are well worth this tiny constraint. As we'll see later, you can add your own content to the structures as well.

The three data structures are illustrated in the following diagram, showing some clients using a resource manager that happens to manifest two devices:



Data structures — the big picture.

The data structures are:

`iofunc_ocb_t` — OCB structure

Contains information on a per-file-descriptor basis `iofunc_attr_t` — attributes structure

Contains information on a per-device basis

`iofunc_mount_t` — mount structure

Contains information on a per-mountpoint basis

When we talked about the I/O and connect tables, you saw the OCB and attributes structures — in the I/O tables, the OCB structure was the last parameter passed. The attributes structure was passed as the *handle* in the connect table functions (third argument). The mount structure is usually a global structure and is bound to the attributes structure "by hand" (in the initialization code that you supply for your resource manager).

The `iofunc_ocb_t` OCB structure

The OCB structure contains information on a per-file-descriptor basis. What this means is that when a client performs an *open()* call and gets back a file descriptor (as opposed to an error indication), the resource manager will have created an OCB and associated it with the client. This OCB will be around for as long as the client has the file descriptor open. Effectively, the OCB and the file descriptor are a matched pair. Whenever the client calls an I/O function, the resource manager library will automatically associate the OCB, and pass it along with the message to the I/O function specified by the I/O function table entry. This is why the I/O functions all had the *ocb* parameter passed to them. Finally, the client will close the file descriptor (via *close()*), which will cause the resource manager to dissociate the OCB from the file descriptor and client. Note that the client's *dup()* function simply increments a reference count. In this case, the OCB gets dissociated from the file descriptor and client only when the reference count reaches zero (i.e., when the same number of *close()*s have been called as *open()* and *dup()*s.)

As you might suspect, the OCB contains things that are important on a per-open or per-file-descriptor basis. Here are the contents (from `<sys/iofunc.h>`):

```
typedef struct _iofunc_ocb {
  IOFUNC_ATTR_T *attr;
  int32_t       ioflag;
  SEE_BELOW!!!  offset;
  uint16_t      sflag;
  uint16_t      flags;
} iofunc_ocb_t;
```

Ignore the comment about the *offset* field for now; we'll come back to it immediately after this discussion.

The `iofunc_ocb_t` members are:

attr A pointer to the attributes structure related to this OCB. A common coding idiom you'll see in the I/O functions is "`ocb->attr`," used to access a member of the attributes structure.

ioflag The open mode — how this resource was opened (e.g., read only). Note that the *ioflag* contains the open mode (as passed to *open()* on the client side) plus one. For example, an open mode of O_RDONLY (the value 0) will show up in the *ioflag* as the value 1 (the constant _READ from `<stdio.h>`). This effectively allows the two least significant bits of the *ioflag* to be treated as read and write permissions (`ioflag & _READ` indicates read permission; `ioflag & _WRITE` indicates write permission).

offset The current *lseek()* offset into this resource.

sflag The sharing flag (see `<share.h>`) used with the client's *sopen()* function call. These are the flags SH_COMPAT, SH_DENYRW, SH_DENYWR, SH_DENYRD, and SH_DENYNO.

flags System flags. The two flags currently supported are IOFUNC_OCB_PRIVILEGED, which indicates whether a privileged process issued the connect message that resulted in this OCB, and IOFUNC_OCB_MMAP, which indicates whether this OCB is in use by a *mmap()* call on the client side. No other flags are defined at this time. You can use the bits defined by IOFUNC_OCB_FLAGS_PRIVATE for your own private flags.

If you wish to store additional data along with the "normal" OCB, rest assured that you can "extend" the OCB. We'll discuss this in the "Advanced topics" section.

The strange case of the *offset* member

The *offset* field is, to say the least, interesting. Have a look at **<sys/iofunc.h>** to see how it's implemented. Depending on what preprocessor flags you've set, you may get one of six (!) possible layouts for the *offset* area. But don't worry too much about the implementation — there are really only two cases to consider, depending on whether you want to support 64-bit offsets:

- yes — the *offset* member is 64 bits
- no (32-bit integers) — the *offset* member is the lower 32 bits; another member, *offset_hi*, contains the upper 32 bits.

For our purposes here, unless we're specifically going to talk about 32 versus 64 bits, we'll just assume that all offsets are 64 bits, of type **off_t**, and that the platform knows how to deal with 64-bit quantities.

The iofunc_attr_t attributes structure

Whereas the OCB was a per-open or per-file-descriptor structure, the attributes structure is a per-device data structure. You saw that the standard **iofunc_ocb_t** OCB had a member called *attr* that's a pointer to the attribute structure. This was done so the OCB has access to information about the device. Let's take a look at the attributes structure (from **<sys/iofunc.h>**):

```
typedef struct _iofunc_attr {
  IOFUNC_MOUNT_T             *mount;
  uint32_t                   flags;
  int32_t                    lock_tid;
```

```
    uint16_t                      lock_count;
    uint16_t                      count;
    uint16_t                      rcount;
    uint16_t                      wcount;
    uint16_t                      rlocks;
    uint16_t                      wlocks;
    struct _iofunc_mmap_list      *mmap_list;
    struct _iofunc_lock_list      *lock_list;
    void                          *list;
    uint32_t                      list_size;
    SEE_BELOW!!!                  nbytes;
    SEE_BELOW!!!                  inode;
    uid_t                         uid;
    gid_t                         gid;
    time_t                        mtime;
    time_t                        atime;
    time_t                        ctime;
    mode_t                        mode;
    nlink_t                       nlink;
    dev_t                         rdev;
} iofunc_attr_t;
```

The *nbytes* and *inode* members have the same set of **#ifdef** conditionals as the *offset* member of the OCB (see "The strange case of the *offset* member" above).

Note that some of the fields of the attributes structure are useful only to the POSIX helper routines.

Let's look at the fields individually:

mount

A pointer to the optional **iofunc_mount_t** mount structure. This is used in the same way that the pointer from the OCB to the attribute structure was used, except that this value can be NULL in which case the mount structure defaults are used (see "The **iofunc_mount_t** mount structure" below). As mentioned, the mount structure is generally bound "by hand" into the attributes structure in code that you supply for your resource manager initialization.

flags Contains flags that describe the state of other attributes structure fields. We'll discuss these shortly.

lock_tid In order to prevent synchronization problems, multiple threads using the same attributes structure will be mutually exclusive. The *lock_tid* contains the thread ID of the thread that currently has the attributes structure locked.

lock_count Indicates how many threads are trying to use this attributes structure. A value of zero indicates that the structure is unlocked. A value of one or more indicates that one or more threads are using the structure.

count Indicates the number of OCBs that have this attributes structure open for any reason. For example, if one client has an OCB open for read, another client has another OCB open for read/write, and both OCBs point to this attribute structure, then the value of *count* would be 2, to indicate that two clients have this resource open.

rcount Count readers. In the example given for *count*, *rcount* would also have the value 2, because two clients have the resource open for reading.

wcount Count writers. In the example given for *count*, *wcount* would have the value 1, because only one of the clients has this resource open for writing.

rlocks Indicates the number of OCBs that have read locks on the particular resource. If zero, means there are no read locks, but there may be write locks.

wlocks Same as *rlocks* but for write locks.

mmap_list Used internally by POSIX *iofunc_mmap_default()*.

lock_list Used internally by POSIX *iofunc_lock_default()*.

list Reserved for future use.

list_size Size of area reserved by *list*.

nbytes Size of the resource, in bytes. For example, if this resource described a particular file, and that file was 7756 bytes in size, then the *nbytes* member would contain the number 7756.

inode Contains a file or resource serial number, that must be unique per mountpoint. The *inode* should never be zero, because zero indicates a file that's not in use.

uid User ID of the owner of this resource.

gid Group ID of the owner of this resource.

mtime File modification time, updated or at least invalidated whenever a client *write()* is processed.

atime File access time, updated or at least invalidated whenever a client *read()* that returns more than zero bytes is processed.

ctime File change time, updated or at least invalidated whenever a client *write()*, *chown()*, or *chmod()* is processed.

mode File's mode. These are the standard S_* values from **`<sys/stat.h>`**, such as S_IFCHR, or in octal representation, such as 0664 to indicate read/write permission for owner and group, and read-only permission for other.

nlink Number of links to the file, returned by the client's *stat()* function call.

rdev For a character special device, this field consists of a major and minor device code (10 bits minor in the least-significant positions; next 6 bits are the major device number). For other types of devices, contains the device number. (See below in "Of device numbers, inodes, and our friend *rdev*," for more discussion.)

As with the OCB, you can extend the "normal" attributes structure with your own data. See the "Advanced topics" section.

The `iofunc_mount_t` mount structure

The mount structure contains information that's common across multiple attributes structures.

Here are the contents of the mount structure (from `<sys/iofunc.h>`):

```
typedef struct _iofunc_mount {
  uint32_t        flags;
  uint32_t        conf;
  dev_t           dev;
  int32_t         blocksize;
  iofunc_funcs_t  *funcs;
} iofunc_mount_t;
```

The *flags* member contains just one flag, IOFUNC_MOUNT_32BIT. This flag indicates that *offset* in the OCB, and *nbytes* and *inode* in the attributes structure, are 32-bit. Note that you can define your own flags in *flags*, using any of the bits from the constant IOFUNC_MOUNT_FLAGS_PRIVATE.

The *conf* member contains the following flags:

IOFUNC_PC_CHOWN_RESTRICTED

Indicates if the filesystem is operating in a "**chown**-restricted" manner, meaning if only **root** is allowed to **chown** a file.

IOFUNC_PC_NO_TRUNC

Indicates that the filesystem doesn't truncate the name.

IOFUNC_PC_SYNC_IO

Indicates that the filesystem supports synchronous I/O operations.

IOFUNC_PC_LINK_DIR

Indicates that linking/unlinking of directories is allowed.

The *dev* member contains the device number and is described below in "Of device numbers, inodes, and our friend *rdev*."

The *blocksize* describes the native blocksize of the device in bytes. For example, on a typical rotating-medium storage system, this would be the value 512.

Finally, the *funcs* pointer points to a structure (from **<sys/iofunc.h>**):

```
typedef struct _iofunc_funcs {
  unsigned      nfuncs;

  IOFUNC_OCB_T  *(*ocb_calloc)
                    (resmgr_context_t *ctp,
                     IOFUNC_ATTR_T *attr);

  void          (*ocb_free)
                    (IOFUNC_OCB_T *ocb);
} iofunc_funcs_t;
```

As with the connect and I/O functions tables, the *nfuncs* member should be stuffed with the current size of the table. Use the constant _IOFUNC_NFUNCS for this.

The *ocb_calloc* and *ocb_free* function pointers can be filled with addresses of functions to call whenever an OCB is to be allocated or deallocated. We'll discuss why you'd want to use these functions later when we talk about extending OCBs.

Of device numbers, inodes, and our friend *rdev*

The mount structure contains a member called *dev*. The attributes structure contains two members: *inode* and *rdev*. Let's look at their relationships by examining a traditional disk-based filesystem. The filesystem is mounted on a block device (which is the entire disk). This block device might be known as **/dev/hd0** (the first hard disk in the system). On this disk, there might be a number of partitions, such as **/dev/hd0t77** (the first QNX filesystem partition on that particular device). Finally, within that partition, there might be an arbitrary number of files, one of which might be **/hd/spud.txt**.

The *dev* (or "device number") member, contains a number that's unique to the node that this resource manager is registered with. The *rdev* member is the *dev* number of the root device. Finally, the *inode* is the file serial number. (Note that you can obtain major and minor device numbers by calling *rsrcdbmgr_devno_attach()*; see the Library Reference for more details. You are limited to 64 major devices and 1024 minor devices per major device.)

Let's relate that to our disk example. The following table shows some example numbers; after the table we'll take a look at where these numbers came from and how they're related.

Device	***dev***	***inode***	***rdev***
/dev/hd0	6	2	1
/dev/hd0t77	1	12	77
/hd/spud.txt	77	47343	n/a

For the raw block device, **/dev/hd0**, the process manager assigned both the *dev* and *inode* values (the 6 and the 2 in the table above). The resource manager picked a unique *rdev* value (of 1) for the device when it started.

For the partition, **/dev/hd0t77**, the *dev* value came from the raw block device's *rdev* number (the 1). The inode was selected by the resource manager as a unique number (within the *rdev*). This is where the 12 came from. Finally, the *rdev* number was selected by the resource manager as well — in this case, the writer of the resource manager selected 77 because it corresponded to the partition type.

Finally, for the file, `/hd/spud.txt`, the *dev* value (77) came from the partition's *rdev* value. The *inode* was selected by the resource manager (in the case of a file, the number is selected to correspond to some internal representation of the file — it doesn't matter what it is so long as it's not zero, and it's unique within the *rdev*). This is where the 47343 came from. For a file, the *rdev* field is not meaningful.

Handler routines

Not all outcalls correspond to client messages — some are synthesized by the kernel, and some by the library.

I've organized this section into the following:

- general notes
- connect functions notes
- alphabetical listing of connect and I/O messages

General notes

Each handler function gets passed an internal context block (the *ctp* argument) which should be treated as "read-only," except for the *iov* member. This context block contains a few items of interest, as described above in "**`resmgr_context_t`** internal context block." Also, each function gets passed a pointer to the message (in the *msg* argument). You'll be using this message pointer extensively, as that contains the parameters that the client's C library call has placed there for your use.

The function that you supply must return a value (all functions are prototyped as returning in **`int`**). The values are selected from the following list:

_RESMGR_NOREPLY

Indicates to the resource manager library that it should *not* perform the *MsgReplyv()* — the assumption is that you've either performed it yourself in your handler function, or that you're going to do it some time later.

_RESMGR_NPARTS (*n*)

The resource manager library should return an *n*-part IOV when it does the *MsgReplyv()* (the IOV is located in `ctp -> iov`). Your function is responsible for filling in the *iov* member of the *ctp* structure, and then returning _RESMGR_NPARTS with the correct number of parts.

☞ The *iov* member of *ctp* is allocated dynamically, so it must be *big enough* to hold the number of array elements that you're writing into the *iov* member! See the section "`resmgr_attr_t` control structure" above, for information on setting the *nparts_max* member.

_RESMGR_DEFAULT

This instructs the resource manager library to perform the *low-level default* function (This is *not* the same as the iofunc_*_default() functions!) You'd rarely ever use this return value. In general, it causes the resource manager library to return an errno of ENOSYS to the client, which indicates that the function is not supported.

_RESMGR_ERRNO (*errno*)

(Deprecated) This return value had been used to "wrap" an errno number as the return value of the message. For example, if a client issued an *open()* request for a read-only device, it would be appropriate to return the error value EROFS. Since this function is deprecated, you can return the error number directly instead of wrapping it with the _RESMGR_ERRNO macro (e.g., `return (EROFS);` instead of the more cumbersome `return (_RESMGR_ERRNO (EROFS));`.)

_RESMGR_PTR (*ctp*, *addr*, *len*)

This is a convenience macro that accepts the context pointer *ctp*, and fills its first IOV element to point to the address specified by *addr* for the length specified by *len*, and then returns the equivalent of `_RESMGR_NPARTS (1)` to the library. You'd generally use this if you return single-part IOVs from your function.

Locking, unlocking, and combine message handling

We saw the client side of a combine message when we looked at *readblock()* (in "Combine messages"). The client was able to atomically construct a message that contained multiple resource manager "submessages" — in the example, these were messages corresponding to the individual functions *lseek()* and *read()*. From the client's perspective, the two (or more) functions were at least *sent* atomically (and, due to the nature of message passing, will be *received* atomically by the resource manager). What we haven't yet talked about is how we ensure that the messages are *processed* atomically.

This discussion applies not only to combine messages, but to *all* I/O messages received by the resource manager library (except the close message, which we'll come back to shortly).

☞ The very first thing that the resource manager library does is to lock the attribute structure corresponding to the resource being used by the received message. Then, it processes one or more submessages from the incoming message. Finally, it unlocks the attribute structure.

This ensures that the incoming messages are handled atomically, for no other thread in the resource manager (in the case of a multithreaded resource manager, of course) can "jump in" and modify the resource while a thread is busy using it. Without the locking in place, two client threads could both issue what they believe to be an atomic combine message (say *lseek()* and *read()*). Since the resource manager might have two different threads running in it and processing messages, the two resource manager threads could possibly preempt each other, and the *lseek()* components could interfere with each other. With locking and unlocking, this is prevented, because each message that accesses a resource will be completed in its entirety atomically.

Locking and unlocking the resource is handled by default helper functions (*iofunc_lock_ocb_default()* and *iofunc_unlock_ocb_default()*) which are placed in the I/O table at the *lock_ocb* and *unlock_ocb* positions. You can, of course, override these functions if you want to perform further actions during this locking and unlocking phase.

Note that the resource *is unlocked before* the *io_close()* function is called. This is necessary because the *io_close()* function will free the OCB, which would effectively invalidate the pointer used to access the attributes structure, which is where the lock is stored! Also note that none of the connect functions do this locking, because the handle that's passed to them does not *have to be* an attribute structure (and the locks are stored in the attribute structure).

Connect functions notes

Before we dive into the individual messages, however, it's worth pointing out that the connect functions all have an identical message structure (rearranged slightly, see `<sys/iomsg.h>` for the original):

```
struct _io_connect {
    // Internal use
    uint16_t type;
    uint16_t subtype;
    uint32_t file_type;
    uint16_t reply_max;
    uint16_t entry_max;
    uint32_t key;
    uint32_t handle;
    uint32_t ioflag;
    uint32_t mode;
    uint16_t sflag;
    uint16_t access;
    uint16_t zero;
    uint8_t  eflag;

    // End-user parameters
    uint16_t path_len;
    uint8_t  extra_type;
    uint16_t extra_len;
    char     path [1];
};
```

You'll notice that I've divided the `struct _io_connect` structure into two areas, an "Internal use" part and an "End-user parameters" part.

Internal use part

The first part consists of fields that the resource manager library uses to:

- determine the type of message sent from the client.
- validate (ensure that the message is not spoofed).
- track access mode (used by helper functions).

To keep things simple, I recommend that you *always* use the helper functions (the *iofunc_*_default()* ones) in *all* connect functions. These will return a pass/fail indication, and after that point, you can then use the "End-user parameters" members within the connect function.

End-user parameter part

The second half of the members directly concern your implementation of the connect functions:

path_len and *path*

The pathname (and its length) that's the *operand* (i.e., the pathname you're operating on).

extra_type and *extra_len*

Additional parameters (pathnames, for example) relevant to the connect function.

To get a sense of how the *path* member is used as "the pathname you're operating on," let's examine something like the *rename()* function. This function takes two pathnames; the "original" pathname and the "new" pathname. The original pathname is passed in *path*, because it's the thing being worked on (it's the filename that's undergoing the name change). The new pathname is the argument to the operation. You'll see that the *extra* parameter passed to the connect functions conveniently contains a pointer to the argument of the operation — in this case, the new pathname. (Implementation-wise, the new pathname is stored just past the original pathname in the *path* pointer, with alignment taken into consideration, but you don't have to do anything about this — the *extra* parameter conveniently gives you the correct pointer.)

Alphabetical listing of connect and I/O functions

This section gives an alphabetical listing of the connect and I/O function entry points that you can fill in (the two tables passed to *pathname_attach()*). Remember that if you simply call *iofunc_func_init()*, all these entries will be filled in with the appropriate defaults; you'd want to modify a particular entry only if you wish to handle that particular message. In the "Examples" section, below, you'll see some examples of the common functions.

☞ It may seem confusing at first, but note that there are in fact *two* unblock outcalls — one is a connect function and one is an I/O function. This is correct; it's a reflection of *when* the unblock occurs. The connect version of the unblock function is used when the kernel unblocks the client immediately after the client has sent the connect message; the I/O version of the unblock function is used when the kernel unblocks the client immediately after the client has sent an I/O message.

In order not to confuse the client's C-library call (for example, *open()*) with the resource manager connect outcall that goes into that particular slot, we've given all of our functions an "`io_`" prefix. For example, the function description for the *open* connect outcall slot will be under *io_open()*.

io_chmod()

`int io_chmod (resmgr_context_t *`*ctp*`, io_chmod_t *`*msg*`, RESMGR_OCB_T *`*ocb*`)`

Classification: I/O function

Default handler: *iofunc_chmod_default()*

Helper functions: *iofunc_chmod()*

Client function: *chmod()*, *fchmod()*

Messages: _IO_CHMOD

Data structure:

```
struct _io_chmod {
  uint16_t type;
  uint16_t combine_len;
  mode_t   mode;
};

typedef union {
  struct _io_chmod i;
} io_chmod_t;
```

Description: Responsible for changing the mode for the resource identified by the passed *ocb* to the value specified by the *mode* message member.

Returns: The status via the helper macro _RESMGR_STATUS.

io_chown()

int io_chown (resmgr_context_t ***ctp*****, io_chown_t** ***msg*****, RESMGR_OCB_T** ***ocb*****)**

Classification: I/O function

Default handler: *iofunc_chown_default()*

Helper functions: *iofunc_chown()*

Client function: *chown()*, *fchown()*

Messages: _IO_CHOWN

Data structure:

```
struct _io_chown {
  uint16_t type;
  uint16_t combine_len;
  int32_t  gid;
  int32_t  uid;
};

typedef union {
  struct _io_chown i;
} io_chown_t;
```

Description: Responsible for changing the user ID and group ID fields for the resource identified by the passed *ocb* to *uid* and *gid*, respectively. Note that the mount structure flag IOFUNC_PC_CHOWN_RESTRICTED and the OCB *flag* field should be examined to determine whether the filesystem allows *chown()* to be performed by non-`root` users.

Returns: The status via the helper macro _RESMGR_STATUS.

io_close_dup()

```
int io_close_dup (resmgr_context_t *ctp, io_close_t
*msg, RESMGR_OCB_T *ocb)
```

Classification: I/O function

Default handler: *iofunc_close_dup_default()*

Helper functions: *iofunc_close_dup()*

Client function: *close(),fclose()*

Messages: _IO_CLOSE_DUP

Data structure:

```
struct _io_close {
  uint16_t type;
  uint16_t combine_len;
};

typedef union {
  struct _io_close i;
} io_close_t;
```

Description: This is the *real* function handler for the client's *close()* or *fclose()* function calls. Note that you'd almost *never* take over this function; you'd leave it as *iofunc_close_dup_default()* in the I/O table. This is because the base layer keeps track of the number of *open()*, *dup()* and *close()* messages issued for a particular OCB, and will then synthesize an *io_close_ocb()* outcall (see below) when the *last close()* message has been received for a particular OCB. Note that the receive IDs present in `ctp->rcvid` may not necessarily match up with those passed to *io_open()*. However, it's guaranteed that at least one receive ID will match the receive ID from the *io_open()* function. The "extra" receive IDs are the result of (possibly internal) *dup()*-type functionality.

Returns: The status via the helper macro _RESMGR_STATUS.

io_close_ocb()

`int io_close_ocb (resmgr_context_t *ctp, void *reserved, RESMGR_OCB_T *ocb)`

Classification: I/O function (synthesized by library)

Default handler: *iofunc_close_default()*

Helper functions: none

Client function: none — synthesized by library

Messages: none — synthesized by library

Data structure:

```
// synthesized by library
struct _io_close {
  uint16_t type;
  uint16_t combine_len;
};

typedef union {
  struct _io_close i;
} io_close_t;
```

Description: This is the function that gets synthesized by the base-layer library when the last *close()* has been received for a particular OCB. This is where you'd perform any final cleanup you needed to do before the OCB is destroyed. Note that the receive ID present in **ctp->rcvid** is zero, because this function is synthesized by the library and doesn't necessarily correspond to any particular message.

Returns: The status via the helper macro _RESMGR_STATUS.

io_devctl()

int io_devctl (resmgr_context_t ***ctp*****, io_devctl_t** ***msg*****, RESMGR_OCB_T** ***ocb*****)**

Classification: I/O

Default handler: *iofunc_devctl_default()*

Helper functions: *iofunc_devctl()*

Client function: *devctl()*, *ioctl()*

Messages: _IO_DEVCTL

Data structure:

```
struct _io_devctl {
  uint16_t type;
  uint16_t combine_len;
  int32_t  dcmd;
  int32_t  nbytes;
  int32_t  zero;
};

struct _io_devctl_reply {
  uint32_t zero;
  int32_t  ret_val;
  int32_t  nbytes;
  int32_t  zero2;
};

typedef union {
  struct _io_devctl       i;
  struct _io_devctl_reply o;
} io_devctl_t;
```

Description: Performs the device I/O operation as passed from the client's *devctl()* in *dcmd*. The client encodes a direction into the top two bits of *dcmd*, indicating how the *devctl()* is to transfer data (the "to" field refers to the _POSIX_DEVDIR_TO bit; the "from" field refers to the _POSIX_DEVDIR_FROM bit):

***to* field**	***from* field**	**Meaning**
0	0	no data transfer
0	1	transfer from driver to client
1	0	transfer from client to driver
1	1	transfer bidirectionally

In the case of no data transfer, the driver is expected to simply perform the command given in *dcmd*. In the case of a data transfer, the driver is expected to transfer the data from and/or to the client, using the helper functions *resmgr_msgreadv()* and *resmgr_msgwritev()*. The client indicates the size of the transfer in the *nbytes* member; the driver is to set the outgoing structure's *nbytes* member to the number of bytes transferred.

Note that the input and output data structures are zero-padded so that they align with each other. This means that the implicit data area begins at the same address in the input and output structures.

If using the helper routine *iofunc_devctl()*, beware that it'll return the constant _RESMGR_DEFAULT in the case where it can't do anything with the *devctl()* message. This return value is there to decouple legitimate *errno* return values from an "unrecognized command" return value. Upon receiving a _RESMGR_DEFAULT, the base-layer library will respond with an *errno* of ENOSYS, which the client's *devctl()* library function will translate into ENOTTY (which is the "correct" POSIX value).

It's up to your function to check the open mode against the operation; no checking is done anywhere in either the client's *devctl()* library or in the resource manager library. For example, it's possible to open a resource manager "read-only" and then issue a *devctl()* to it telling it to "format the hard disk" (which is very much a "write" operation). It would be prudent to verify the open mode first before proceeding with the operation.

Note that the range of *dcmd* values you can use is limited (0x0000 through 0x0FFF inclusive is reserved for QSSL). Other values may be in use; take a look through the include files that have the name `<sys/dcmd_*.h>`.

Returns: The status via the helper macro _RESMGR_STATUS and the reply buffer (with reply data, if required).

For an example, take a look at "A simple *io_devctl()* example," below.

io_dup()

int io_dup (resmgr_context_t ***ctp*****, io_dup_t** ***msg*****, RESMGR_OCB_T** ***ocb*****)**

Classification: I/O

Default handler: NULL — handled by base layer

Helper functions: none

Client function: *dup(), dup2(), fcntl(), fork(), spawn*(), vfork()*

Messages: _IO_DUP

Data structure:

```
struct _io_dup {
  uint16_t          type;
  uint16_t          combine_len;
  struct _msg_info info;
  uint32_t          reserved;
  uint32_t          key;
};

typedef union {
  struct _io_dup    i;
} io_dup_t;
```

Description: This is the *dup()* message handler. As with the *io_close_dup()*, you won't likely handle this message yourself. Instead, the base-layer library will handle it.

Returns: The status via the helper macro _RESMGR_STATUS.

io_fdinfo()

```
int io_fdinfo (resmgr_context_t *ctp, io_fdinfo_t
*msg, RESMGR_OCB_T *ocb)
```

Classification: I/O

Default handler: *iofunc_fdinfo_default()*

Helper functions: *iofunc_fdinfo()*

Client function: *iofdinfo()*

Messages: _IO_FDINFO

Data structure:

```
struct _io_fdinfo {
  uint16_t          type;
  uint16_t          combine_len;
  uint32_t         flags;
  int32_t          path_len;
  uint32_t         reserved;
};

struct _io_fdinfo_reply {
  uint32_t         zero [2];
  struct _fdinfo   info;
};

typedef union {
  struct _io_fdinfo         i;
  struct _io_fdinfo_reply   o;
} io_fdinfo_t;
```

Description: This function is used to allow clients to retrieve information directly about the attributes and pathname which is associated with a file descriptor. The client-side function *iofdinfo()* is used. The path string implicitly follows the **struct _io_fdinfo_reply** data structure. Use of the default function is sufficient for discretely-manifested pathname resource managers.

Returns: The length of the path string being returned is set via the helper macro _IO_SET_FDINFO_LEN.

io_link()

int io_link (resmgr_context_t ***ctp*****, io_link_t** ***msg*****, RESMGR_HANDLE_T** ***handle*****, io_link_extra_t** ***extra*****)**

Classification: Connect

Default handler: none

Helper functions: *iofunc_link()*

Client function: *link()*

Messages: _IO_CONNECT with subtype _IO_CONNECT_LINK

Data structure:

```
struct _io_connect {
  // internal fields (as described above)
  uint16_t path_len;
  uint8_t  extra_type;
  uint16_t extra_len;
  char     path [1];
};

struct _io_connect_link_reply {
  uint32_t reserved1 [2];
  uint8_t  eflag;
  uint8_t  reserved2 [3];
  uint32_t umask;
  uint16_t nentries;
  uint16_t path_len;
};

typedef union {
  struct _io_connect                connect;
  struct _io_connect_link_reply link_reply;
} io_link_t;

typedef union _io_link_extra {
  struct _msg_info                 info;
  void                             *ocb;
  char                             path [1];
  struct _io_resmgr_link_extra     resmgr;
} io_link_extra_t;
```

Description: Creates a new link with the name given in the *path* member of *msg* to the already-existing pathname specified by the *path* member of *extra* (passed to your function). For convenience, the *ocb* member of *extra* contains a pointer to the OCB for the existing pathname.

Returns: The status via the helper macro _RESMGR_STATUS.

io_lock()

```
int io_lock (resmgr_context_t *ctp, io_lock_t *msg,
RESMGR_OCB_T *ocb)
```

Classification: I/O

Default handler: *iofunc_lock_default()*

Helper functions: *iofunc_lock()*

Client functions: *fcntl()*, *lockf()*, *flock()*

Messages: _IO_LOCK

Data structure:

```
struct _io_lock {
  uint16_t                type;
  uint16_t                combine_len;
  uint32_t                subtype;
  int32_t                 nbytes;
};

struct _io_lock_reply {
  uint32_t                zero [3];
};

typedef union {
  struct _io_lock         i;
  struct _io_lock_reply   o;
} io_lock_t;
```

Description: This provides advisory range-based file locking for a device. The default function is most likely sufficient for most resource managers.

Returns: The status via the helper macro _RESMGR_STATUS.

io_lock_ocb()

```
int io_lock_ocb (resmgr_context_t *ctp, void
*reserved, RESMGR_OCB_T *ocb)
```

Classification: I/O (synthesized by library)

Default handler: *iofunc_lock_ocb_default()*

Helper functions: none

Client function: all

Messages: none — synthesized by library

Data structure: none

Description: This function is responsible for locking the attributes structure pointed to by the OCB. This is done to ensure that only one thread at a time is operating on both the OCB and the corresponding attributes structure. The lock (and corresponding unlock) functions are synthesized by the resource manager library before and after completion of message handling. See the section on "Combine messages" above for more details. You'll almost never use this outcall yourself; instead, use the POSIX-layer default function.

Returns: The status via the helper macro _RESMGR_STATUS.

io_lseek()

`int io_lseek (resmgr_context_t *ctp, io_lseek_t *msg, RESMGR_OCB_T *ocb)`

Classification: I/O

Default handler: *iofunc_lseek_default()*

Helper functions: *iofunc_lseek()*

Client function: *lseek(), fseek()*, *rewinddir()*

Messages: _IO_LSEEK

Data structure:

```
struct _io_lseek {
  uint16_t        type;
  uint16_t        combine_len;
  short           whence;
  uint16_t        zero;
  uint64_t        offset;
};
```

```
typedef union {
  struct _io_lseek i;
  uint64_t         o;
} io_lseek_t;
```

Description: Handles the client's *lseek()* function. Note that a resource manager that handles directories will also need to interpret the _IO_LSEEK message for directory operations. The *whence* and *offset* parameters are passed from the client's *lseek()* function. The routine should adjust the OCB's *offset* parameter after interpreting the *whence* and *offset* parameters from the message and should return the new offset or an error.

Returns: The status via the helper macro _RESMGR_STATUS, and optionally (if no error and if not part of a combine message) the current offset.

io_mknod()

```
int io_mknod (resmgr_context_t *ctp, io_mknod_t
*msg, RESMGR_HANDLE_T *handle, void *reserved)
```

Classification: Connect

Default handler: none

Helper functions: *iofunc_mknod()*

Client function: *mknod()*, *mkdir()*, *mkfifo()*

Messages: _IO_CONNECT, subtype _IO_CONNECT_MKNOD

Data structure:

```
struct _io_connect {
  // internal fields (as described above)
  uint16_t path_len;
  uint8_t  extra_type;
  uint16_t extra_len;
  char      path [1];
};

struct _io_connect_link_reply {
  uint32_t reserved1 [2];
  uint8_t  eflag;
  uint8_t  reserved2 [3];
  uint32_t umask;
  uint16_t nentries;
  uint16_t path_len;
};

typedef union {
    struct _io_connect                 connect;
    struct _io_connect_link_reply      link_reply;
} io_mknod_t;
```

Description: Creates a new filesystem entry point. The message is issued to create a file, named by the *path* member, using the filetype encoded in the *mode* member (from the "internal fields" part of the `struct _io_connect` structure, not shown).

This is really used only for the *mkfifo()*, *mkdir()*, and *mknod()* client functions.

Returns: The status via the helper macro _RESMGR_STATUS.

io_mmap()

int io_mmap (resmgr_context_t **ctp*, io_mmap_t **msg*, RESMGR_OCB_T **ocb*)

Classification: I/O

Default handler: *iofunc_mmap_default()*

Helper functions: *iofunc_mmap()*

Client function: *mmap()*, *munmap()*, *mmap_device_io()*, *mmap_device_memory()*

Messages: _IO_MMAP

Data structure:

```
struct _io_mmap {
  uint16_t                type;
  uint16_t                combine_len;
  uint32_t                prot;
  uint64_t                offset;
  struct _msg_info        info;
  uint32_t                zero [6];
};

struct _io_mmap_reply {
  uint32_t                zero;
  uint32_t                flags;
  uint64_t                offset;
  int32_t                 coid;
  int32_t                 fd;
};

typedef union {
  struct _io_mmap         i;
  struct _io_mmap_reply o;
} io_mmap_t;
```

Description: Allows the process manager to *mmap()* files from your resource manager. Generally, you should not code this function yourself (use the defaults provided by *iofunc_func_init()* — the default handler), unless you specifically wish to disable the functionality (for example, a serial port driver could choose to return ENOSYS, because it doesn't make sense to support this operation).

Only the process manager will call this resource manager function.

Note that a side effect of the process manager's calling this function is that an OCB will be created (i.e., *iofunc_ocb_calloc()* will be called), but this should have no consequences to a properly implemented resource manager.

Returns: The status via the helper macro _RESMGR_STATUS.

io_mount()

```
int io_mount (resmgr_context_t *ctp, io_mount_t
*msg, RESMGR_HANDLE_T *handle, io_mount_extra_t
*extra)
```

Classification: Connect

Default handler: none

Client function: *mount()*, *umount()*

Helper functions: none

Messages: _IO_CONNECT with the _IO_CONNECT_MOUNT subtype.

Data structure:

```
struct _io_connect {
  // internal fields (as described above)
  uint16_t path_len;
  uint8_t  extra_type;
  uint16_t extra_len;
  char     path [1];
};

struct _io_connect_link_reply {
  uint32_t reserved1 [2];
  uint8_t  eflag;
  uint8_t  reserved2 [3];
  uint32_t umask;
  uint16_t nentries;
  uint16_t path_len;
};

typedef union {
  struct _io_connect            connect;
  struct _io_connect_link_reply link_reply;
} io_mount_t;
```

Description: This function is called whenever a *mount()* or *umount()* client function sends your resource manager a message. QSSL's Thomas Fletcher has written an excellent article, including some very interesting code examples, that you can find at the following URLs: `http://qdn.qnx.com/articles/apr0601/index.html` (the article) and `http://staff.qnx.com/~thomasf/nto.html` (the code examples).

Returns: The status via the helper macro _IO_SET_CONNECT_RET.

io_msg()

```
int io_msg (resmgr_context_t *ctp, io_msg_t *msg,
RESMGR_OCB_T *ocb)
```

Classification: I/O

Default handler: none.

Helper functions: none.

Client function: none — manually assembled and sent via *MsgSend()*

Messages: _IO_MSG

Data structure:

```
struct _io_msg {
  uint16_t        type;
  uint16_t        combine_len;
  uint16_t        mgrid;
  uint16_t        subtype;
};

typedef union {
  struct _io_msg i;
} io_msg_t;
```

Description: The _IO_MSG interface is a more general, but less portable, variation on the *ioctl()*/*devctl()* theme. The *mgrid* is used to identify a particular manager — you should not perform actions for requests that don't conform to your manager ID. The *subtype* is effectively the command that the client wishes to perform. Any data that's transferred implicitly follows the input structure. Data that's returned to the client is sent on its own, with the status returned via _RESMGR_STATUS. You can get a "manager ID" from QSSL.

Returns: The status via the helper macro _RESMGR_STATUS.

io_notify()

int io_notify (resmgr_context_t ***ctp*, io_notify_t** ***msg*, RESMGR_OCB_T** ***ocb*)**

Classification: I/O

Default handler: none

Helper functions: *iofunc_notify()*, *iofunc_notify_remove()*, *iofunc_notify_trigger()*

Client function: *select()*, *ionotify()*

Messages: _IO_NOTIFY

Data structure:

```
struct _io_notify {
  uint16_t                type;
  uint16_t                combine_len;
  int32_t                 action;
  int32_t                 flags;
  struct sigevent         event;
};

struct _io_notify_reply {
  uint32_t                zero;
  uint32_t                flags;
};

typedef union {
  struct _io_notify       i;
  struct _io_notify_reply o;
} io_notify_t;
```

Description: The handler is responsible for installing, polling, or removing a notification handler. The *action* and *flags* determine the kind of notification operation and conditions; the *event* is a **struct sigevent** structure that defines the notification event (if any) that the client wishes to be signalled with. You'd use the *MsgDeliverEvent()* or *iofunc_notify_trigger()* functions to deliver the *event* to the client.

Returns: The status via the helper macro _RESMGR_STATUS; the flags are returned via message reply.

io_open()

```
int io_open (resmgr_context_t *ctp, io_open_t *msg,
RESMGR_HANDLE_T *handle, void *extra)
```

Classification: Connect

Default handler: *iofunc_open_default()*

Helper functions: *iofunc_open()*, *iofunc_ocb_attach()*

Client function: *open()*, *fopen()*, *sopen()* (and others)

Messages: _IO_CONNECT with one of _IO_CONNECT_COMBINE, _IO_CONNECT_COMBINE_CLOSE or _IO_CONNECT_OPEN subtypes.

Data structure:

```
struct _io_connect {
  // internal fields (as described above)
  uint16_t path_len;
  uint8_t  extra_type;
  uint16_t extra_len;
  char     path [1];
};

struct _io_connect_link_reply {
  uint32_t reserved1 [2];
  uint8_t  eflag;
  uint8_t  reserved2 [3];
  uint32_t umask;
  uint16_t nentries;
  uint16_t path_len;
};

typedef union {
  struct _io_connect            connect;
  struct _io_connect_link_reply link_reply;
} io_open_t;
```

Description: This is the main entry point into the resource manager. It checks that the client indeed has the appropriate permissions to open the file, binds the OCB to the internal library structures (via *resmgr_bind_ocb()*, or *iofunc_ocb_attach()*), and returns an *errno*. Note that not all input and output structure members are relevant for this function.

Returns: The status via the helper macro _IO_SET_CONNECT_RET.

io_openfd()

**int io_openfd (resmgr_context_t ****ctp*, **io_openfd_t ****msg*, **RESMGR_OCB_T ****ocb*)

Classification: I/O

Default handler: *iofunc_openfd_default()*

Helper functions: *iofunc_openfd()*

Client function: *openfd()*

Messages: _IO_OPENFD

Data structure:

```
struct _io_openfd {
  uint16_t        type;
  uint16_t        combine_len;
  uint32_t        ioflag;
  uint16_t          sflag;
  uint16_t          reserved1;
  struct _msg_info  info;
  uint32_t          reserved2;
  uint32_t          key;
};

typedef union {
  struct _io_openfd i;
} io_openfd_t;
```

Description: This function is similar to the handler provided for *io_open()*, except that instead of a pathname, an already-open file descriptor is passed (by virtue of passing you the *ocb* in the function call).

Returns: The status via the helper macro _RESMGR_STATUS.

io_pathconf()

**int io_pathconf (resmgr_context_t ****ctp*, **io_pathconf_t ****msg*, **RESMGR_OCB_T ****ocb*)

Classification: I/O

Default handler: *iofunc_pathconf_default()*

Helper functions: *iofunc_pathconf()*

Client function: *fpathconf()*, *pathconf()*

Messages: _IO_PATHCONF

Data structure:

```
struct _io_pathconf {
  uint16_t          type;
  uint16_t          combine_len;
  short             name;
  uint16_t          zero;
};
```

```
typedef union {
  struct _io_pathconf i;
} io_pathconf_t;
```

Description: The handler for this message is responsible for returning the value of the configurable parameter *name* for the resource associated with this OCB. Use the default function and add additional cases for the *name* member as appropriate for your device.

Returns: The status via the helper macro _IO_SET_PATHCONF_VALUE and the data via message reply.

io_read()

int io_read (resmgr_context_t ***ctp*****, io_read_t** ***msg*****, RESMGR_OCB_T** ***ocb*****)**

Classification: I/O

Default handler: *iofunc_read_default()*

Helper functions: *iofunc_read()*, *iofunc_read_verify()*

Client function: *read()*, *readdir()*

Messages: _IO_READ

Data structure:

```
struct _io_read {
  uint16_t        type;
  uint16_t        combine_len;
  int32_t         nbytes;
  uint32_t        xtype;
};

typedef union {
  struct _io_read i;
} io_read_t;
```

Description: Responsible for reading data from the resource. The client specifies the number of bytes it's prepared to read in the *nbytes* input member. You return the data, advance the offset in the OCB, and update the appropriate time fields.

Note that the *xtype* member may specify a per-read-message override flag. This should be examined. If you don't support any extended override flags, you should return an EINVAL. We'll see the handling of one particularly important (and tricky!) override flag called _IO_XTYPE_OFFSET in the *io_read()* and *io_write()* examples below.

Note also that the _IO_READ message arrives not only for regular files, but also for reading the contents of directories. You must ensure that you return an integral number of `struct dirent` members in the directory case. For more information about returning directory entries, see the example in the "Advanced topics" section under "Returning directory entries."

The helper function *iofunc_read_verify()* should be called to ascertain that the file was opened in a mode compatible with reading. Also, the *iofunc_sync_verify()* function should be called to verify if the data needs to be synchronized to the medium. (For a *read()*, that means that the data returned is guaranteed to be on-media.)

Returns: The number of bytes read, or the status, via the helper macro _IO_SET_READ_NBYTES, and the data itself via message reply.

For an example of returning just data, take a look at "A simple *io_read()* example" below. For a more complicated example of returning both data and directory entries, look in the "Advanced topics" section under "Returning directory entries."

io_readlink()

```
int io_readlink (resmgr_context_t *ctp,
io_readlink_t *msg, RESMGR_HANDLE_T *handle, void
*reserved)
```

Classification: Connect

Default handler: none

Helper functions: *iofunc_readlink()*

Client function: *readlink()*

Messages: _IO_CONNECT with subtype _IO_CONNECT_READLINK

Data structure:

```
struct _io_connect {
  // internal fields (as described above)
  uint16_t path_len;
  uint8_t  extra_type;
  uint16_t extra_len;
  char     path [1];
};

struct _io_connect_link_reply {
  uint32_t reserved1 [2];
  uint8_t  eflag;
  uint8_t  reserved2 [3];
  uint32_t umask;
  uint16_t nentries;
  uint16_t path_len;
};

typedef union {
  struct _io_connect            connect;
  struct _io_connect_link_reply link_reply;
} io_open_t;
```

Description: Responsible for reading the contents of a symbolic link as specified by the *path* member of the input structure. The bytes returned are the contents of the symbolic link; the status returned is the number of bytes in the reply. A valid return should be done only for a symbolic link; all other accesses should return an error code.

Returns: The status via the helper macro _RESMGR_STATUS and the data via message reply.

io_rename()

int io_rename (resmgr_context_t ***ctp*****, io_rename_t *****msg*****, RESMGR_HANDLE_T *****handle*****, io_rename_extra_t *****extra*****)**

Classification: Connect

Default handler: none

Helper functions: *iofunc_rename()*

Client function: *rename()*

Messages: _IO_CONNECT with subtype _IO_CONNECT_RENAME

Data structure:

```
struct _io_connect {
  // internal fields (as described above)
  uint16_t path_len;
  uint8_t  extra_type;
  uint16_t extra_len;
  char     path [1];
};

struct _io_connect_link_reply {
  uint32_t reserved1 [2];
  uint8_t  eflag;
  uint8_t  reserved2 [3];
  uint32_t umask;
  uint16_t nentries;
  uint16_t path_len;
};

typedef union _io_rename_extra {
  char     path [1];
} io_rename_extra_t;

typedef union {
  struct _io_connect            connect;
  struct _io_connect_link_reply link_reply;
} io_rename_t;
```

Description: Performs the rename operation, given the new name in *path* and the original name in the *path* member of the passed *extra* parameter. Implementation note: the *pathname* of the original name is given (rather than an OCB) specifically for the case of handling a rename of a file that's hard-linked to another file. If the OCB were given, there would be no way to tell apart the two (or more) versions of the hard-linked file.

This function will be called only with two filenames that are on the same filesystem (same device). Therefore, there's no need to check for a case where you'd return EXDEV. This doesn't prevent you from returning EXDEV if you don't wish to perform the *rename()* yourself (for example, it may be very complicated to do the rename operation from one directory to another). In the case of returning EXDEV, the shell utility **mv** will perform a **cp** followed by an **rm** (the C library function *rename()* will do no such thing — it will return only an *errno* of EXDEV).

Also, all symlinks will be resolved, where applicable, before this function is called, and the pathnames passed will be absolute and rooted in the filesystem for which this resource manager is responsible.

Returns: The status via the helper macro _RESMGR_STATUS.

io_shutdown()

```
int io_shutdown (resmgr_context_t *ctp,
io_shutdown_t *msg, RESMGR_OCB_T *ocb)
```

This function is reserved by QSSL for future use. You should initialize the I/O table using *iofunc_func_init()* and not modify this entry.

io_space()

int io_space (resmgr_context_t ***ctp*****, io_space_t** ***msg*****, RESMGR_OCB_T** ***ocb*****)**

Classification: I/O

Default handler: none

Helper functions: *iofunc_space_verify()*

Client function: *chsize(), fcntl(), ftruncate(), ltrunc()*

Messages: _IO_SPACE

Data structure:

```
struct _io_space {
  uint16_t          type;
  uint16_t          combine_len;
  uint16_t          subtype;
  short             whence;
  uint64_t          start;
  uint64_t          len;
};

typedef union {
  struct _io_space i;
  uint64_t          o;
} io_space_t;
```

Description: This is used to allocate or free space occupied by the resource. The *subtype* parameter indicates whether to allocate (if set to F_ALLOCSP) or deallocate (if set to F_FREESP) storage space. The combination of *whence* and *start* give the location where the beginning of the allocation or deallocation should occur; the member *len* indicates the size of the operation.

Returns: The number of bytes (size of the resource) via the helper macro _RESMGR_STATUS.

io_stat()

```
int io_stat (resmgr_context_t *ctp, io_stat_t *msg,
RESMGR_OCB_T *ocb)
```

Classification: I/O

Default handler: *iofunc_stat_default()*

Helper functions: *iofunc_stat()*

Client function: *stat()*, *lstat()*, *fstat()*

Messages: _IO_STAT

Data structure:

```
struct _io_stat {
  uint16_t        type;
  uint16_t        combine_len;
  uint32_t        zero;
};

typedef union {
  struct _io_stat i;
  struct stat     o;
} io_stat_t;
```

Description: Handles the message that requests information about the resource associated with the passed OCB. Note that the attributes structure contains all the information required to fulfill the *stat()* request; the helper function *iofunc_stat()* fills a `struct stat` structure based on the attributes structure. Also, the helper function modifies the stored *dev*/*rdev* members to be unique from a single node's point of view (useful for performing *stat()* calls to files over a network). There's almost no reason to write your own handler for this function.

Returns: The status via the helper macro _RESMGR_STATUS and the `struct stat` via message reply.

io_sync()

```
int io_sync (resmgr_context_t *ctp, io_sync_t *msg,
RESMGR_OCB_T *ocb)
```

Classification: I/O

Default handler: *iofunc_sync_default()*

Helper functions: *iofunc_sync_verify()*, *iofunc_sync()*

Client function: *fsync()*, *fdatasync()*

Messages: _IO_SYNC

Data structure:

```
struct _io_sync {
  uint16_t          type;
  uint16_t          combine_len;
  uint32_t          flag;
};

typedef union {
  struct _io_sync i;
} io_sync_t;
```

Description: This is the entry point for a flush command. The helper function *iofunc_sync()* is passed the *flag* member from the input message, and returns one of the following values, which indicate what actions your resource manager must take:

- 0 — do nothing.
- O_SYNC — everything associated with the file (including the file contents, directory structures, inodes, etc.) must be present and recoverable from media.

- O_DSYNC — only the data portion of the file must be present and recoverable from media.

Note that this outcall will occur only if you've agreed to provide sync services by setting the mount structure flag.

Returns: Returns the status via the helper macro _RESMGR_STATUS.

io_unblock() [CONNECT]

int io_unblock (resmgr_context_t ***ctp*, io_pulse_t** ***msg*, RESMGR_HANDLE_T** ***handle*, void** ***reserved*)**

Classification: Connect (synthesized by kernel, synthesized by library)

Default handler: none

Helper functions: *iofunc_unblock()*

Client function: none — kernel action due to signal or timeout

Messages: none — synthesized by library

Data structure: (See I/O version of *io_unblock()*, next)

Description: This is the connect message version of the unblock outcall, synthesized by the library as a result of a kernel pulse due to the client's attempt to unblock during the connect message phase. See the I/O version of *io_unblock()* for more details.

Returns: The status via the helper macro _RESMGR_STATUS.

See the section in the Message Passing chapter, titled "Using the _NTO_MI_UNBLOCK_REQ" for a detailed discussion of unblocking strategies.

io_unblock() [I/O]

`int io_unblock (resmgr_context_t *ctp, io_pulse_t *msg, RESMGR_OCB_T *ocb)`

Classification: I/O (synthesized by kernel, synthesized by library)

Default handler: *iofunc_unblock_default()*

Helper functions: *iofunc_unblock()*

Client function: none — kernel action due to signal or timeout

Messages: none — synthesized by library

Data structure: pointer to message structure being interrupted

Description: This is the I/O message version of the unblock outcall, synthesized by the library as a result of a kernel pulse due to the client's attempt to unblock during the I/O message phase. The connect message phase *io_unblock()* handler is substantially the same (see the preceding section).

Common to both unblock handlers (connect and I/O) is the characteristic that the client wishes to unblock, but is at the mercy of the resource manager. The resource manager *must* reply to the client's message in order to unblock the client. (This is discussed in the Message Passing chapter when we looked at the *ChannelCreate()* flags, particularly the _NTO_CHF_UNBLOCK flag).

Returns: The status via the helper macro _RESMGR_STATUS.

See the section in the Message Passing chapter, titled "Using the _NTO_MI_UNBLOCK_REQ" for a detailed discussion of unblocking strategies.

io_unlink()

```
int io_unlink (resmgr_context_t *ctp, io_unlink_t
*msg, RESMGR_HANDLE_T *handle, void *reserved)
```

Classification: Connect

Default handler: none

Helper functions: *iofunc_unlink()*

Client function: *unlink()*

Messages: _IO_CONNECT with subtype _IO_CONNECT_UNLINK

Data structure:

```
struct _io_connect {
  // internal fields (as described above)
  uint16_t path_len;
  uint8_t  extra_type;
  uint16_t extra_len;
  char     path [1];
};

struct _io_connect_link_reply {
  uint32_t reserved1 [2];
  uint8_t  eflag;
  uint8_t  reserved2 [3];
  uint32_t umask;
  uint16_t nentries;
  uint16_t path_len;
};

typedef union {
  struct _io_connect            connect;
  struct _io_connect_link_reply link_reply;
} io_unlink_t;
```

Description: Responsible for unlinking the file whose pathname is passed in the input message structure's *path* member.

Returns: The status via the helper macro _RESMGR_STATUS.

io_unlock_ocb()

int io_unlock_ocb (resmgr_context_t ***ctp*****, void** ***reserved*****, RESMGR_OCB_T** ***ocb*****)**

Classification: I/O (synthesized by library)

Default handler: *iofunc_unlock_ocb_default()*

Helper functions: none

Client function: all

Messages: none — synthesized by library

Data structure: none

Description: Inverse of *io_lock_ocb()* above. That is, it's responsible for unlocking the attributes structure pointed to by the OCB. This operation releases the attributes structure so that other threads in the resource manager may operate on it. See the section on "Combine messages" above for more details.

Returns: The status via the helper macro _RESMGR_STATUS.

io_utime()

int io_utime (resmgr_context_t ***ctp*****, io_utime_t** ***msg*****, RESMGR_OCB_T** ***ocb*****)**

Classification: I/O

Default handler: *iofunc_utime_default()*

Helper functions: *iofunc_utime()*

Client function: *utime()*

Messages: _IO_UTIME

Data structure:

```
struct _io_utime {
  uint16_t          type;
  uint16_t          combine_len;
  int32_t           cur_flag;
  struct utimbuf    times;
};

typedef union {
  struct _io_utime i;
} io_utime_t;
```

Description: Changes the access and modification times to either "now" (if they are zero) or the specified values. Note that this message handler may be required to modify the IOFUNC_ATTR_* flags in the attribute structure as per POSIX rules. You'll almost never use this outcall yourself, but will instead use the POSIX-layer helper function.

Returns: The status via the helper macro _RESMGR_STATUS.

io_write()

```
int io_write (resmgr_context_t *ctp, io_write_t
*msg, RESMGR_OCB_T *ocb)
```

Classification: I/O

Default handler: *iofunc_write_default()*

Helper functions: *iofunc_write_verify()*

Client function: *write()*, *fwrite()*, etc.

Messages: _IO_WRITE

Data structure:

```
struct _io_write {
  uint16_t          type;
  uint16_t          combine_len;
  int32_t          nbytes;
  uint32_t         xtype;
};

typedef union {
  struct _io_write i;
} io_write_t;
```

Description: This message handler is responsible for getting data that the client wrote to the resource manager. It gets passed the number of bytes the client is attempting to write in the *nbytes* member; the data implicitly follows the input data structure (unless the *xtype* override is _IO_XTYPE_OFFSET; see "A simple *io_write()* example" below!) The implementation will need to re-read the data portion of the message from the client, using *resmgr_msgreadv()* or equivalent. The return status is the number of bytes actually written or an *errno*.

Note that the helper function *iofunc_write_verify()* should be called to ascertain that the file was opened in a mode compatible with writing. Also, the *iofunc_sync_verify()* function should be called to verify if the data needs to be synchronized to the medium.

Returns: The status via the helper macro _IO_SET_WRITE_NBYTES.

For an example, take a look at "A simple *io_write()* example" below.

Examples

I'm now going to show you a number of "cookbook" examples you can cut and paste into your code, to use as a basis for your projects. These aren't complete resource managers — you'll need to add the thread pool and dispatch "skeleton" shown immediately below, and ensure that your versions of the I/O functions are placed into the I/O functions table *after* you've done the *iofunc_func_init()*, in order to override the defaults!

I'll start with a number of simple examples that show basic functionality for the various resource manager message handlers:

- *io_read()*
- *io_write()*
- *io_devctl()* (without data transfer)
- *io_devctl()* (with data transfer)

And then in the advanced topics section, we'll look at an *io_read()* that returns directory entries.

The basic skeleton of a resource manager

The following can be used as a template for a resource manager with multiple threads. (We've already seen a template that can be used for a single-threaded resource manager above in "The resource manager library," when we discussed a **/dev/null** resource manager).

```
/*
 * rms.c
*/

#include <stdio.h>
#include <stdlib.h>
#include <stddef.h>
#include <sys/iofunc.h>
#include <sys/dispatch.h>

static resmgr_connect_funcs_t   connect_func;
static resmgr_io_funcs_t        io_func;
static iofunc_attr_t            attr;

int
main (int argc, char **argv)
{
    thread_pool_attr_t    pool_attr;
    thread_pool_t         *tpp;
    dispatch_t            *dpp;
    resmgr_attr_t         resmgr_attr;
    resmgr_context_t      *ctp;
    int                    id;

    if ((dpp = dispatch_create ()) == NULL) {
        fprintf (stderr, "%s:  Unable to dispatch_create.\n",
                 argv [0]);
        return (EXIT_FAILURE);
    }

    memset (&pool_attr, 0, sizeof (pool_attr));
    pool_attr.handle = dpp;
    pool_attr.context_alloc = resmgr_context_alloc;
    pool_attr.block_func = resmgr_block;
    pool_attr.handler_func = resmgr_handler;
    pool_attr.context_free = resmgr_context_free;

    // 1) set up the number of threads that you want
    pool_attr.lo_water = 2;
    pool_attr.hi_water = 4;
    pool_attr.increment = 1;
    pool_attr.maximum = 50;

    tpp = thread_pool_create (&pool_attr, POOL_FLAG_EXIT_SELF);
    if (tpp == NULL) {
        fprintf (stderr, "%s:  Unable to thread_pool_create.\n",
                 argv [0]);
        return (EXIT_FAILURE);
    }

    iofunc_func_init (_RESMGR_CONNECT_NFUNCS, &connect_func,
                      _RESMGR_IO_NFUNCS, &io_func);
    iofunc_attr_init (&attr, S_IFNAM | 0777, 0, 0);

    // 2) override functions in "connect_func" and "io_func"
    //    as required here
    ...

    memset (&resmgr_attr, 0, sizeof (resmgr_attr));
    resmgr_attr.nparts_max = 1;
    resmgr_attr.msg_max_size = 2048;

    // 3) replace "/dev/whatever" with your device name
    id = resmgr_attach (dpp, &resmgr_attr, "/dev/whatever",
                         _FTYPE_ANY, 0,
                         &connect_func, &io_func,
                         &attr);
    if (id == -1) {
        fprintf (stderr, "%s:  Unable to resmgr_attach\n",
                 argv [0]);
        return (EXIT_FAILURE);
    }

    // Never returns
    thread_pool_start (tpp);

    // so you'll never get here
    return (EXIT_SUCCESS);
}
```

For more information about the dispatch interface (i.e., the *dispatch_create()* function), see the documentation in the *C Library Reference.*

Step 1 Here you'd use the thread pool functions to create a pool of threads that will be able to service messages in your resource manager. Generally, I recommend that you start off with a single-threaded resource manager, as we did with the `/dev/null` example mentioned above. Once you have the basic functionality running, you can *then* add threads. You'd modify the *lo_water*, *hi_water*, *increment*, and *maximum* members of the *pool_attr* structure as described in the "Threads & Processes" chapter where we discuss the thread pool functions.

Step 2 Here you'd add whatever functions *you* want to supply. These are the outcalls we just discussed (e.g. *io_read()*, *io_devctl()*, etc.) For example, to add your own handler for the _IO_READ message that points to a function supplied by you called *my_io_read()*, you'd add the following line of code:

```
io_func.io_read = my_io_read;
```

This will override the POSIX-layer default function that got put into the table by *iofunc_func_init()* with a pointer to your function, *my_io_read()*.

Step 3 You probably don't want your resource manager called `/dev/whatever`, so you should select an appropriate name. Note that the *resmgr_attach()* function is where you bind the attributes structure (the *attr* parameter) to the name — if you wish to have multiple devices handled by your resource manager, you'd call *resmgr_attach()* multiple times, with different attributes structures (so that you could tell the different registered names apart at runtime).

A simple *io_read()* example

To illustrate how your resource manager might return data to a client, consider a simple resource manager that always returns the constant string ``Hello, world!\n''. There are a number of issues involved, even in this very simple case:

- matching of client's data area size to data being returned
- handling of EOF case
- maintenance of context information (the *lseek()* index)
- updating of POSIX *stat()* information

Data area size considerations

In our case, the resource manager is returning a fixed string of 14 bytes — there is exactly that much data available. This is identical to a read-only file on a disk that contains the string in question; the only real difference is that this "file" is maintained in our C program via the statement:

```
char    *data_string = "Hello, world!\n";
```

The client, on the other hand, can issue a *read()* request of any size — the client could ask for one byte, 14 bytes, or more. The impact of this on the *io_read()* functionality you're going to provide is that you must be able to match the client's requested data size with what's available.

Handling of EOF case

A natural fallout of the way you handle the client's data area size considerations is the corner case of dealing with the End-Of-File (EOF) on the fixed string. Once the client has read the final "\n" character, further attempts by the client to read more data should return EOF.

Maintenance of context information

Both the "Data area size considerations" and the "Handling of EOF case" scenarios will require that context be maintained in the OCB passed to your *io_read()* function, specifically the *offset* member.

Updating POSIX information

One final consideration: when data is read from a resource manager, the POSIX *access time* (*atime*) variable needs to be updated. This is so that a client *stat()* function will show that someone has indeed accessed the device.

The code

Here's the code that addresses all the above points. We'll go through it step-by-step in the discussion that follows:

```
/*
 * io_read1.c
*/

#include <stdio.h>
#include <errno.h>
#include <sys/neutrino.h>
#include <sys/iofunc.h>

// our data string
char    *data_string = "Hello, world!\n";

int
io_read (resmgr_context_t *ctp, io_read_t *msg,
         iofunc_ocb_t *ocb)
{
    int     sts;
    int     nbytes;
    int     nleft;
    int     off;
    int     xtype;
    struct _xtype_offset *xoffset;

    // 1) verify that the device is opened for read
    sts = iofunc_read_verify (ctp, msg, ocb, NULL);
    if (sts != EOK) {
        return (sts);
    }

    // 2) check for and handle an XTYPE override
    xtype = msg -> i.xtype & _IO_XTYPE_MASK;
    if (xtype == _IO_XTYPE_OFFSET) {
        xoffset = (struct _xtype_offset *) (&msg -> i + 1);
        off = xoffset -> offset;
    } else if (xtype == _IO_XTYPE_NONE) {
        off = ocb -> offset;
    } else {   // unknown, fail it
        return (ENOSYS);
    }
    // 3) how many bytes are left?
    nleft = ocb -> attr -> nbytes - off;

    // 4) how many bytes can we return to the client?
    nbytes = min (nleft, msg -> i.nbytes);

    // 5) if returning data, write it to client
    if (nbytes) {
        MsgReply (ctp -> rcvid, nbytes, data_string + off,
                  nbytes);

        // 6) set up POSIX stat() "atime" data
        ocb -> attr -> flags |= IOFUNC_ATTR_ATIME
                             | IOFUNC_ATTR_DIRTY_TIME;

        // 7) advance the lseek() index by the number of bytes
        //    read if not _IO_XTYPE_OFFSET
        if (xtype == _IO_XTYPE_NONE) {
            ocb -> offset += nbytes;
        }
    } else {
        // 8) not returning data, just unblock client
        MsgReply (ctp -> rcvid, EOK, NULL, 0);
    }

    // 9) indicate we already did the MsgReply to the library
    return (_RESMGR_NOREPLY);
}
```

Step 1 Here we ensured that the client's *open()* call had in fact specified that the device was to be opened for reading. If the client opened the device for writing only, and then attempted to perform a read from it, it would be considered an error. In that case, the helper function *iofunc_read_verify()* would return EBADF, and not EOK, so we'd return that value to the library, which would then pass it along to the client.

Step 2 Here we checked to see if the client had specified an *xtype-override* — a per-message override (e.g., because while the device had been opened in non-blocking mode, this specifies for this one request that we'd like blocking behavior). Note that the blocking aspect of the "xtype" override can be noted by the *iofunc_read_verify()* function's last parameter — since we're illustrating a very simple example, we just passed in a NULL indicating that we don't care about this aspect.

More important, however, is to see how particular "xtype" modifiers are handled. An interesting one is the _IO_XTYPE_OFFSET modifier, which, if present, indicates that the message passed from the client contains an offset and that the read operation should *not* modify the "current file position" of the file descriptor (this is used by the function *pread()*, for example). If the _IO_XTYPE_OFFSET modifier is not present, then the read operation can go ahead and modify the "current file position." We use the variable *xtype* to store the "xtype" that we received in the message, and the variable *off* to represent the current offset that we should be using during processing. You'll see some additional handling of the _IO_XTYPE_OFFSET modifier below, in step 7.

If there is a different "xtype override" than _IO_XTYPE_OFFSET (and not the no-op one of _IO_XTYPE_NONE), we fail the request with ENOSYS. This simply means that we don't know how to handle it, and we therefore return the error up to the client.

Steps 3 & 4 To calculate how many bytes we can actually return to the client, we perform steps 3 and 4, which figure out how many bytes are available on the device (by taking the total device size from `ocb -> attr -> nbytes` and subtracting the current offset into the device). Once we know how many bytes are left, we take the smaller of that number and the number of bytes that the client specified that they wish to read. For example, we may have seven bytes left, and the client wants to only read two. In that case, we can return only two bytes to the client. Alternatively, if the client wanted 4096 bytes, but we had only seven left, we could return only seven bytes.

Step 5 Now that we've calculated how many bytes we're going to return to the client, we need to do different things based on whether or not we're returning data. If we are returning data, then after the check in step 5, we reply to the client with the data. Notice that we use `data_string + off` to return data starting at the correct offset (the *off* is calculated based on the xtype override). Also notice the second parameter to *MsgReply()* — it's documented as the *status* argument, but in this case we're using it to return the number of bytes. This is because the implementation of the client's *read()* function knows that the return value from its *MsgSendv()* (which is the *status* argument to *MsgReply()*, by the way) is the number of bytes that were read. This is a common convention.

Step 6 Since we're returning data from the device, we know that the device has been accessed. We set the IOFUNC_ATTR_ATIME and IOFUNC_ATTR_DIRTY_TIME bits in the *flags* member of the attribute structure. This serves as a reminder to the *io_stat()* function that the access time is not valid and should be fetched from the system clock before replying. If we really wanted to, we could have stuffed the current time into the *atime* member of the attributes structure, and cleared the IOFUNC_ATTR_DIRTY_TIME flag. But this isn't very efficient, since we're expecting to get a lot more *read()* requests from the client than *stat()* requests. However, your usage patterns may dictate otherwise.

☞ So which time does the client see when it finally *does* call *stat()*? The *iofunc_stat_default()* function provided by the resource manager library will look at the *flags* member of the attribute structure to see if the times are valid (the *atime*, *ctime*, and *mtime* fields). If they are not (as will be the case after our *io_read()* has been called that returned data), the *iofunc_stat_default()* function will update the time(s) with the current time. The real value of the time is also updated on a *close()*, as you'd expect.

Step 7 Now we advance the *lseek()* offset by the number of bytes that we returned to the client, only if we are *not* processing the _IO_XTYPE_OFFSET override modifier. This ensures that, in the non-_IO_XTYPE_OFFSET case, if the client calls *lseek()* to get the current position, or (more importantly) when the client calls *read()* to get the next few bytes, the offset into the resource is set to the correct value. In the case of the _IO_XTYPE_OFFSET override, we leave the *ocb* version of the offset alone.

Step 8 Contrast step 6 with this step. Here we only unblock the client, we don't perform any other functions. Notice also that there is no data area specified to the *MsgReply()*, because we're not returning data.

Step 9 Finally, in step 9, we perform processing that's common regardless of whether or not we returned data to the client. Since we've already unblocked the client via the *MsgReply()*, we certainly don't want the resource manager library doing that for us, so we tell it that we've already done that by returning _RESMGR_NOREPLY.

Effective use of other messaging functions

As you'll recall from the Message Passing chapter, we discussed a few other message-passing functions — namely *MsgWrite()*, *MsgWritev()*, and *MsgReplyv()*. The reason I'm mentioning them here again is because your *io_read()* function may be in an excellent position to use these functions. In the simple example shown above, we were returning a contiguous array of bytes from one memory location. In the real world, you may need to return multiple pieces of data from various buffers that you've allocated. A classical example of this is a ring buffer, as might be found in a serial device driver. Part of the data may be near the end of the buffer, with the rest of it "wrapped" to the top of the buffer. In this case, you'll want to use a two-part IOV with *MsgReplyv()* to return both parts. The first part of the IOV would contain the address (and length) of the bottom part of the data, and the second part of the IOV would contain the address (and length) of the top part of the data. Or, if the data is going to arrive in pieces, you may instead choose to use *MsgWrite()* or *MsgWritev()* to place the data into the client's address space as it arrives and then specify a final *MsgReply()* or *MsgReplyv()* to unblock the client. As we've seen above, there's no requirement to actually *transfer* data with the *MsgReply()* function — you can use it to simply unblock the client.

A simple *io_write()* example

The *io_read()* example was fairly simple; let's take a look at *io_write()*. The major hurdle to overcome with the *io_write()* is to access the data. Since the resource manager library reads in a small portion of the message from the client, the data content that the client sent (immediately after the _IO_WRITE header) may have only partially arrived at the *io_write()* function. To illustrate this, consider the client writing one megabyte — only the header and a few bytes of the data will get read by the resource manager library. The rest of the megabyte of data is still available on the client side — the resource manager can access it at will.

There are really two cases to consider:

- the entire contents of the client's *write()* message were read by the resource manager library, or
- they were not.

The real design decision, however, is, "how much trouble is it worth to try to save the kernel copy of the data already present?" The answer is that it's not worth it. There are a number of reasons for this:

- Message passing (the kernel copy operation) is extremely fast.
- There is overhead required to see if the data all fits or not.
- There is additional overhead in trying to "save" the first dribble of data that arrived, in light of the fact that more data is waiting.

I think the first two points are self-explanatory. The third point deserves clarification. Let's say the client sent us a large chunk of data, and we *did* decide that it would be a good idea to try to save the part of the data that had already arrived. Unfortunately, that part is very small. This means that instead of being able to deal with the large chunk all as one contiguous array of bytes, we have to deal with it as one small part plus the rest. Effectively, we have to "special case" the small part, which may have an impact on the overall efficiency of the code that deals with the data. This can lead to headaches, so don't do this!

The real answer, then, is to simply re-read the data into buffers that you've prepared. In our simple *io_write()* example, I'm just going to *malloc()* the buffer each time, read the data into the buffer, and then release the buffer via *free()*. Granted, there are certainly far more efficient ways of allocating and managing buffers!

One further wrinkle introduced in the *io_write()* example is the handling of the _IO_XTYPE_OFFSET modifier (and associated data; it's done slightly differently than in the *io_read()* example).

Here's the code:

```
/*
 * io_write1.c
*/

#include <stdio.h>
#include <stdlib.h>
#include <errno.h>
#include <sys/neutrino.h>
#include <sys/iofunc.h>

void
process_data (int offet, void *buffer, int nbytes)
{
    // do something with the data
}

int
io_write (resmgr_context_t *ctp, io_write_t *msg,
          iofunc_ocb_t *ocb)
{
    int     sts;
    int     nbytes;
    int     off;
    int     doffset;
    int     xtype;
    char    *buffer;
    struct _xtype_offset *xoffset;

    // verify that the device is opened for write
    sts = iofunc_write_verify (ctp, msg, ocb, NULL);
    if (sts != EOK) {
        return (sts);
    }

    // 1) check for and handle an XTYPE override
    xtype = msg -> i.xtype & _IO_XTYPE_MASK;
    if (xtype == _IO_XTYPE_OFFSET) {
        xoffset = (struct _xtype_offset *) (&msg -> i + 1);
        doffset = sizeof (msg -> i) + sizeof (*xoffset);
        off = xoffset -> offset;
    } else if (xtype == _IO_XTYPE_NONE) {
        off = ocb -> offset;
        doffset = sizeof (msg -> i);
    } else {   // unknown, fail it
        return (ENOSYS);
    }

    // 2) allocate a buffer big enough for the data
    nbytes = msg -> i.nbytes;
    if ((buffer = malloc (nbytes)) == NULL) {
        return (ENOMEM);
    }

    // 3) (re-)read the data from the client
    if (resmgr_msgread (ctp, buffer, nbytes, doffset) == -1) {
        free (buffer);
        return (errno);
    }

    // 4) do something with the data
    process_data (off, buffer, nbytes);

    // 5) free the buffer
    free (buffer);

    // 6) set up the number of bytes for the client's
    //    "write" function to return
    _IO_SET_WRITE_NBYTES (ctp, nbytes);

    // 7) if any data written, update POSIX structures and
    //    OCB offset
    if (nbytes) {
        ocb -> attr -> flags |= IOFUNC_ATTR_MTIME
                             | IOFUNC_ATTR_DIRTY_TIME;
        if (xtype == _IO_XTYPE_NONE) {
            ocb -> offset += nbytes;
        }
    }

    // 8) tell the resource manager library to do the reply,
    //    and that it was okay
    return (EOK);
}
```

As you can see, a few of the initial operations performed were identical to those done in the *io_read()* example — the *iofunc_write_verify()* is analogous to the *iofunc_read_verify()* function, and the xtype override check is the same.

Step 1 Here we performed much the same processing for the "xtype override" as we did in the *io_read()* example, except for the fact that the offset is *not* stored as part of the incoming message structure. The reason it's not stored there is because a common practice is to use the size of the incoming message structure to determine the starting point of the actual data being transferred from the client. We take special pains to ensure the offset of the start of the data (*doffset*) is correct in the xtype handling code.

Step 2 Here we allocate a buffer that's big enough for the data. The number of bytes that the client is writing is presented to us in the *nbytes* member of the *msg* union. This is stuffed automatically by the client's C library in the *write()* routine. Note that if we don't have sufficient memory to handle the *malloc()* request, we return the error number ENOMEM to the client — effectively, we're passing on the return code to the client to let it know why its request wasn't completed.

Step 3 Here we use the helper function *resmgr_msgread()* to read the entire data content from the client directly into the newly allocated buffer. In most cases we could have just used *MsgRead()*, but in the case where this message is part of a "combine message," *resmgr_msgread()* performs the appropriate "magic" for us (see the "Combine message" section for more information on *why* we need to do this.) The parameters to *resmgr_msgread()* are fairly straightforward; we give it the internal context pointer (*ctp*), the buffer into which we want the data placed (*buffer*), and the number of bytes that we wish read (the *nbytes* member of the message *msg* union). The last parameter is the offset into the current message, which we calculated above, in step 1. The offset effectively skips the header information that the client's C library implementation of *write()* put there, and proceeds directly to the data. This actually brings about two interesting points:

- We could use an arbitrary offset value to read chunks of the client's data in any order and size we want.

- We could use *resmgr_msgreadv()* (note the "v") to read data from the client into an IOV, perhaps describing various buffers, similar to what we did with the cache buffers in the filesystem discussion in the Message Passing chapter.

Step 4 Here you'd do whatever you want with the data — I've just called a made-up function called *process_data()* and passed it the buffer and size.

Step 5 This step is crucial! Forgetting to do it is easy, and will lead to "memory leaks." Notice how we also took care to free the memory in the case of a failure in step 3.

Step 6 We're using the macro *_IO_SET_WRITE_NBYTES()* to store the number of bytes we've written, which will then be passed back to the client as the return value from the client's *write()*. It's important to note that you should return the *actual* number of bytes! The client is depending on this.

Step 7 Now we do similar housekeeping for *stat()*, *lseek()*, and further *write()* functions as we did for the *io_read()* routine (and again, we modify the offset in the *ocb* only in the case of this *not* being a _IO_XTYPE_OFFSET type of message). Since we're writing to the device, however, we use the IOFUNC_ATTR_MTIME constant instead of the IOFUNC_ATTR_ATIME constant. The MTIME flag means "modification" time, and a *write()* to a resource certainly "modifies" it.

Step 8 The last step is simple: we return the constant EOK, which tells the resource manager library that it should reply to the client. This ends our processing. The resource manager will use the number of bytes that we stashed away with the *_IO_SET_WRITE_NBYTES()* macro in the reply and the client will unblock; the client's C library *write()*

function will return the number of bytes that were written by our device.

A simple *io_devctl()* example

The client's *devctl()* call is formally defined as:

```
#include <sys/types.h>
#include <unistd.h>
#include <devctl.h>

int
devctl (int fd,
        int dcmd,
        void *dev_data_ptr,
        size_t nbytes,
        int *dev_info_ptr);
```

We should first understand this function before we look at the resource manager side of things. The *devctl()* function is used for "out of band" or "control" operations. For example, you may be writing data to a sound card (the actual digital audio samples that the sound card should convert to analog audio), and you may decide that you need to change the number of channels from 1 (mono) to 2 (stereo), or the sampling rate from the CD-standard (44.1 kHz) to the DAT-standard (48 kHz). The *devctl()* function is the appropriate way to do this. When you write a resource manager, you may find that you don't need any *devctl()* support at all and that you can perform all the functionality needed simply through the standard *read()* and *write()* functions. You may, on the other hand, find that you need to mix *devctl()* calls with the *read()* and *write()* calls, or indeed that your device uses only *devctl()* functions and does *not* use *read()* or *write()*.

The *devctl()* function takes 5 arguments:

fd The file descriptor of the resource manager that you're sending the *devctl()* to.

dcmd The command itself — a combination of two bits worth of direction, and 30 bits worth of command (see discussion below).

dev_data_ptr A pointer to a data area that can be sent to, received from, or both.

nbytes The size of the *dev_data_ptr* data area.

dev_info_ptr An extra information variable that can be set by the resource manager.

The top two bits in the *dcmd* encode the direction of data transfer, if any. For details, see the description in the I/O reference section (under *io_devctl()*).

When the _IO_DEVCTL message is received by the resource manager, it's handled by your *io_devctl()* function. Here is a very simple example, which we'll assume is used to set the number of channels and the sampling rate for the audio device we discussed above:

```
/*
 * io_devctl1.c
*/

int
io_devctl (resmgr_context_t *ctp, io_devctl_t *msg,
           iofunc_ocb_t *ocb)
{
    int     sts;

    // 1) see if it's a standard POSIX-supported devctl()
    sts = iofunc_devctl_default (ctp, msg, ocb);
    if (sts != _RESMGR_DEFAULT) {
        return (sts);
    }

    // 2) see which command it was, and act on it
    switch (msg -> i.dcmd) {
    case    DCMD_AUDIO_SET_CHANNEL_MONO:
        audio_set_nchannels (1);
        break;
    case    DCMD_AUDIO_SET_CHANNEL_STEREO:
        audio_set_nchannels (2);
        break;
    case    DCMD_AUDIO_SET_SAMPLE_RATE_CD:
        audio_set_samplerate (44100);
        break;
    case    DCMD_AUDIO_SET_SAMPLE_RATE_DAT:
        audio_set_samplerate (48000);
        break;

    // 3) in case it's a command that we don't
    //    recognize, fail it
    default:
        return (ENOSYS);
    }

    // 4) tell the client it worked
    memset (&msg -> o, 0, sizeof (msg -> o));
    SETIOV (ctp -> iov, &msg -> o, sizeof (msg -> o));
    return (_RESMGR_NPARTS (1));
}
```

Step 1 In the first step, we see again the use of a helper function, this time *iofunc_devctl_default()*, which is used to perform all default processing for the *devctl()* function. If you didn't supply your own *io_devctl()*, and just let *iofunc_func_init()* initialize the I/O and connect functions tables for you, the *iofunc_devctl_default()* function is what would get called. We include it in our *io_devctl()* function because we want it to handle all the regular POSIX *devctl()* cases for us. We examine the return value; if it's not _RESMGR_DEFAULT, then this means that the *iofunc_devctl_default()* function "handled" the request, so we just pass along its return value as our return value.

If the constant _RESMGR_DEFAULT *is* the return value, then we know that the helper function *didn't* handle the request and that we should check to see if it's one of ours.

Step 2 This checking is done in step 2 via the `switch/case` statement. We simply compare the *dcmd* values that the client code would have stuffed into the second argument to *devctl()* to see if there's a match. Note that we call the fictitious functions *audio_set_nchannels()* and *audio_set_samplerate()* to accomplish the actual "work" for the client. An important note that should be mentioned here is that we've specifically avoided touching the data area aspects of *devctl()* — you may be thinking, "What if I wanted to set the sample rate to some arbitrary number *n*, how would I do that?" That will be answered in the next *io_devctl()* example below.

Step 3 This step is simply good defensive programming. We return an error code of ENOSYS to tell the client that we didn't understand their request.

Step 4 Finally, we clear out the return structure and set up a one-part IOV to point to it. Then we return a value to the resource manager library encoded by the macro *_RESMGR_NPARTS()* telling it that we're returning a one part IOV. This is then returned to the client. We could alternatively have used the *_RESMGR_PTR()* macro:

```
// instead of this
    // 4) tell the client it worked
    memset (&msg -> o, 0, sizeof (msg -> o));
    SETIOV (ctp -> iov, &msg -> o, sizeof (msg -> o));
    return (_RESMGR_NPARTS (1));

// we could have done this
    // 4) tell the client it worked
    memset (&msg -> o, 0, sizeof (msg -> o));
    return (_RESMGR_PTR (ctp, &msg -> o, sizeof (msg -> o)));
```

The reason we cleared out the return structure here (and not in the *io_read()* or *io_write()* examples) is because in this case, the return structure has actual contents! (In the *io_read()* case, the only data returned was the data itself and the number of bytes read — there was no "return data structure," and in the *io_write()* case, the only data returned was the number of bytes written.)

An *io_devctl()* example that deals with data

In the previous *io_devctl()* example, above, we raised the question of how to set arbitrary sampling rates. Obviously, it's not a good solution to create a large number of DCMD_AUDIO_SET_SAMPLE_RATE_* constants — we'd rapidly use up the available bits in the *dcmd* member.

From the client side, we'll use the *dev_data_ptr* pointer to point to the sample rate, which we'll simply pass as an integer. Therefore, the *nbytes* member will simply be the number of bytes in an integer (4 on a 32-bit machine). We'll assume that the constant DCMD_AUDIO_SET_SAMPLE_RATE is defined for this purpose.

Also, we'd like to be able to read the current sampling rate. We'll also use the *dev_data_ptr* and *nbytes* as described above, but in the reverse direction — the resource manager will return data into the memory location pointed to by *dev_data_ptr* (for *nbytes*) instead of getting data from that memory location. Let's assume that the constant DCMD_AUDIO_GET_SAMPLE_RATE is defined for this purpose.

Let's see what happens in the resource manager's *io_devctl()*, as shown here (we won't discuss things that have already been discussed in the previous example):

```
/*
 * io_devctl2.c
*/

int
io_devctl (resmgr_context_t *ctp, io_devctl_t *msg,
           iofunc_ocb_t *ocb)
{
    int     sts;
    void    *data;

    sts = iofunc_devctl_default (ctp, msg, ocb);
    if (sts != _RESMGR_DEFAULT) {
        return (sts);
    }

    // 1) assign a pointer to the data area of the message
    data = _DEVCTL_DATA (*msg);

    // 2) preset the number of bytes that we'll return to zero
    nbytes = 0;

    // check for all commands, we'll just show the ones
    // we're interested in here
    switch (msg -> i.dcmd) {
    ...
    // 3) process the SET command
    case    DCMD_AUDIO_SET_SAMPLE_RATE:
        audio_set_samplerate (* (int *) data);
        break;

    // 4) process the GET command
    case    DCMD_AUDIO_GET_SAMPLE_RATE:
        * (int *) data = audio_get_samplerate ();
        nbytes = sizeof (int);
        break;
    ...
    }

    // 5) return data (if any) to the client
    memset (&msg -> o, 0, sizeof (msg -> o));
    msg -> o.nbytes = nbytes;
    SETIOV (ctp -> iov, &msg -> o, sizeof (msg -> o) + nbytes);
    return (_RESMGR_NPARTS (1));
}
```

Step 1 In the declaration, we've declared a `void *` called *data* that we're going to use as a general purpose pointer to the data area. If you refer to the *io_devctl()* description above, you'll see that the data structure consists of a union of an input and output header structure, with the data area implicitly following that header. In step 1, the *_DEVCTL_DATA()* macro returns a pointer to that data area.

Step 2 Here we need to indicate how many bytes we're going to return to the client. Simply for convenience, I've set the *nbytes* variable to zero before doing any processing — this way I don't have to explicitly set it to zero in each of the `switch/case` statements.

Step 3 Now for the "set" command. We call the fictitious function *audio_set_samplerate()*, and we pass it the sample rate which we obtained by dereferencing the *data* pointer (which we "tricked" into being a pointer to an integer. Well, okay, we didn't trick it, we used a standard C language typecast.) This is a key mechanism, because this is how we "interpret" the data area (the client's *dev_data_ptr*) according to the command. In a more complicated case, you may be typecasting it to a large structure instead of just a simple integer. Obviously, the client's and resource manager's definitions of the structure must be identical — the best place to define the structure, therefore, is in the `.h` file that contains your DCMD_* command code constants.

Step 4 For the "get" command in step 4, the processing is very similar (with the typecast), except this time we're writing into the data structure instead of reading from it. Note that we also set the *nbytes* variable to correspond to the number of bytes that we want to return to the client. For more complicated data accesses, you'd return the size of the data area (i.e., if it's a structure, you'd return the size of the structure).

Step 5 Finally, to return data to the client, we need to note that the client is expecting a header structure, as well as the return data (if any) to immediately follow the header structure. Therefore, in this step, we clear out the header structure to zeros and set the number of bytes (the *nbytes* member) to the number of bytes that we're returning (recall we had pre-initialized this to zero). Then, we set up a one-part IOV with a pointer to the header and extend the size of the header by the number of bytes we're returning. Lastly, we simply tell the resource manager library that we're returning a one-part IOV to the client.

Important note Recall the discussion in the *io_write()* sample above, about the data area following the header. To recap, we stated that the bytes following the header *may or may not* be complete (i.e., the header may or may not have been read in its entirety from the client), depending on how much data was read in by the resource manager library. Then we went on to discuss how it was inefficient to try to "save" a message pass and to "reuse" the data area. However, things are slightly different with *devctl()*, especially if the amount of data being transferred is fairly small (as was the case in our examples). In these cases, there's a good chance that the data *has* in fact been read into the data area, so it is indeed a waste to re-read the data. There is a simple way to tell how much space you have: the *size* member of *ctp* contains the number of bytes that are available for you starting at the *msg* parameter. The size of the data area beyond the end of the message buffer that's available is calculated by subtracting the size of the message buffer from the *size* member of *ctp*:

```
data_area_size = ctp -> size - sizeof (*msg);
```

Note that this size is equally valid when you are *returning* data to the client (as in the DCMD_AUDIO_GET_SAMPLE_RATE command).

For anything larger than the allocated region, you'll want to perform the same processing we did with the *io_write()* example (above) for getting data from the client, and you'll want to allocate a buffer to be used for returning data to the client.

Advanced topics

Now that we've covered the "basics" of resource managers, it's time to look at some more complicated aspects:

- extending the OCB
- extending the attributes structure
- blocking within the resource manager
- returning directory entries

Extending the OCB

In some cases, you may find the need to extend the OCB. This is relatively painless to do. The common uses for extending the OCB are to add extra flags you wish to maintain on a per-open basis. One such flag could be used with the *io_unblock()* handler to cache the value of the kernel's _NTO_MI_UNBLOCK_REQ flag. (See the Message Passing chapter, under "Using the _NTO_MI_UNBLOCK_REQ" for more details.)

To extend the OCB, you'll need to provide two functions; one to allocate (and initialize) the new OCB and one to free it. Then, you'll need to bind these two functions into the mount structure. (Yes, this does mean that you'll need a mount structure, if only for this one purpose.) Finally, you'll need to define your own OCB typedef, so that the prototypes for the code are all correct.

Let's look at the OCB typedef first, and then we'll see how to override the functions:

```
#define IOFUNC_OCB_T struct my_ocb
#include <sys/iofunc.h>
```

This tells the included file, **<sys/iofunc.h>**, that the manifest constant IOFUNC_OCB_T now points to your new and improved OCB structure.

☞ It's *very* important to keep in mind that the "normal" OCB *must* appear as the first entry in your extended OCB! This is because the POSIX helper library passes around a pointer to what it expects is a normal OCB — it doesn't know about your extended OCB, so therefore the first data element at the pointer location must be the normal OCB.

Here's our extended OCB:

```
typedef struct my_ocb
{
    iofunc_ocb_t      normal_ocb;
    int               my_extra_flags;
    ...
} my_ocb_t;
```

Finally, here's the code that illustrates how to override the allocation and deallocation functions in the mount structure:

```
// declare
iofunc_mount_t      mount;
iofunc_funcs_t      mount_funcs;

// set up the mount functions structure
// with our allocate/deallocate functions

// _IOFUNC_NFUNCS is from the .h file
mount_funcs.nfuncs = _IOFUNC_NFUNCS;

// your new OCB allocator
mount_funcs.ocb_calloc = my_ocb_calloc;

// your new OCB deallocator
mount_funcs.ocb_free = my_ocb_free;
```

```
// set up the mount structure
memset (&mount, 0, sizeof (mount));
```

Then all you have to do is bind the mount functions to the mount structure, and the mount structure to the attributes structure:

```
...

mount.funcs = &mount_funcs;
attr.mount = &mount;
```

The *my_ocb_calloc()* and *my_ocb_free()* functions are responsible for allocating and initializing an extended OCB and for freeing the OCB, respectively. They are prototyped as:

```
IOFUNC_OCB_T *
my_ocb_calloc (resmgr_context_t *ctp, IOFUNC_ATTR_T *attr);

void
my_ocb_free (IOFUNC_OCB_T *ocb);
```

This means that the *my_ocb_calloc()* function gets passed both the internal resource manager context and the attributes structure. The function is responsible for returning an initialized OCB. The *my_ocb_free()* function gets passed the OCB and is responsible for releasing the storage for it.

☞ It's important to realize that the OCB may be allocated by functions other than the normal *io_open()* handler — for example, the memory manager may allocate an OCB. The impact of this is that your OCB allocating function must be able to initialize the OCB with the *attr* argument.

There are two interesting uses for these two functions (that have nothing to do with extending the OCB):

- OCB allocation/deallocation monitor
- more efficient allocation/deallocation

OCB monitor

In this case, you can simply "tie in" to the allocator/deallocator and monitor the usage of the OCBs (for example, you may wish to limit the total number of OCBs outstanding at any given time). This may prove to be a good idea if you're not taking over the *io_open()* outcall, and yet still need to intercept the creation of (and possibly deletion of) OCBs.

More efficient allocation

Another use for overriding the library's built-in OCB allocator/deallocator is that you may wish to keep the OCBs on a free list, instead of the library's *calloc()* and *free()* functions. If you're allocating and deallocating OCBs at a high rate, this may prove to be more efficient.

Extending the attributes structure

You may wish to extend the attributes structure in cases where you need to store additional device information. Since the attributes structure is associated on a "per-device" basis, this means that any extra information you store there will be accessible to all OCBs that reference that device (since the OCB contains a pointer to the attributes structure). Often things like serial baud rate, etc. are stored in extended attributes structures.

Extending the attributes structure is much simpler than dealing with extended OCBs, simply because attributes structures are allocated and deallocated by your code anyway.

You have to perform the same "trick" of overriding the header files with the "new" attributes structure as we did with the extended OCB above:

```
#define IOFUNC_ATTR_T struct my_attr
#include <sys/iofunc.h>
```

Next you actually define the contents of your extended attribute structures. Note that the extended attribute structure *must* have the "normal" attribute structure encapsulated as the *very first* element, just as we did with the extended OCB (and for the same reasons).

Blocking within the resource manager

So far we've avoided talking about blocking within the resource manager. We assume that you will supply an outcall function (e.g., a handler for *io_read()*), and that the data will be available immediately. What if you need to block, waiting for the data? For example, performing a *read()* on the serial port might need to block until a character arrives. Obviously, we can't predict how long this will take.

Blocking within a resource manager is based on the same principles that we discussed in the Message Passing chapter — after all, a resource manager is really a server that handles certain, well-defined messages. When the message corresponding to the client's *read()* request arrives, it does so with a receive ID, and the client is blocked. If the resource manager has the data available, it will simply return the data as we've already seen in the various examples above. However, if the data isn't available, the resource manager will need to keep the client blocked (if the client has indeed specified blocking behaviour for the operation) to continue processing other messages. What this really means is that the thread (in the resource manager) that received the message from the client *should not block*, waiting for the data. If it did block, you can imagine that this could eventually use up a great number of threads in the resource manager, with each thread waiting for some data from some device.

The correct solution to this is to store the receive ID that arrived with the client's message onto a queue somewhere, and return the special constant _RESMGR_NOREPLY from your handler. This tells the resource manager library that processing for this message has completed, but that the client shouldn't be unblocked yet.

Some time later, when the data arrives, you would then retrieve the receive ID of the client that was waiting for the message, and construct a reply message containing the data. Finally, you would reply to the client.

You could also extend this concept to implementing timeouts within the server, much as we did with the example in the Clocks, Timers, and Getting a Kick Every So Often chapter (in the "Server-maintained timeouts" section). To summarize, after some period of time, the client's request was deemed to have "timed out" and the server replied with some form of failure message to the receive ID it had stored away .

Returning directory entries

In the example for the *io_read()* function above, we saw how to return data. As mentioned in the description of the *io_read()* function (in the "Alphabetical listing of Connect and I/O functions"), the *io_read()* function may return directory entries as well. Since this isn't something that everyone will want to do, I discuss it here.

First of all, let's look at *why* and *when* you'd want to return directory entries rather than raw data from *io_read()*.

If you discretely manifest entries in the pathname space, and those entries are *not* marked with the _RESMGR_FLAG_DIR, then you won't have to return directory entries in *io_read()*. If you think about this from a "filesystem" perspective, you're effectively creating "file" types of objects. If, on the other hand, you *do* specify _RESMGR_FLAG_DIR, then you're creating a "directory" type of object. Nobody other than you knows what the *contents* of that directory are, so you have to be the one to supply this data. That's exactly why you'd return directory entries from your *io_read()* handler.

Generally speaking ...

Generally speaking, returning directory entries is just like returning raw data, except:

- You must return an *integral* number of `struct dirent` entries.
- You must fill in the `struct dirent` entries.

The first point means that you cannot return, for example, seven and a half `struct dirent` entries. If eight of these structures don't fit into the alloted space, then you must return only seven.

The second point is fairly obvious; it's mentioned here only because filling in the `struct dirent` can be a little tricky compared to the "raw data" approach for a "normal" *io_read()*.

The struct dirent structure and friends

Let's take a look at the **struct dirent** structure, since that's the data structure returned by the *io_read()* function in case of a directory read. We'll also take a quick look at the client calls that deal with directory entries, since there are some interesting relations to the **struct dirent** structure.

In order for a client to work with directories, the client uses the functions *closedir()*, *opendir()*, *readdir()*, *rewinddir()*, *seekdir()*, and *telldir()*.

Notice the similarity to the "normal" file-type functions (and the commonality of the resource manager messages):

Directory Function	File Function	Message (resmgr)
closedir()	*close()*	_IO_CLOSE_DUP
opendir()	*open()*	_IO_CONNECT
readdir()	*read()*	_IO_READ
rewinddir()	*lseek()*	_IO_LSEEK
seekdir()	*lseek()*	_IO_LSEEK
telldir()	*tell()*	_IO_LSEEK

If we assume for a moment that the *opendir()* and *closedir()* functions will be handled automatically for us, we can focus on just the _IO_READ and _IO_LSEEK messages and related functions.

Offsets

The _IO_LSEEK message and related function is used to "seek" (or "move") within a file. It does the exact same thing within a directory; you can move to the "first" directory entry (by explicitly giving an offset to *seekdir()* or by calling *rewinddir()*), or any arbitrary entry (by using *seekdir()*), or you can find out the current location in the directory entry list (by using *telldir()*).

The "trick" with directories, however, is that the seek offsets are *entirely up to you to define and manage*. This means that you may decide to call your directory entry offsets "0," "1," "2" and so on, or you may instead call them "0," "64," "128" and so on. The only important thing here is that the offsets must be consistent in both the *io_lseek()* handler as well as the *io_read()* handler functions.

In the example below, we'll assume that we're using the simple "0," "1," "2" ... approach. (You might use the "0," "64," "128" ... approach if those numbers correspond to, for example, some kind of on-media offsets. Your choice.)

Contents

So now all that's left is to "simply" fill in the **struct dirent** with the "contents" of our directory. Here's what the **struct dirent** looks like (from **<dirent.h>**):

```
struct dirent {
    ino_t       d_ino;
    off_t       d_offset;
    uint16_t    d_reclen;
    uint16_t    d_namelen;
    char        d_name [1];
};
```

Here's a quick explanation of the various members:

d_ino The "inode" — a mountpoint-unique serial number that cannot be zero (zero indicates that the entry corresponding to this inode is free/empty).

d_offset The offset into the directory we just talked about above. In our example, this will be a simple number like "0," "1," "2," etc.

d_reclen The size of the entire **struct dirent** field and any extensions that may be placed within it. The size includes any alignment filler required.

d_namelen The number of characters in the *d_name* field, *not including* the NUL terminator.

d_name The name of this directory entry, which must be NUL terminated.

When returning the `struct dirent` entries, the return code passed back to the client is the number of bytes returned.

Example

In this example, we're going to create a resource manager called `/dev/atoz` that will be a directory resource manager. It's going to manifest the "files" `/dev/atoz/a` through to `dev/atoz/z`, with a `cat` of any of the files returning the uppercase letter corresponding to the filename. Here's a sample command-line session to give you an idea of how this works:

```
# cd /dev
# ls
atoz    null    ptyp2   socket  ttyp0   ttyp3
enet0   ptyp0   ptyp3   text    ttyp1   zero
mem     ptyp1   shmem   tty     ttyp2
# ls -ld atoz
dr-xr-xr-x  1 root      0               26 Sep 05 07:59 atoz
# cd atoz
# ls
a       e       i       m       q       u       y
b       f       j       n       r       v       z
c       g       k       o       s       w
d       h       l       p       t       x
# ls -l e
-r--r--r--  1 root      0                1 Sep 05 07:59 e
# cat m
M# cat q
Q#
```

The example above illustrates that the directory `atoz` shows up in the `/dev` directory, and that you can do an `ls` of the directory itself and `cd` into it. The `/dev/atoz` directory has a size of "26," which is the number that we selected in the code. Once in the `atoz` directory, doing another `ls` shows the contents — the files `a` through `z`. Doing an `ls` of a particular file, say `e`, shows that the file is readable by all (the `-r--r--r--` part) and is one byte in size. Finally, doing a few random `cat`'s shows that the files indeed have the stated contents. (Note that since the files contain only one byte, there's no linefeed after the character is printed, which is why the prompt shows up on the same line as the output.)

Now that we've seen the characterstics, let's take a look at the code, which is organized into the following functions:

main() and declarations
: Main function; this is where we initialize everything and start the resource manager running.

my_open()
: The handler routine for the _IO_CONNECT message.

my_read()
: The handler routine for the _IO_READ message.

my_read_dir() and *my_read_file()*
: These two routines perform the actual work of the *my_read()* function.

dirent_size() and *dirent_fill()*
: Utility functions to deal with **`struct dirent`** structure.

Note that while the code is broken up here into several short sections with text, the source is present on the web site (`http://www.parse.com/`) in the archive as a single file (`atoz.c`).

main() and declarations

The first section of code presented is the *main()* function and some of the declarations. There's a convenience macro, *ALIGN()*, that's used for alignment by the *dirent_fill()* and *dirent_size()* functions.

The *atoz_attrs* array contains the attributes structures used for the "files" in this example. We declare NUM_ENTS array members, because we have NUM_ENTS (26) files "`a`" through "`z`." The attributes structure used for the directory itself (i.e., the `/dev/atoz` directory) is declared within *main()* and is called simply *attr*. Notice the differences in the way the two types of attributes structures are filled:

file attribute structure

Marked as a regular file (the S_IFREG constant) with an access mode of 0444 (meaning everyone has read access, no one has write access). The size is "1" — the file contains only one byte, namely, the uppercase letter corresponding to the filename. The inodes for these individual files are numbered "1" through "26" inclusive (it would have been more convenient to number them "0" through "25," but "0" is reserved).

directory attribute structure

Marked as a directory file (the S_IFDIR constant) with an access mode of 0555 (meaning that everyone has read and seek access, no one has write access). The size is "26" — this is simply a number picked based on the number of entries in the directory. The inode is "27" — a number known not to be in use by any of the other attributes structures.

Notice how we've overridden only the *open* member of the *connect_func* structure and the *read* member of the *io_func* structure. We've left all the others to use the POSIX defaults.

Finally, notice how we created the name `/dev/atoz` using *resmgr_attach()*. Most importantly, we used the flag _RESMGR_FLAG_DIR, which tells the process manager that it can resolve requests *at and below* this mountpoint.

```
/*
 *  atoz.c
 *
 *  /dev/atoz using the resource manager library
*/

#include <stdio.h>
#include <stddef.h>
#include <stdlib.h>
#include <errno.h>
#include <dirent.h>
#include <limits.h>
#include <sys/iofunc.h>
#include <sys/dispatch.h>
```

```
#define ALIGN(x) (((x) + 3) & ~3)
#define NUM_ENTS            26

static  iofunc_attr_t   atoz_attrs [NUM_ENTS];

int
main (int argc, char **argv)
{
    dispatch_t              *dpp;
    resmgr_attr_t           resmgr_attr;
    resmgr_context_t        *ctp;
    resmgr_connect_funcs_t  connect_func;
    resmgr_io_funcs_t       io_func;
    iofunc_attr_t           attr;
    int                     i;

    // create the dispatch structure
    if ((dpp = dispatch_create ()) == NULL) {
        perror ("Unable to dispatch_create\n");
        exit (EXIT_FAILURE);
    }

    // initialize the various data structures
    memset (&resmgr_attr, 0, sizeof (resmgr_attr));
    resmgr_attr.nparts_max = 1;
    resmgr_attr.msg_max_size = 2048;

    // bind default functions into the outcall tables
    iofunc_func_init (_RESMGR_CONNECT_NFUNCS, &connect_func,
                      _RESMGR_IO_NFUNCS, &io_func);

    // create and initialize the attributes structure
    // for the directory.  Inodes 1-26 are reserved for the
    // files 'a' through 'z'.  The number of bytes is 26
    // because that's how many entries there are.
    iofunc_attr_init (&attr, S_IFDIR | 0555, 0, 0);
    attr.inode = NUM_ENTS + 1;
    attr.nbytes = NUM_ENTS;

    // and for the "a" through "z" names
    for (i = 0; i < NUM_ENTS; i++) {
        iofunc_attr_init (&atoz_attrs [i],
                          S_IFREG | 0444, 0, 0);
        atoz_attrs [i].inode = i + 1;
        atoz_attrs [i].nbytes = 1;
    }

    // add our functions; we're interested only in
    // io_open and io_read
    connect_func.open = my_open;
    io_func.read = my_read;

    // establish a name in the pathname space
    if (resmgr_attach (dpp, &resmgr_attr, "/dev/atoz",
                       _FTYPE_ANY, _RESMGR_FLAG_DIR,
                       &connect_func, &io_func,
                       &attr) == -1) {
        perror ("Unable to resmgr_attach\n");
        exit (EXIT_FAILURE);
    }

    // allocate a context
    ctp = resmgr_context_alloc (dpp);

    // wait here forever, handling messages
    while (1) {
        if ((ctp = resmgr_block (ctp)) == NULL) {
            perror ("Unable to resmgr_block\n");
            exit (EXIT_FAILURE);
        }
        resmgr_handler (ctp);
    }

    // you'll never get here
    return (EXIT_SUCCESS);
}
```

my_open()

While *my_open()* is very short, it has a number of crucial points. Notice how we decide if the resource being opened is a "file" or a "directory" based only on the pathname length. We can do this "trick" because we know that there are no other directories in this resource manager apart from the main one. If you want to have multiple directories below the mountpoint, you have to do more complicated analysis of the *path* member of the *msg* structure. For our simple example, if there's nothing in the pathname, we know it's the directory. Also, notice the extremely simplified pathname validation checking: we simply compare to make sure that there's only one character passed to us, and that the character lies within the range "**a**" through "**z**" inclusive. Again, for more complex resource managers, you'd be responsible for parsing the name past the registered mountpoint.

Now, the most important feature! Notice how we used the POSIX layer default functions to do all the work for us! The *iofunc_open_default()* function is usually installed in the connect functions table at the same spot that our new *my_open()* function is now occupying. This means that it takes the identical set of arguments! All we have to do is decide *which* attributes structure we want to have bound with the OCB that the default function is going to create: either the directory one (in which case we pass *attr*), or one of the 26 different ones for the 26 different files (in which case we pass an appropriate element out of *atoz_attrs*). This is key, because the handler that you put in the *open* slot in the connect functions table acts as the gatekeeper to all further accesses to your resource manager.

```
static int
my_open (resmgr_context_t *ctp, io_open_t *msg,
         iofunc_attr_t *attr, void *extra)
{
    // an empty path means the directory, is that what we have?
    if (msg -> connect.path [0] == 0) {
        return (iofunc_open_default (ctp, msg, attr, extra));

    // else check if it's a single char 'a' -> 'z'
    } else if (msg -> connect.path [1] == 0 &&
              (msg -> connect.path [0] >= 'a' &&
               msg -> connect.path [0] <= 'z')) {

        // yes, that means it's the file (/dev/atoz/[a-z])
        return (iofunc_open_default (ctp, msg,
                atoz_attrs + msg -> connect.path [0] - 'a',
                extra));
    } else {
        return (ENOENT);
    }
}
```

my_read()

In the *my_read()* function, to decide what kind of processing we needed to do, we looked at the attribute structure's *mode* member. If the *S_ISDIR()* macro says that it's a directory, we call *my_read_dir()*; if the *S_ISREG()* macro says that it's a file, we call *my_read_file()*. (Note that if we can't tell what it is, we return EBADF; this indicates to the client that something bad happened).

The code here doesn't know anything about our special devices, nor does it care; it simply makes a decision based on standard, well-known data.

```
static int
my_read (resmgr_context_t *ctp, io_read_t *msg,
         iofunc_ocb_t *ocb)
{
    int     sts;

    // use the helper function to decide if valid
    if ((sts = iofunc_read_verify (ctp, msg, ocb,
                                   NULL)) != EOK) {
        return (sts);
    }

    // decide if we should perform the "file" or "dir" read
    if (S_ISDIR (ocb -> attr -> mode)) {
        return (my_read_dir (ctp, msg, ocb));
    } else if (S_ISREG (ocb -> attr -> mode)) {
        return (my_read_file (ctp, msg, ocb));
    } else {
        return (EBADF);
    }
}
```

my_read_dir()

In *my_read_dir()* is where the fun begins. From a high level perspective, we allocate a buffer that's going to hold the result of this operation (called *reply_msg*). We then use *dp* to "walk" along the output buffer, stuffing `struct dirent` entries as we go along. The helper routine *dirent_size()* is used to determine if we have sufficient room in the output buffer to stuff the next entry; the helper routine *dirent_fill()* is used to perform the stuffing. (Note that these routines are not part of the resource manager library; they're discussed and documented below.)

On first glance this code may look inefficient; we're using *sprintf()* to create a two-byte filename (the filename character and a NUL terminator) into a buffer that's _POSIX_PATH_MAX (256) bytes long. This was done to keep the code as generic as possible.

Finally, notice that we use the OCB's *offset* member to indicate to us which particular filename we're generating the `struct dirent` for at any given time. This means that we also have to update the *offset* field whenever we return data.

The return of data to the client is accomplished in the "usual" way, via *MsgReply()*. Note that the status field of *MsgReply()* is used to indicate the number of bytes that were sent to the client.

```
static int
my_read_dir (resmgr_context_t *ctp, io_read_t *msg,
             iofunc_ocb_t *ocb)
{
    int     nbytes;
    int     nleft;
    struct  dirent *dp;
    char    *reply_msg;
    char    fname [_POSIX_PATH_MAX];

    // allocate a buffer for the reply
    reply_msg = calloc (1, msg -> i.nbytes);
    if (reply_msg == NULL) {
        return (ENOMEM);
    }

    // assign output buffer
    dp = (struct dirent *) reply_msg;

    // we have "nleft" bytes left
    nleft = msg -> i.nbytes;
    while (ocb -> offset < NUM_ENTS) {

        // create the filename
        sprintf (fname, "%c", ocb -> offset + 'a');

        // see how big the result is
        nbytes = dirent_size (fname);

        // do we have room for it?
        if (nleft - nbytes >= 0) {

            // fill the dirent, and advance the dirent pointer
            dp = dirent_fill (dp, ocb -> offset + 1,
                              ocb -> offset, fname);

            // move the OCB offset
            ocb -> offset++;

            // account for the bytes we just used up
            nleft -= nbytes;
        } else {

            // don't have any more room, stop
            break;
        }
    }

    // return info back to the client
    MsgReply (ctp -> rcvid, (char *) dp - reply_msg,
              reply_msg, (char *) dp - reply_msg);

    // release our buffer
    free (reply_msg);

    // tell resource manager library we already did the reply
    return (_RESMGR_NOREPLY);
}
```

my_read_file()

In *my_read_file()*, we see much the same code as we saw in the simple read example above. The only strange thing we're doing is we "know" there's only one byte of data being returned, so if *nbytes* is non-zero then it must be one (and nothing else). So, we can construct the data to be returned to the client by stuffing the character variable *string* directly. Notice how we used the *inode* member of the attribute structure as the basis of which data to return. This is a common trick used in resource managers that must deal with multiple resources. Another trick would be to extend the attributes structure (as discussed above in "Extending the attributes structure") and have either the data stored there directly or a pointer to it.

```
static int
my_read_file (resmgr_context_t *ctp, io_read_t *msg,
              iofunc_ocb_t *ocb)
{
    int     nbytes;
    int     nleft;
    char    string;

    // we don't do any xtypes here...
    if ((msg -> i.xtype & _IO_XTYPE_MASK) !=
         _IO_XTYPE_NONE) {
        return (ENOSYS);
    }

    // figure out how many bytes are left
    nleft = ocb -> attr -> nbytes - ocb -> offset;

    // and how many we can return to the client
    nbytes = min (nleft, msg -> i.nbytes);
    if (nbytes) {
        // create the output string
        string = ocb -> attr -> inode - 1 + 'A';

        // return it to the client
        MsgReply (ctp -> rcvid, nbytes,
                  &string + ocb -> offset,
                  nbytes);

        // update flags and offset
        ocb -> attr -> flags |= IOFUNC_ATTR_ATIME
                             | IOFUNC_ATTR_DIRTY_TIME;
        ocb -> offset += nbytes;
    } else {
        // nothing to return, indicate End Of File
        MsgReply (ctp -> rcvid, EOK, NULL, 0);
    }

    // already done the reply ourselves
    return (_RESMGR_NOREPLY);
}
```

dirent_size()

The helper routine *dirent_size()* simply calculates the number of bytes required for the `struct dirent`, given the alignment constraints. Again, this is slight overkill for our simple resource manager, because we know how big each directory entry is going to be — all filenames are exactly one byte in length. However, it's a useful utility routine.

```
int
dirent_size (char *fname)
{
  return (ALIGN (sizeof (struct dirent) + strlen (fname)));
}
```

dirent_fill()

Finally, the helper routine *dirent_fill()* is used to stuff the values passed to it (namely, the *inode*, *offset* and *fname* fields) into the directory entry also passed. As an added bonus, it returns a pointer to where the next directory entry should begin, taking into account alignment.

```
struct dirent *
dirent_fill (struct dirent *dp, int inode, int offset,
             char *fname)
{
    dp -> d_ino = inode;
    dp -> d_offset = offset;
    strcpy (dp -> d_name, fname);
    dp -> d_namelen = strlen (dp -> d_name);
    dp -> d_reclen = ALIGN (sizeof (struct dirent)
                   + dp -> d_namelen);
    return ((struct dirent *) ((char *) dp +
            dp -> d_reclen));
}
```

Summary

Writing a resource manager is by far the most complicated task that we've discussed in this book.

A resource manager is a server that receives certain, well-defined messages. These messages fall into two broad categories:

Connect messages

Related to pathname-based operations, these may establish a context for further work.

I/O messages

Always arrive *after* a connect message and indicate the actual work that the client wishes to have done (e.g., *stat()*).

The operations of the resource manager are controlled by the thread pool functions (discussed in the Processes and Threads chapter) and the dispatch interface functions.

QSSL provides a set of POSIX helper functions in the resource manager library that perform much of the work of dealing with the client's Connect and I/O messages that arrive.

There are a number of data structures relating to the clients and devices manifested by the resource manager to keep in mind:

OCB Allocated on a per-open basis, this contains the context for the client (e.g., current *lseek()* position)

Attributes structure

Allocated on a per-device basis, this contains information about the device (e.g., size of the device, permissions, etc.)

Mount structure

Allocated on a per-resource-manager basis, and contains information about the characteristics of the entire resource manager.

The clients communicate with the resource manager via message passing by resolving the pathname (via the *open()* and other calls) into a node descriptor, process ID, channel ID, and handle.

Finally you supply the functionality you wish to actually *do* in your resource manager by overriding some of the callouts in the Connect and I/O functions table.

Appendix A

QNX 4 to Neutrino

In this appendix. . .

QNX 4 and Neutrino

In this appendix, we'll take a look at QSSL's previous operating system, QNX 4, and see how it compares to Neutrino. This appendix will mainly be of interest if you are a current QNX 4 customer and want to see:

- What's so great about Neutrino?
- How hard will it be when I port to Neutrino?

Or you may be developing for, or porting to, both operating systems.

Similarities

Let's first start with how the two generations of operating systems are similar:

- message passing is at the heart of the architecture
- network-distributed message passing
- realtime
- microkernel architecture
- processes are memory-protected
- POSIX compatibility
- relatively simple "device driver" model
- embeddable

Note that while some of the basic features listed above are indeed similar, in general Neutrino has extended the support. For example, Neutrino has more POSIX support than QNX 4, simply because a large number of the POSIX specifications were still in draft status when QNX 4 was released. While less of them are in draft status as of Neutrino's release, there are still more *new* drafts being released as this book is written. It's a never-ending game of catch-up.

Improvements

Now that you've seen what's the same about the two generations of OS, let's look at where Neutrino has improved functionality over QNX 4:

- more POSIX standards supported
- more embeddable
- kernel is more readily customizable for a variety of hardware platforms
- thread support
- simpler device driver model
- portable architecture; currently supports MIPS, PPC, SH4 and ARM processors as well as x86
- supports SMP
- more documentation

While some of these improvements are "free," meaning that there are no compatibility issues (for example, POSIX pthreads weren't supported under QNX 4), some things did require fundamental changes. I'll briefly mention the classes of changes that were required, and then we'll look in detail at the compatibility issues caused as well as suggestions on how to port to Neutrino (or keep your code portable between the two).

Embeddability

Neutrino totally redesigned the way that the operating system was embedded. Under QNX 4, in the original release, it was marginally embeddable. Then Neutrino came along, designed to be embeddable. As a bonus, QNX 4 underwent some changes as a result of the experience gained in Neutrino, and now QNX 4 is vastly more embeddable than it had been. In any event, embedding QNX 4 versus embedding Neutrino is almost like night and day. QNX 4 has no real support for things like:

- kernel callouts (interrupt, timer)

- startup configurability
- image filesystem

whereas Neutrino does. The definitive book on that subject is QSSL's *Building Embedded Systems.*

Thread support

QNX 4 had a function called *tfork()* that let you use "threads" by creating a process with its code *and data* segments mapped to the same memory locations as the creating process. This gave the illusion of a thread by creating a process, and then changing the characteristics of the newly created process to make it look like a thread. While there is a thread library available for QNX 4 on QSSL's update system, the kernel itself doesn't support threads directly.

Under Neutrino, the POSIX "pthread" model is used for all threading. This means that you'll see (and have seen in this book) familiar function calls like *pthread_create()*, *pthread_mutex_lock()*, and others.

Message passing

While the impact of threads on message passing may seem minimal, it resulted in a fundamental change to the way message passing was done (not to the fundamental *concepts* of message passing, like SEND/RECEIVE/REPLY, but to the *implementation*).

Under QNX 4, messages were targeted at process IDs. To send a message, you simply found the process ID of the target and did your *Send()*. For servers to receive a message under QNX 4 they just did a *Receive()*. This would block until a message arrived. The server would then reply with the *Reply()* function.

Under Neutrino, message passing is identical (different function names, though). What's changed is the mechanism. The client now has to create a connection to a server before it can do the standard message-passing functions. And the server has to create a channel before it can do the standard message-passing functions.

☞ Note that the QNX 4 *Creceive()* function, which would do a non-blocking *Receive()*, is missing from Neutrino. We generally discourage such "polling" functions, especially when you can start a thread, but if you really insist on performing a non-blocking *MsgReceive()* you should take a look at the Clocks, Timers, and Getting a Kick Every So Often chapter (under "Kernel timeouts") for more information. For the short story version, here's the relevant code sample:

```
TimerTimeout (CLOCK_REALTIME, _NTO_TIMEOUT_RECEIVE,
              NULL, NULL, NULL);
rcvid = MsgReceive (...
```

Pulses and events

QNX 4 provided something called a "proxy." A proxy is best described as a "canned" (or "fixed") message, which could be sent by processes or kernel services (like a timer or interrupt service routine) to the owner of the proxy. The proxy is non-blocking for the sender and would arrive just like any other message. The way to identify a proxy (as opposed to another process actually sending a message) was to either look at the proxy message contents (not 100% reliable, as a process could send something that *looked* like the contents of the proxy) or to examine the process ID associated with the message. If the process ID of the message was the same as the proxy ID, then you could be assured it was a proxy, because proxy IDs and process IDs were taken from the same pool of numbers (there'd be no overlap).

Neutrino extends the concept of proxies with "pulses." Pulses are still non-blocking messages, they can still be sent from a thread to another thread, or from a kernel service (like the timer and ISR mentioned above for proxies) to a thread. The differences are that while proxies were of fixed-content, Neutrino pulses are fixed-length, but the content can be set by the sender of the pulse at any time. For example, an ISR could save away a key piece of data into the pulse and then send that to a thread.

Under QNX 4, some services were able to deliver a signal or a proxy, while other services were able to deliver only one or the other. To complicate matters, the delivery of these services was usually done in several different ways. For example, to deliver a signal, you'd have to use the *kill()* function. To deliver a proxy or signal as a result of a timer, you'd have to use a negative signal number (to indicate it was a proxy) or a positive signal number (to indicate it was a signal). Finally, an ISR could deliver *only* a proxy.

Under Neutrino this was abstracted into an extension of the POSIX `struct sigevent` data structure. Anything that used or returned the `struct sigevent` structure can use a signal or a pulse.

In fact, this has been extended further, in that the `struct sigevent` can even cause a thread to be created! We talked about this in the Clocks, Timers, and Getting a Kick Every So Often chapter (under "Getting notified with a thread").

Device driver model

Under the previous-previous version of the operating system (the QNX 2 family), writing device drivers was an arcane black art. Under QNX 4, it was initially a mystery, but then eventually some samples appeared. Under Neutrino, there are books and courses on the topic. As it turns out, the Neutrino model and the QNX 4 model are, at the highest architectural level, reasonably similar. Whereas QNX 4 had somewhat muddled concepts of what needed to be done as a "connect" function, and what needed to be done as an "I/O" function, Neutrino has a very clear separation. Also, under QNX 4, you (the device driver writer) were responsible for most of the work — you'd supply the main message handling loop, you'd have to associate context on each I/O message, and so on. Neutrino has simplified this greatly with the resource manager library.

MIPS, PPC, SH4, and ARM support

One of the driving changes behind the embeddability differences between QNX 4 and Neutrino is the fact that Neutrino supports the MIPS, PowerPC, SH4, and ARM processors. Whereas QNX 4 was initially "at home" on an IBM PC with a BIOS and *very* standard hardware, Neutrino is equally at home on multiple processor platforms with or without a BIOS (or ROM monitor), and with customized hardware chosen by the manufacturer (often, it would appear, without regard for the requirements of the OS). This means that the Neutrino kernel had to have provision for callouts, so you could, for example, decide what kind of interrupt controller hardware you had, and, without having to buy a source license for the operating system, run on that hardware.

A bunch of other changes you'll notice when you port QNX 4 applications to Neutrino, especially on these different processor platforms, is that they're fussy about alignment issues. You can't access an N-byte object on anything other than an N-byte multiple of an address. Under the x86 (with the alignment flag turned off), you could access memory willy-nilly. By modifying your code to have properly aligned structures (for non-x86 processors), you'll also find that your code runs faster on x86, because the x86 processor can access aligned data faster.

Another thing that often comes to haunt people is the issue of big-endian versus little-endian. The x86 process is a mono-endian processor (meaning it has only one "endian-ness"), and that's little-endian. MIPS and PPC, for example, are bi-endian processors (meaning that the processor can operate in either big-endian or little-endian mode). Furthermore, these non-x86 processors are "RISC" (Reduced Instruction Set CPU) machines, meaning that certain operations, such as a simple C language `|=` (bitwise set operation) may or may not be performed in an atomic manner. This can have startling consequences! Look at the file `<atomic.h>` for a list of helper functions that ensure atomic operation.

SMP support

Released versions of QNX 4 are strictly single-processor, whereas Neutrino, at the time of this second printing, has support for SMP on the x86 and PPC architectures at least. SMP is a great feature, especially in an operating system that supports threads, but it's also a bigger gun that you can shoot yourself in the foot with. For example, on a single-processor box, an ISR will preempt a thread, but *never* the other way around. On a single-processor box, it's a worthwhile abstraction to "pretend" that threads run simultaneously, when they don't really.

On an SMP box, a thread and ISR can be running simultaneously, and multiple threads can also be running simultaneously. Not only is an SMP system a great workstation, it's also an excellent SQA (Software Quality Assurance) testing tool — if you've made any "bad" assumptions about protection in a multithreaded environment, an SMP system will find them eventually.

☞ To illustrate just how true that statement is, one of the bugs in an early internal version of SMP had a "window" of *one machine cycle*! On one processor, what was supposedly coded to be an atomic read/modify/write operation could be interfered with by the second processor's compare and exchange instruction.

Porting philosophy

Let's now turn our attention to the "big picture." We'll look at:

- Message passing and clients & servers
- Interrupt Service Routines

Message passing considerations

Under QNX 4, the way a client would find a server was either:

1. Use the global namespace.
   Or:
2. Perform an *open()* on an I/O manager.

Client/server using the global namespace

If the client/server relationship that you're porting depended on the global namespace, then the client used:

qnx_name_locate()

and the server would "register" its name via:

qnx_name_attach()

In this case, you have two choices. You can try to retain the global namespace idiom, or you can modify your client and server to act like a standard resource manager. If you wish to retain the global namespace, then you should look at the *name_attach()* and *name_detach()* functions for your server, and *name_open()* and *name_close()* for your clients.

However, I'd recommend that you do the latter; it's "the Neutrino way" to do everything with resource managers, rather than try to bolt a resource manager "kludge" onto the side of a global namespace server.

The modification is actually reasonably simple. Chances are that the client side calls a function that returns either the process ID of the server or uses the "VC" (*V*irtual *C*ircuit) approach to create a VC from the client's node to a remote server's node. In both cases, the process ID or the VC to the remote process ID was found based on calling *qnx_name_locate()*. Here, the "magic cookie" that binds the client to the server is some form of process ID (we're considering the VC to be a process ID, because VCs are taken from the same number space, and for all intents and purposes, they look just like process IDs).

If you were to return a connection ID instead of a process ID, you'd have conquered the major difference. Since the QNX 4 client probably doesn't examine the process ID in any way (what meaning would it have, anyway? — it's just a number), you can probably trick the QNX 4 client into performing an *open()* on the "global name." In this case, however, the global name would be the pathname that the resource manager attached as its "id." For example, the following is typical QNX 4 client code, stolen from my caller ID (CLID) server library:

```
/*
 *  CLID_Attach (serverName)
 *
 *  This routine is responsible for establishing a connection to
 *  the CLID server.
 *
 *  Returns the process ID or VC to the CLID server.
*/

// a place to store the name, for other library calls
static char CLID_serverName [MAX_CLID_SERVER_NAME + 1];

// a place to store the clid server id
static int clid_pid = -1;

int
CLID_Attach (char *serverName)
{
    if (serverName == NULL) {
        sprintf (CLID_serverName, "/PARSE/CLID");
    } else {
        strcpy (CLID_serverName, serverName);
    }
    clid_pid = qnx_name_locate (0, CLID_serverName,
                                sizeof (CLID_ServerIPC), NULL);
    if (clid_pid != -1) {
        CLID_IPC (CLID_MsgAttach);  // send it an ATTACH message
        return (clid_pid);
    }
    return (-1);
}
```

You could change this to be:

```
/*
 *  CLID_Attach (serverName) Neutrino version
*/

int
CLID_Attach (char *serverName)
{
    if (serverName == NULL) {
        sprintf (CLID_serverName, "/PARSE/CLID");
    } else {
        strcpy (CLID_serverName, serverName);
    }
    return (clid_pid = open (CLID_serverName, O_RDWR));
}
```

and the client wouldn't even notice the difference.

Two implementation notes: I've simply left the default name "**/PARSE/CLID**" as the registered name of the resource manager. Most likely a better name would be "**/dev/clid**" — it's up to you how "POSIX-like" you want to make things. In any event, it's a one-line change and is only marginally related to the discussion here.

The second note is that I've still *called* the file descriptor *clid_pid*, even though now it should *really* be called *clid_fd*. Again, this is a style issue and relates to just how much change you want to perform between your QNX 4 version and the Neutrino one.

In any event, to be totally portable to both, you'll want to abstract the client binding portion of the code into a function call — as I did above with the *CLID_Attach()*.

At some point, the client would actually perform the message pass operation. This is where things get a little trickier. Since the client/server relationship is *not* based on an I/O manager relationship, the client generally creates "customized" messages. Again from the CLID library (*CLID_AddSingleNPANXX()* is the client's exposed API call; I've also included *checkAttach()* and *CLID_IPC()* to show the actual message passing and checking logic):

```
/*
 *  CLID_AddSingleNPANXX (npa, nxx)
*/

int
CLID_AddSingleNPANXX (int npa, int nxx)
{
    checkAttach ();
    CLID_IPCData.npa = npa;
    CLID_IPCData.nxx = nxx;
    CLID_IPC (CLID_MsgAddSingleNPANXX);
    return (CLID_IPCData.returnValue);
}

/*
 *  CLID_IPC (IPC message number)
 *
 *  This routine will call the server with the global buffer
 *  CLID_IPCData, and will stuff in the message number passed
 *  as the argument.
 *
 *  Should the server not exist, this routine will stuff the
 *  .returnValue field with CLID_NoServer.  Otherwise, no
 *  fields are affected.
*/

void
CLID_IPC (IPCMessage)
int     IPCMessage;
{
    if (clid_pid == -1) {
        CLID_IPCData.returnValue = CLID_NoServer;
        return;
    }
    CLID_IPCData.serverFunction = IPCMessage;
    CLID_IPCData.type = 0x8001;
    CLID_IPCData.subtype = 0;
    if (Send (clid_pid, &CLID_IPCData, &CLID_IPCData,
              sizeof (CLID_IPCData),
              sizeof (CLID_IPCData))) {
        CLID_IPCData.returnValue = CLID_IPCError;
        return;
    }
}

void
checkAttach ()
{
    if (clid_pid == -1) {
        CLID_Attach (NULL);
        }
}
```

As you can see, the *checkAttach()* function is used to ensure that a connection exists to the CLID server. If you didn't have a connection, it would be like calling *read()* with an invalid file descriptor. In my case here, the *checkAttach()* automagically creates the connection. It would be like having the *read()* function determine that there is no valid file descriptor and just create one out of the blue. Another style issue.

The customized messaging occurs in the *CLID_IPC()* function. It takes the global variable *CLID_IPCData* and tries to send it to the server using the QNX 4 *Send()* function.

The customized messages can be handled in one of two ways:

1 Functionally translate them into standard, file-descriptor-based POSIX calls.
Or:

2 Encapsulate them into either a *devctl()* or a customized message wrapper using the _IO_MSG message type.

In both cases, you've effectively converted the client to communicating using standard resource manager mechanisms for communications. What? You don't have a file descriptor? You have only a connection ID? Or vice versa? This isn't a problem! Under Neutrino, *a file descriptor is a connection ID*!

Translating messages to standard file-descriptor-based POSIX calls

In the case of the CLID server, this really isn't an option. There is no standard POSIX file-descriptor-based call to "add an NPA/NXX pair to a CLID resource manager." However, there is the general *devctl()* mechanism, so if your client/server relationship requires this form, see below.

Now, before you write off this approach (translating to standard fd-based messages), let's stop and think about some of the places where this would be useful. In an audio driver, you *may* have used customized QNX 4 messages to transfer the audio data to and from the resource manager. When you really look at it, *read()* and *write()* are probably much more suited to the task at hand — bulk data transfer. Setting the sampling rate, on the other hand, would be much better accomplished via the *devctl()* function.

Granted, not every client/server relationship will have a bulk data transfer requirement (the CLID server is such an example).

Translating messages to *devctl()* or _IO_MSG

So the question becomes, how do you perform control operations? The easiest way is to use the *devctl()* POSIX call. Our CLID library example (above) now becomes:

```
/*
 *  CLID_AddSingleNPANXX (npa, nxx)
*/

int
CLID_AddSingleNPANXX (int npa, int nxx)
{
    struct  clid_addnpanxx_t    msg;

    checkAttach ();  // keep or delete, style issue

    msg.npa = npa;
    msg.nxx = nxx;
    return (devctl (clid_pid, DCMD_CLID_ADD_NPANXX, &msg,
                    sizeof (msg), NULL));
}
```

As you can see, this was a relatively painless operation. (For those people who don't like *devctl()* because it forces data transfers to be the same size in both directions, see the discussion below on the _IO_MSG message.) Again, if you're maintaining source that needs to run on both operating systems, you'd abstract the message-passing function into one common point, and then supply different versions of a library, depending on the operating system.

We actually killed two birds with one stone:

1. Removed a global variable, and assembled the messages based on a stack variable — this now makes our code thread-safe.
2. Passed only the correct-sized data structure, instead of the maximum-sized data structure as we did in the previous (QNX 4) example.

Note that we had to define DCMD_CLID_ADD_NPANXX — we could have also kludged around this and used the CLID_MsgAddSingleNPANXX manifest constant (with appropriate modification in the header file) for the same purpose. I just wanted to highlight the fact that the two constants weren't identical.

The second point that we made in the list above (about killing birds) was that we passed only the "correct-sized data structure." That's actually a tiny lie. You'll notice that the *devctl()* has only one size parameter (the 4th parameter, which we set to `sizeof (msg)`). How does the data transfer *actually* occur? The 2nd parameter to *devctl()* contains the device command (hence "DCMD"). Encoded within the top two bits of the device command is the direction, which can be one of four possibilities:

1. "00" — no data being transferred
2. "01" — transfer from driver to client
3. "10" — transfer from client to driver
4. "11" — transfer bidirectionally

If you're not transferring data (meaning that the command itself suffices), or if you're transferring data unidirectionally, then *devctl()* is fine. The interesting case is when you're transferring data bidirectionally, because (since there's only one data size parameter to *devctl()*) both data transfers (to the driver and back) will transfer the entire data buffer! This is okay in the sub-case where the "input" and "output" data buffer sizes are identical, but consider the case where the data buffer going to the driver is a few bytes, and the data coming back from the driver is large. Since we have only one size parameter, we're effectively forced to transfer the entire data buffer to the driver, even though only a few bytes were required!

This can be solved by "rolling your own" messages, using the general "escape" mechanism provided by the _IO_MSG message.

The _IO_MSG message is provided to allow you to add your own message types, while not conflicting with any of the "standard" resource manager message types — it's already a resource manager message type.

The first thing that you must do when using _IO_MSG is define your particular "custom" messages. In this example, we'll define two types, and model it after the standard resource manager messages — one data type will be the input message, and one will be the output message:

```
typedef struct
{
    int     data_rate;
    int     more_stuff;
} my_input_xyz_t;

typedef struct
{
    int     old_data_rate;
    int     new_data_rate;
    int     more_stuff;
} my_output_xyz_t;

typedef union
{
    my_input_xyz_t  i;
    my_output_xyz_t o;
} my_message_xyz_t;
```

Here, we've defined a **union** of an input and output message, and called it **my_message_xyz_t**. The naming convention is that this is the message that relates to the "**xyz**" service, whatever that may be. The input message is of type **my_input_xyz_t**, and the output message is of type **my_output_xyz_t**. Note that "input" and "output" are from the point of view of the resource manager — "input" is data going *into* the resource manager, and "output" is data coming *from* the resource manager (back to the client).

We need to make some form of API call for the client to use — we *could* just force the client to manually fill in the data structures `my_input_xyz_t` and `my_output_xyz_t`, but I don't recommend doing that. The reason is that the API is supposed to "decouple" the implementation of the message being transferred from the functionality. Let's assume this is the API for the client:

```
int
adjust_xyz (int *data_rate,
            int *odata_rate,
            int *more_stuff);
```

Now we have a well-documented function, *adjust_xyz()*, that performs something useful from the client's point of view. Note that we've used pointers to integers for the data transfer — this was simply an example of implementation. Here's the source code for the *adjust_xyz()* function:

```
int
adjust_xyz (int *dr, int *odr, int *ms)
{
    my_message_xyz_t    msg;
    int                 sts;

    msg.i.data_rate = *dr;
    msg.i.more_stuff = *ms;
    sts = io_msg (global_fd, COMMAND_XYZ, &msg,
                  sizeof (msg.i),
                  sizeof (msg.o));
    if (sts == EOK) {
        *odr = msg.o.old_data_rate;
        *ms = msg.o.more_stuff;
    }
    return (sts);
}
```

This is an example of using *io_msg()* (which we'll define shortly — it's *not* a standard QSSL supplied library call!). The *io_msg()* function does the magic of assembling the _IO_MSG message. To get around the problems that we discussed about *devctl()* having only one "size" parameter, we've given *io_msg()* two size parameters, one for the input (to the resource manager, `sizeof (msg.i)`) and one for the output (from the resource manager, `sizeof (msg.o)`). Notice how we update the values of _*odr_ and _*ms only_ if the *io_msg()* function returns an EOK. This is a common trick, and is useful in this case because the passed arguments don't get modified *unless* the actual command succeeded. (This prevents the client program from having to maintain copies of its passed data, just in case the function fails.)

One last thing that I've done in the *adjust_xyz()* function, is that I depend on the *global_fd* variable containing the file descriptor of the resource manager. Again, there are a number of ways that you could handle it:

- Bury the file descriptor within the *io_msg()* function (this would be useful if you wanted to avoid having to pass around the file descriptor on each and every call; useful if you're ever going to talk to only the one resource manager, and thus most likely not suitable as a general purpose solution).
  Or:

- Pass the file descriptor from the client itself to each function in the API library (useful if the client's going to be responsible for talking to the resource manager in other ways, such as the standard POSIX file descriptor calls like *read()*, or if the client may be talking to multiple resource managers).

Here's the source for *io_msg()*:

```
int
io_msg (int fd, int cmd, void *msg, int isize, int osize)
{
    io_msg_t    io_message;
    iov_t       rx_iov [2];
    iov_t       tx_iov [2];
    int         sts;

    // set up the transmit IOV
    SETIOV (tx_iov + 0, &io_msg.o, sizeof (io_msg.o));
    SETIOV (tx_iov + 1, msg, osize);
    // set up the receive IOV
    SETIOV (rx_iov + 0, &io_msg.i, sizeof (io_msg.i));
    SETIOV (rx_iov + 1, msg, isize);

    // set up the _IO_MSG itself
    memset (&io_message, 0, sizeof (io_message));
    io_message.type = _IO_MSG;
    io_message.mgrid = cmd;

    return (MsgSendv (fd, tx_iov, 2, rx_iov, 2));
}
```

Notice a few things.

The *io_msg()* function used a two-part IOV to "encapsulate" the custom message (as passed by *msg*) into the *io_message* structure.

The *io_message* was zeroed out and initialized with the _IO_MSG message identification type, as well as the *cmd* (which will be used by the resource manager to decide what kind of message was being sent).

The *MsgSendv()* function's return status was used directly as the return status of *io_msg()*.

The only "funny" thing that we did was in the *mgrid* field. QSSL reserves a range of values for this field, with a special range reserved for "unregistered" or "prototype" drivers. These are values in the range _IOMGR_PRIVATE_BASE through to _IOMGR_PRIVATE_MAX , respectively. If you're building a deeply embedded system where you know that no inappropriate messages will be sent to your resource manager, then you can go ahead and use the special range. On the other hand, if you are building more of a "desktop" or "generic" system, you may not have enough control over the final configuration of the system to determine whether inappropriate messages will be sent to your resource manager. In that case, you should contact QSSL to obtain a *mgrid* value that will be reserved for you — no one else should use that number. Consult the file **<sys/iomgr.h>** for the ranges currently in use. In our example above, we could assume that COMMAND_XYZ is something based on _IOMGR_PRIVATE_BASE:

```
#define COMMAND_XYZ (_IOMGR_PRIVATE_BASE + 0x0007)
```

Or that we've been assigned a specific number by QSSL:

```
#define COMMAND_XYZ (_IOMGR_ACME_CORP + 0x0007)
```

Client/Server using an I/O manager

Now, what if the client that you're porting used an I/O manager? How would we convert that to Neutrino? Answer: we already did. Once we establish a file-descriptor-based interface, we're using a resource manager. Under Neutrino, you'd almost *never* use a "raw" message interface. Why not?

1. You'd have to worry about the _IO_CONNECT message that came in with the client's *open()* call, or you'd have to figure out how to find the resource manager if you weren't going to use *open()*.
2. You'd have to figure out a way to associate a client with a particular context block inside of the resource manager. This isn't rocket science, but it does involve some amount of data management.
3. You'd have to provide encapsulation of all your messages, instead of using the standard POSIX file-descriptor-based functions to do that for you.
4. Your resource manager won't work with *stdin*/*stdout*-based applications. For the audio driver example, you couldn't just do `mp3_decode spud.mp3 >/dev/audio`; the *open()* would most likely fail (if not, then the *write()* would, and so on).

Proxies

Under QNX 4, the only way to send a non-blocking message was to create a proxy via *qnx_proxy_attach()*. This function returns a proxy ID (which is taken from the same number space as process IDs), which you can then *Trigger()* or return from an interrupt service routine (see below).

Under Neutrino, you'd set up a `struct sigevent` to contain a "pulse," and either use *MsgDeliverEvent()* to deliver the event or bind the event to a timer or ISR.

The usual trick under QNX 4 to detect proxy messages (via *Receive()* or *Creceive()*) was to compare the process ID returned by the receiving function against the proxy IDs that you're expecting. If you got a match, you knew it was a proxy. Alternatively, you could ignore the process ID returned by the receiving function and handle the message as if it were a "regular" message. Unfortunately, this has some porting complications.

Proxies for their IDs

If you're comparing the received process ID against the list of proxies that you're expecting, then you'll usually ignore the actual contents of the proxy. After all, since the proxy message couldn't be changed once you've created it, what additional information would you have gained by looking at the message once you knew it was one of your proxies? You could argue that as a convenience you'd place a message into the proxy that you could then look at with your standard message decoding. If that's the case, see below, "Proxies for their contents."

Therefore, under QNX 4, you'd see code like:

```
pid = Receive (0, &msg, sizeof (msg));
if (pid == proxyPidTimer) {
    // we got hit with the timer, do something
} else if (pid == proxyPidISR) {
    // our ISR went off, do something
} else {
    // not one of our proxies, must have been a regular
    // message for a client.  Do something.
}
```

Under Neutrino, you'd replace this code with the following:

```
rcvid = MsgReceive (chid, &msg, sizeof (msg), NULL);
if (rcvid == 0) {   // 0 indicates it was a pulse
    switch (msg.pulse.code) {
    case    MyCodeTimer:
        // we got hit with the timer, do something
        break;
    case    MyCodeISR:
        // our ISR went off, do something
        break;
    default:
        // unknown pulse code, log it, whatever.
        break;
    }
} else {
    // rcvid is not zero, therefore not a pulse but a
    // regular message from a client.  Do something.
}
```

Note that this example would be used if you're handling all messages yourself. Since we recommend using the resource manager library, your code would really look more like this:

```
int
main (int argc, char **argv)
{
    ...
    // do the usual initializations

    pulse_attach (dpp, 0, MyCodeTimer, my_timer_pulse_handler,
                  NULL);
    pulse_attach (dpp, 0, MyCodeISR, my_isr_pulse_handler,
                  NULL);

    ...
}
```

This time, we're telling the resource manager library to put the two checks that we showed in the previous example into its receive loop and call our two handling functions (*my_timer_pulse_handler()* and *my_isr_pulse_handler()*) whenever those codes show up. Much simpler.

Proxies for their contents

If you're looking at proxies for their contents (you're ignoring the fact that it's a proxy and just treating it like a message), then you already have to deal with the fact that you can't reply to a proxy under QNX

4. Under Neutrino, you can't reply to a pulse. What this means is, you've already got code in place that either looks at the proxy ID returned by the receive function and determines that it shouldn't reply, or the proxy has encoded within it special indications that this is a message that shouldn't be replied to.

Unfortunately under Neutrino, you can't stuff arbitrary data into a pulse. A pulse has a well-defined structure, and there's just no getting around that fact. A clever solution would be to "simulate" the message that you'd ordinarily receive from the proxy by using a pulse with a table. The table would contain the equivalent messages that would have been sent by the proxies. When a pulse arrives, you'd use the value field in the pulse as an index into this table and "pretend" that the given proxy message had arrived.

Interrupt service routines

QNX 4's interrupt service routines had the ability to either return a proxy ID (indicating that the proxy should be sent to its owner) or a zero, indicating nothing further needed to be done. Under Neutrino, this mechanism is almost identical, except that instead of returning a proxy, you're returning a pointer to a **`struct sigevent`**. The event that you return can be a pulse, which will give you the "closest" analog to a proxy, or it can be a signal or the creation of a thread. Your choice.

Also, under QNX 4 you *had* to have an interrupt service routine, even if all that the ISR did was return a proxy and nothing else. Under Neutrino, using *InterruptAttachEvent()*, you can bind a **`struct sigevent`** to an interrupt vector, and that event will be delivered every time the vector is activated.

Summary

Porting from QNX 4 to Neutrino, or maintaining a program that must function on both, is possible, if you follow these rules:

- abstract, abstract, and abstract

- decouple, decouple, and decouple

The key is to not tie yourself to a particular "handle" that represents the "connection" between the client and the server, and to not rely on a particular mechanism for finding the server. If you abstract the connection and the detection services into a set of function calls, you can then conditionally compile the code for whatever platform you wish to port to.

The exact same discussion applies to the message transport — always abstract the client's API away from "knowing" how the messages are transported from client to server to some generic API which can then rely upon a single-point transport API; this single-point transport API can then be conditionally compiled for either platform.

Porting a *server* from QNX 4 to Neutrino is more difficult, owing to the fact that QNX 4 servers were generally "hand-made" and didn't follow a rigorous structure like that imposed by the resource manager library under Neutrino. Generally, though, if you're porting something hardware specific (for example, a sound card driver, or a block-level disk driver), the main "code" that you'll be porting has nothing to do with the operating system, and everything to do with the hardware itself. The approach I've adopted in these cases is to code a shell "driver" structure, and provide well-defined hardware-specific functions. The entire shell driver will be different between operating systems, but the hardware-specific functions can be amazingly portable.

Note also that QSSL provides a QNX 4 to Neutrino migration kit — see the online docs.

Appendix B

Calling 911

In this appendix. . .

Seeking professional help

No matter how good a developer you are, there are times when you:

- get stuck with a problem you can't solve
- encounter a bug and wish to report it and/or find a workaround
- need assistance with your design.

In this chapter, we'll look at the resources available when you face these problems.

So you've got a problem...

We'll talk about the first two problems together, because it's often hard to tell which problem you're actually experiencing.

Something no longer works, or doesn't work as expected. What should you do about it?

RTFM

Read the *fine* manual! While this may seem like an obvious first step, it's *amazing* the number of people who don't do this!

All the manuals for the Neutrino operating system are online:

- *Library Reference*
- *System Architecture*
- *Technotes*
- *Utilities Reference*
- *Audio Developer's Guide*
- *Programmer's Guide*
- *DDKs*
- *Photon Documentation (multiple volumes)*

Library Reference

This is the *A through Z* of the C library — use this to find information about each and every function call that's provided by Neutrino's C library. This is the ultimate "authority" on function calls. Often in this book, I've referred you to this library (for example, to find out more about a particular function, such as arguments that aren't commonly used).

System Architecture

A "top-level" architecture document, this describes the Neutrino system from a high-level view, giving enough details about the implementation that you can get a good idea of what the pieces are and how they all fit together.

Technotes

The *Technotes* bookset describes special features of Neutrino and may vary from release to release. Take a look at the online version to see what's in the release you currently have. For example, for the QNX 6.1.0 July 5th 2001 release, the following topics were in the *Technotes* bookset:

- *The QNX 4 Filesystem*
- *Compression Rules with the Flash Filesystem*

Utilities Reference

This is the *A through Z* of the command-line utilities available. It covers all command-line utilities such as **`grep`**, **`make`**, **`ls`**, etc.

Contact technical support

Once you've determined to the best of your abilities that the problem isn't some misunderstanding of the function call or utility you're using, or a mere typo, you may enter the realm of QSSL's technical support department. This is nothing to be afraid of — most customers are extremely pleased with the level of technical support they get from QSSL.

There are two ways of contacting QNX's technical support group: by phone or via the web (QDN — *Q*NX *D*eveloper's *N*etwork).

Before we talk about which method you should use, there are a few things you can do to make the turnaround time on your bug report *much* shorter.

Describe the problem

Often customers try to fix the problems themselves by trying various things that come to mind. This is great. Unfortunately, what tends to happen is that customers get frustrated and post messages something like:

```
I just ran the TCP/IP package connected to a Windows box
and it doesn't work.

What's going on?!?
```

The very next message from tech support looks like the following (I think they should have a standard template for it, myself):

```
Can you describe what you mean by "doesn't work"?  Do you mean
the TCP/IP on the QNX side?  Do you mean the TCP/IP on the
Windows box?  What part of TCP/IP doesn't work?  What are you
trying to do?  What versions of the OS, and TCP/IP package do
you have?  What version of Windows?  What TCP/IP package
were you using there?
```

The moral of the story: if you're having a problem, then you're probably in a hurry for the answer. If you're in a hurry for the answer, supply as much information as possible in your initial post so that someone at QSSL can try right away to reproduce the problem.

Here are the things that tech support almost always asks for:

- precise descriptions of failure
- versions

- configuration
- platform (x86, PPC, etc.)

Precise information

To supply this information, state what you had expected to happen, and what actually happened. In our above example, a much better problem description would have been:

```
I just ran telnet from Neutrino 2.0, patch level "A", to my
Windows box, and, immediately after the login prompt, got a
"Connection closed by foreign host".
```

Versions

The next thing that you should supply is the versions of the various commands that you may have been using. This can be done by using the `ls` and `cksum` commands. For our example above, you'll want to tell tech support which version of the `telnet` command you were using, and the version of the TCP/IP protocol stack etc.

```
# ls -l /usr/bin/telnet /lib/dll/devn-ne2000.so /lib/dll/npm-ttcpip.so
-rwxrwxr-x  1 root     bin          64220 Jun 22 05:36 /usr/bin/telnet
-rwxrwxr-x  1 root     bin          27428 Jun 22 03:29 /lib/dll/devn-ne2000.so
-rwxrwxr-x  1 root     bin          84148 Jun 22 04:15 /lib/dll/npm-ttcpip.so

# cksum /usr/bin/telnet /lib/dll/devn-ne2000.so /lib/dll/npm-ttcpip.so
1217616014      64220 /usr/bin/telnet
  50089252      27428 /lib/dll/devn-ne2000.so
1123749911      84148 /lib/dll/npm-ttcpip.so
```

This gives tech support at least some idea of the dates, sizes, and checksums of some of the products that might be involved in the problem.

If you suspect your problem might be related to a platform-specific interaction, you should of course specify the name, brand, and relevant chipsets used on that particular platform.

Another thing that tech support usually requests, especially if they suspect some problems with insufficient memory, licensing, configuration, etc., is the runtime configuration of your system. You should try to give them an idea of how much memory is installed, how many processes are running, what the approximate load on the system might be, etc.

The more information you have, the faster they can help you.

If you're using a beta...

If you're using a beta version of the product (i.e., you're on QSSL's list of beta sites), all the above information is critical, because you'll typically be using different versions of the software than what is released. Note, however, that the technical support department generally doesn't handle telephone support of beta products. The only way to get help on these is to post in the conference or, if the developer has requested direct contact, talk to the developer. Posting is generally the best solution anyway, because then other members of the beta conference can see what problems are out there and can learn what the solution is (i.e., if it's a bug, what the workaround for it is). In any event, the above information is crucial in order to determine which products you have from the beta release and which ones are "stock."

Also, keep in mind that if you're talking with a developer, they often have a million things on their plates and might not be able to get back to you right away. Sending a friendly "ping" reminder after a few days doesn't hurt. Sending a demanding one after 15 minutes will not gain you any new friends!

An issue that frequently comes up with betas is that you may forget to install an update. Due to the way that the beta process works, missing an update may cause strange behavior on your system. Certain new drivers or resource managers may behave differently towards their respective client programs than they did in previous versions.

In this case, you should ensure (because the support staff will ask!) that you have indeed installed all the beta updates in the order listed.

Reproduce the problem

One of the first things that tech support usually wants to know is, "Does it happen just once in a blue moon, or can you make it happen on demand?"

They don't ask this question idly. If it's a problem that happens infrequently, it's just as serious as a problem that happens regularly. The point is to try to determine how to proceed.

Generally, for problems that happen infrequently, the support staff will recommend that you configure the machine with the operating system and components set up in such a way that when the problem happens again, some form of log will be left around or perhaps the debugger will be invoked so that the problem can be diagnosed later.

For a problem that's easily reproducible, they'll want to reproduce it at QSSL so that they can show the developer on a live system. "Hey, look! It dies when I..."

Narrow it down

Even if it's reproducible, tech support most likely doesn't want to see 6000 lines of C code with a problem buried in the middle of it.

In most cases that I've witnessed, a bug can usually be narrowed down to about 20 to 30 lines of C *at the most.* The only cases where a really large file is actually useful is when reporting bugs with something where you suspect it's a size problem, rather than a library or kernel problem. For example, some utilities may have a default array size that may cause trouble when it needs to resize that array for something bigger. In this case, tech support may ask you for a **tar** file with *everything* in it. Luckily, **tar** files are easy to create. For example, if you're developing your product in **/src/projects/xyzzy** and they want to see everything in that directory, you can perform the following steps:

```
# cd /src/projects
# tar cvf xyzzy.tar xyzzy
```

This will "suck" everything out of the **xyzzy** directory (and *all* subdirectories too!) into the file called **xyzzy.tar**. If this resulting **tar** file is huge, you can save some download time and disk space by compressing it with **gzip**:

```
# gzip -9v xyzzy.tar
xyzzy.tar:       60.2% -- replaced with xyzzy.tar.gz
```

You'd then send the support people the `xyzzy.tar.gz` file (generally by `ftp` rather than as an email attachment `:-)`).

Other sources

There are several resources other than QDN for providing help, information, or services. This is by no means an extensive list, but should get you started in your search for more information.

`qdn.qnx.com`

QSSL's web site (at `http://www.qnx.com`), has a support area at `http://qdn.qnx.com` which is full of useful information and files. The whole idea of the QDN is that it contains a knowledge-base of previous questions and answers, and is searchable, so you may be able to find answers quickly to common problems.

As an example, I found that my CD-ROM wasn't showing up in `/dev/cd0` if I booted my machine without a CD present in the drive. Searching in QDN for the string "cd rom" showed 18 matches. I read one of them, and found the hints that I needed — basically, that I needed to run the driver again, and it would automagically detect the CD-ROM. Total time: 5 minutes.

`www.qnxstart.com`

The *QNX Start* website is an excellent place to reach the QNX community. The website contains various active discussion groups, pointers to source code, and so on.

`comp.os.qnx`

There's a USENET newsgroup called `comp.os.qnx` on the Internet. It was created for QNX users to talk among themselves about problems, features, solutions, and so on.

This newsgroup may or may not be followed by QNX staff (some staff lurk there). Generally, it's used as a way for people who don't have the product to ask questions. The QNX FAQ (*F*requently *A*sked *Q*uestions) is posted periodically to that newsgroup and provides a good way of learning about the product.

If you *need* an answer, QDN is still your best resource.

IRC

There are several IRC servers available, including `irc.qnxstart.com` and `irc.joher.com` — join the `#qnx` channel. You'll be surprised who you can find online (and at what hours!).

`cvs.qnx.com`

QSSL provides a CVS repository for the source code to various pieces of the QNX Realtime Platform. This is the web-based interface to it. Eventually, most of the sourcebase will be placed online there; although you probably won't ever find the kernel source there (QSSL will most likely keep that proprietary), you *will* find things like driver source, and resource manager library source, etc. This is particularly helpful in gaining a deeper understanding of the internal operations of resource managers.

Third-Party Directory — products & consultants

QNX used to publish a *Third-Party Directory* that listed companies with third-party products for QNX (e.g., multiport serial cards, X.25 hardware, software) or who provided design assistance via consulting services.

This book has since been replaced with an online directory available at the main QSSL website.

Training

Finally, several companies offer training courses for QNX products — PARSE Software Devices offers onsite training, see `http://www.parse.com/training`), and QSSL offers onsite as well as periodic training at their facility.

Glossary

absolute timer

A timer with an expiration point defined as a fixed time, for example, January 20, 2005 at 09:43:12 AM, EDT. Contrast with **relative timer**.

alignment

The characteristic that accessing an N-byte data element must be performed only on an address that is a multiple of N. For example, to access a 4-byte integer, the address of the integer must be a multiple of 4 bytes (e.g., 0x2304B008, and not 0x2304B009). On some CPU architectures, an alignment fault will occur if an attempt is made to perform a non-aligned access. On other CPU architectures (e.g., x86) a non-aligned access is simply slower than an aligned access.

asynchronous

Used to indicate that a given operation is not synchronized to another operation. For example, the timer tick interrupt that is generated by the system's timer chip is said to be "asynchronous" to a thread that's requesting a delay of a certain amount of time, because the thread's request is not synchronized in any way to the arrival of the incoming timer tick interrupt. Contrast with **synchronous**.

atomic (operation)

An operation that is "indivisible," that is to say, one that will not get interrupted by any other operation. Atomic operations are critical especially in interrupt service routines and multi-threaded programs, as often a "test and set" sequence of events must occur in one thread without the chance of another thread interrupting this sequence. A sequence can be made atomic from the perspective of multiple threads not interfering with each other through the use of **mutexes** or via *InterruptLock()* and *InterruptUnlock()* when used with **Interrupt service routines**. See the header file `<atomic.h>` as well.

attribute (structure)

A structure used within a **resource manager** that contains information relating to the device that the resource manager is manifesting in the pathname space. If the resource manager is manifesting multiple devices in the pathname space (for example, the serial port resource manager might manifest `/dev/ser1` and `/dev/ser2`) there will be an equal number of attribute structures in the resource manager. Contrast with **OCB**.

barrier (synchronization object)

A thread-level synchronization object with an associated count. Threads that call the blocking barrier call (*pthread_barrier_wait()*) will block until the number of threads specified by the count have all called the blocking barrier call, and then they will all be released. Contrast this with the operation of **semaphores**.

blocking

A means for threads to synchronize to other threads or events. In the blocking state (of which there are about a dozen), a thread doesn't consume any CPU — it's waiting on a list maintained within the kernel. When the event occurs that the thread was waiting for, the thread is **unblocked** and is able to consume CPU again.

channel

An abstract object on which a **server receives a message**. This is the same object to which a **client** creates a **connection** in order to **send a message** to the server. When the channel is created via *ChannelCreate()*, a "channel ID" is returned. This channel ID (or "chid" for short) is what a **resource manager** will advertise as part of its registered mountpoint.

client

Neutrino's **message-passing** architecture is structured around a client/**server** relationship. In the case of the client, it's the one that is requesting services of a particular server. The client generally accesses these services using standard file-descriptor-based function calls (e.g., *lseek()*), which are **synchronous**, in that the client's call doesn't return until the request is completed by the server. A **thread** can be both a client and a server at the same time.

condition variable

A synchronization object used between multiple **threads**, characterized by acting as a rendezvous point where multiple threads can **block**, waiting for a signal (not to be confused with a UNIX-style **signal**). When the signal is delivered, one or more of the threads will **unblock**.

connection The concept of a **client** being attached to a **channel**. A connection is established by the client either directly by calling *ConnectAttach()* or on behalf of the client by the client's C library function *open()*. In either case, the **connection ID** returned is usable as a handle for all communications between the client and the **server**.

connection ID A "handle" returned by *ConnectAttach()* (on the **client** side) and used for all communications between the client and the **server**. The connection ID is *identical* to the traditional C library's "file descriptor." That is to say, when *open()* returns a file descriptor, it's really returning a connection ID.

deadlock A failure condition reached when two threads are mutually **blocked** on each other, with each thread waiting for the other to respond. This condition can be generated quite easily; simply have two threads **send each other a message** — at this point, both threads are waiting for the other thread to **reply to the request**. Since each thread is blocked, it will not have a chance to reply, hence deadlock. To avoid deadlock, **clients** and **servers** should be structured around a **send hierarchy** (see below). (Of course, deadlock can occur with more than two threads; A sends to B, B sends to C, and C sends back to A, for example.)

FIFO (scheduling) In FIFO scheduling, a **thread** will consume CPU until a higher priority thread is ready to run, or until the thread voluntarily **gives up CPU**. If there are no higher priority threads, and the thread does not voluntarily give up CPU, it will run forever. Contrast with **round robin** scheduling.

interrupt service routine Code that gets executed (in privileged mode) by the kernel as a result of a hardware interrupt. This code cannot perform any kernel calls and should return as soon as possible, since it runs at a priority level effectively higher than any other thread priority in the system. Neutrino's interrupt service routines can return a `struct sigevent` that indicates what event, if any, should be triggered.

IOV (I/O Vector)

A structure where each member contains a pointer and a length. Generally used as an array of IOVs, rather than as a single IOV. When used in the array form, this array of structures of pointers and lengths defines a **scatter/gather** list, which allows the **message-passing** operations to proceed much more efficiently (than would otherwise be accomplished by copying data individually so as to form one contiguous buffer).

kernel callouts

The Neutrino operating system can be customized to run on various hardware, without requiring a source license, by supplying kernel callouts to the startup program. Kernel callouts let the developer supply code that knows how to deal with the specifics of the hardware. For example, how to ask an interrupt controller chip about which interrupt fired, or how to interface to the timer chip to be able to arrange for periodic interrupts, etc. This is documented in great depth in the *Building Embedded Systems* book.

message-passing

The Neutrino operating system is based on a message passing model, where all services are provided in a **synchronous** manner by passing messages around from **client** to **server**. The client will **send a message** to the server and **block**. The server will **receive a message** from the client, perform some amount of processing, and then **reply to the client's message**, which will **unblock** the client.

MMU (Memory Management Unit)

A piece of hardware (usually embedded within the CPU) that provides for **virtual address** to **physical address** translation, and can be used to implement a **virtual memory** system. Under Neutrino, the primary benefit of an MMU is the ability to detect when a **thread** has accessed a virtual address that is not mapped into the **process's** address space.

mutex

A *Mut*ual *Ex*clusion object used to serialize a number of threads so that only one thread at a time has access to the resources defined by the mutex. By using a mutex every time (for example) that you access a given variable, you're ensuring that only one thread at a time has access to that variable, preventing race conditions. See also **atomic (operation)**.

Neutrino Quoting from the Sudbury Neutrino Observatory web pages (found at `http://www.sno.phy.queensu.ca/`):

> Neutrinos are tiny, possibly massless, neutral elementary particles which interact with matter via the weak nuclear force. The weakness of the weak force gives neutrinos the property that matter is almost transparent to them. The sun, and all other stars, produce neutrinos copiously due to nuclear fusion and decay processes within the core. Since they rarely interact, these neutrinos pass through the sun and the earth (and you) unhindered. Other sources of neutrinos include exploding stars (supernovae), relic neutrinos (from the birth of the universe) and nuclear power plants (in fact a lot of the fuel's energy is taken away by neutrinos). For example, the sun produces over two hundred trillion trillion trillion neutrinos every second, and a supernova blast can unleash 1000 times more neutrinos than our sun will produce in its 10-billion year lifetime. Billions of neutrinos stream through your body every second, yet only one or two of the higher energy neutrinos will scatter from you in your lifetime.

OCB (open context block) A data structure used by a **resource manager** that contains information for each **client's** *open()* call. If a client has opened several files, there will exist a corresponding OCB for each file descriptor that the client has in the respective resource managers. Contrast with the **attribute** (**structure**).

PDP-8 An antique computer, "Programmable Data Processor," manufactured between 1965 and the mid 1970's by Digital Equipment Corporation (now Compaq) with the *coolest* front panel. Also, the first computer I ever programmed. If you have one (particularly a PDP-8/I), or parts, manuals, etc., send me an email (`rk@parse.com`), I collect them! Unfortunately, this wonderful 12-bit machine does *not* run Neutrino `:-(`!

periodic timer See **Repeating timer**

physical address An address that is emitted by the CPU onto the bus connected to the memory subsystem. Since Neutrino runs in **virtual address** mode, this means that an **MMU** must translate the virtual addresses used by the **threads** into physical addresses usable by the memory subsystem. Contrast with **virtual address** and **virtual memory**.

process A non-schedulable entity that occupies memory, effectively acting as a container for one or more **threads**.

pthreads Common name given to the set of function calls of the general form pthread_*(). The vast majority of these function calls are defined by the POSIX committee, and are used with **threads**.

pulse A non-blocking message which is **received** in a manner similar to a **regular message**. It is non-blocking for the sender, and can be waited upon by the receiver using the standard message-passing functions *MsgReceive()* and *MsgReceivev()* or the special pulse-only receive function *MsgReceivePulse()*. While most messages are typically sent from **client** to **server**, pulses are generally sent in the opposite direction, so as not to break the **send hierarchy** (breaking which would cause **deadlock**). Contrast with **signal**.

QNX Software Systems Limited The company responsible for the QNX 2, QNX 4, and Neutrino operating systems.

QSSL An abbreviation for **QNX Software Systems Limited**.

receive a message A thread can receive a message by calling *MsgReceive()* or *MsgReceivev()*. If there is no message available, the thread will **block**, waiting for one. See **Message passing**. A thread that receives a message is said to be a **Server**.

receive ID

When a **server receives a message** from a **client**, the server's *MsgReceive()* or *MsgReceivev()* function returns a "receive ID" (often abbreviated in code as *rcvid*). This *rcvid* then acts as a handle to the **blocked** client, allowing the server to **reply with the data** back to the client, effectively unblocking the client. Once the *rcvid* has been used in a reply operation, the *rcvid* ceases to have any meaning for all function calls, except *MsgDeliverEvent()*.

relative timer

A timer that has an expiration point defined as an offset from the current time, for example, 5 minutes from now. Contrast with **absolute timer**.

repeating timer

An **absolute** or **relative** timer that, once expired, will automatically reload with another relative interval and will keep doing that until it is canceled. Useful for receiving periodic notifications.

reply to a message

A **server** will reply to a **client's** message in order to deliver the results of the client's request back to the client.

resource manager

Also abbreviated "resmgr." This is a **server** process which provides certain well-defined file-descriptor-based services to arbitrary **clients**. A resource manager supports a limited set of messages, which correspond to standard client C library functions such as *open()*, *read()*, *write()*, *lseek()*, *devctl()*, etc.

round robin (scheduling)

In Round Robin (or "RR") scheduling, a **thread** will consume CPU until a higher priority thread is ready to run, until the thread voluntarily **gives up CPU**, or until the thread's timeslice expires. If there are no higher priority threads, the thread doesn't voluntarily give up CPU, and there are no other threads at the same priority, it will run forever. If all the above conditions are met except that a thread at the same priority is ready to run, then this thread will give up CPU after its timeslice expires, and the other thread will be given a chance to run. Contrast with **FIFO** scheduling.

scatter/gather Used to define the operation of **message passing** where a number of different pieces of data are "gathered" by the kernel (on either the **client** or **server** side) and then "scattered" into a (possibly) different number of pieces of data on the other side. This is extremely useful when, for example, a header needs to be prepended to the client's data before it's sent to the server. The client would set up an **IOV** which would contain a pointer and length of the header as the first element, and a pointer and length of the data as the second element. The kernel would then "gather" this data as if it were one contiguous piece and **send** it to the server. The server would operate analogously.

semaphore A **thread** synchronization primitive characterized by having a count associated with it. Threads may call the *sem_wait()* function and not **block** if the count was non-zero at the time of the call. Every thread that calls *sem_wait()* decrements the count. If a thread calls *sem_wait()* when the count is zero, the thread will block until some other thread calls *sem_post()* to increment the count. Contrast with **barrier**.

send a message A thread can send a message to another thread. The *MsgSend*()* series of functions are used to send the message; the sending thread blocks until the receiving thread **replies to the message**. See **Message passing**. A thread that sends a message is said to be a **Client**.

send hierarchy A design paradigm whereby **messages sent** flow in one direction, and **messages replied to** flow in another direction. The primary purpose of having a send hierarchy is to avoid **deadlock**. A send hierarchy is accomplished by assigning **clients** and **servers** a "level," and ensuring that messages that are being sent go only to a higher level. This avoids the potential for deadlock where two threads would send to each other, because it would violate the send hierarchy — one thread should not have sent to the other thread, as that other thread must have been at a lower level.

server A server is a regular, user-level **process** that provides certain types of functionality (usually file-descriptor-based) to **clients**. Servers are typically **Resource Managers**, and there's an extensive library provided by **QSSL** which performs much of the functionality of a resource manager for you. The server's job is to **receive messages** from clients, process them, and then **reply to the messages**, which **unblocks** the clients. A **thread** can be both a client and a server at the same time.

signal

A mechanism dating back to early UNIX systems that is used to send **asynchronous** notification of events from one **thread** to another. Signals are non-blocking for the sender. The receiver of the signal may decide to treat the signal in a **synchronous** manner by explicitly waiting for it. Contrast with **pulse**.

synchronous

Used to indicate that a given operation has some synchronization to another operation. For example, during a **message-passing operation**, when the **server** does a *MsgReply()* (to reply to the **client**), the unblocking of the client is said to be synchronous to the reply operation. Contrast with **Asynchronous**.

thread

A single, schedulable, flow of execution. Threads are implemented directly within the Neutrino kernel and correspond to the POSIX *pthread*()* function calls. A thread will need to synchronize with other threads (if any) by using various synchronization primitives such as **mutexes**, **condition variables**, **semaphores**, etc. Threads are scheduled in either **FIFO** or **Round Robin** scheduling mode.

unblock

A thread that had been **blocked** will be unblocked when the condition it has been blocked on is met. For example, a thread might be blocked waiting to **receive a message**. When the **message is sent**, the thread will be unblocked.

virtual address

An address that's not necessarily equivalent to a **physical address**. Under Neutrino, all **threads** operate in virtual addressing mode, where, through the magic of an **MMU**, the virtual addresses are translated into physical addresses. Contrast with **physical address** and **virtual memory**.

virtual memory A "virtual memory" system is one in which the **virtual address** space may not necessarily map on a one-to-one basis with the **physical address** space. The typical example (which Neutrino doesn't support as of this writing) is a "paged" system where, in the case of a lack of RAM, certain parts of a **process's** address space may be swapped out to disk. What Neutrino does support is the dynamic mapping of stack pages.

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Getting Started with QNX Neutrino 2

A Guide for Realtime Programmers

Getting Started with QNX Neutrino 2 gives you a thorough treatment of the ins and outs of QNX's next-generation operating system, QNX Neutrino 2. Written in an informal, easy-to-read style, the book allows anyone from junior programmers to seasoned system architects to get a head start on designing and developing robust realtime systems – from tiny embedded control applications to large network-distributed systems.

This book features an in-depth treatment of the fundamental components of QNX Neutrino. Here are some of the highlights:

- message passing – what it is, how to use it, and why it's key
- processes and threads – concepts, caveats, and design tips
- timers – how to schedule periodic events in your programs
- resource managers – all about how to write device drivers
- interrupts – how to handle them efficiently and effectively

This book comes with many *tested* code samples, explanations, and diagrams to help you understand all the concepts involved. The author's web site, `www.parse.com`, contains the code samples from the book as well as periodic updates.

Praise for the author's previous book, Getting Started with QNX 4:

"*Getting Started with QNX 4* is an excellent reference; I wish all OS books were written like that."

Dr. J. A. Rueda, Data Networks Management and Performance,
TRLabs, Winnipeg, Manitoba, Canada

"*Even with many years of experience using QNX, and knowledge of the subjects covered, I enjoyed reading the book, and no doubt learned some finer points. I can highly recommend this book to anyone interested in this subject matter.*"

Mitchell Schoenbrun, Micro Business Applications, San Francisco, California, USA

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