QNX® NEUTRINO® RTOS V6.3

PROGRAMMER'S GUIDE

QNX SOFTWARE SYSTEMS

QNX® Neutrino® Realtime Operating System

Programmer's Guide

For QNX® Neutrino® 6.3

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About This Book

Typographical conventions

Throughout this manual, 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*
User-interface components	**Cancel**

We format single-step instructions like this:

➤ To reload the current page, press Ctrl – R.

We use an arrow (→) in directions for accessing menu items, like this:

You'll find the **Other...** menu item under **Perspective→Show View**.

We use notes, cautions, and warnings to highlight important messages:

Notes point out something important or useful.

CAUTION: Cautions tell you about commands or procedures that may have unwanted or undesirable side effects.

WARNING: Warnings tell you about commands or procedures that could be dangerous to your files, your hardware, or even yourself.

Note to Windows users

In our documentation, we use a forward slash (/) as a delimiter in *all* pathnames, including those pointing to Windows files.

We also generally follow POSIX/UNIX filesystem conventions.

What you'll find in this guide

The Neutrino *Programmer's Guide* is intended for developers who are building applications that will run under the QNX Neutrino Realtime Operating System.

Depending on the nature of your application and target platform, you may also need to refer to *Building Embedded Systems*. If you're using the Integrated Development Environment, see the IDE *User's Guide*.

This table may help you find what you need in the *Programmer's Guide*:

When you want to:	Go to:
Get started with a "Hello, world!" program	Compiling and Debugging
Get an overview of the Neutrino process model and scheduling methods	Programming Overview
Create and terminate processes	Processes
Develop a device driver and/or resource manager	Writing a Resource Manager
Use native networking	Transparent Distributed Processing Using Qnet
Learn about ISRs in Neutrino	Writing an Interrupt Handler
Analyze and detect problems related to dynamic memory management	Heap Analysis: Making Memory Errors a Thing of the Past

continued…

When you want to:	Go to:
Deal with non-x86 issues (e.g. big-endian vs little-endian)	Appendix A: Freedom from Hardware and Platform Dependencies
Understand our makefile methodology	Appendix B: Conventions for Makefiles and Directories
Write programs for SMP machines	Appendix C: Developing SMP Systems
Learn how to use the GDB debugger	Appendix D: Using GDB
Find out about using memory on ARM targets	Appendix E: ARM Memory Management
Find out about advanced Qnet topics	Appendix F: Advanced Qnet Topics

This guide also contains a glossary of terms used in the QNX Neutrino OS docs.

We assume that you've already installed Neutrino and that you're familiar with its architecture. For a detailed overview, see the *System Architecture* manual.

Note to Windows users

In the QNX documentation, we use a forward slash (/) as a delimiter in *all* pathnames, including those pointing to Windows files.

We also generally follow POSIX/UNIX filesystem conventions.

Recommended reading

For the most part, the information that's documented in the *Programmer's Guide* is specific to QNX. For more general information, we recommend the following books:

Threads:

- Butenhof, David R. 1997. *Programming with POSIX Threads*. Reading, MA: Addison-Wesley Publishing Company. ISBN 0-201-63392-2.

TCP/IP programming (note that some of the advanced API features mentioned in the following books might not be supported):

- Hunt, Craig. 2002. *TCP/IP Network Administration*. Sebastopol, CA: O'Reilly & Associates. ISBN 0-596-00297-1.
- Stevens, W. Richard. 1997. *Unix Network Programming: Networking APIs: Sockets and XTI*. Upper Saddle River, NJ: Prentice-Hall PTR. ISBN 0-13-490012-X.
- — . 1993. *TCP/IP Illustrated, Volume 1 The Protocols*. Reading, MA: Addison-Wesley Publishing Company. ISBN 0-201-63346-9.
- — . 1995. *TCP/IP Illustrated, Volume 2 The Implementation*. Reading, MA: Addison-Wesley Publishing Company. ISBN 0-201-63354-X.

Chapter 1

Compiling and Debugging

In this chapter. . .

Choosing the version of the OS

The QNX Momentics development suite lets you install and work with multiple versions of Neutrino. Whether you're using the command line or the IDE, you can choose which version of the OS to build programs for.

Coexistence of 6.3.0 and 6.2.1 is supported only on Windows and Solaris hosts.

When you install QNX Momentics, you get a set of configuration files that indicate where you've install the software. The **QNX_CONFIGURATION** environment variable stores the location of the configuration files for the installed versions of Neutrino; on a self-hosted Neutrino machine, the default is **`/etc/qconfig`**.

If you're using the command-line tools, use the **`qconfig`** utility to configure your machine to use a specific version of Neutrino.

On Windows hosts, use **`QWinCfg`**, a graphical front end for **`qconfig`**. You can launch it from the Start menu.

Here's what **`qconfig`** does:

- If you run it without any options, **`qconfig`** lists the versions that are installed on your machine.
- If you use the **`-e`** option, you can use **`qconfig`** to set up the environment for building software for a specific version of the OS. For example, if you're using the Korn shell (**`ksh`**), you can configure your machine like this:

  ```
  eval `qconfig -n "QNX Neutrino 6.3.0" -e`
  ```

When you start the IDE, it uses your current **`qconfig`** choice as the default version of the OS; if you haven't chosen a version, the IDE chooses an entry from the directory identified by **QNX_CONFIGURATION**. If you want to override the IDE's choice,

you can choose the appropriate build target. For details, see "Version coexistence" in the Concepts chapter of the IDE *User's Guide*.

Neutrino uses these environment variables to locate files on the *host* machine:

QNX_HOST The location of host-specific files.

QNX_TARGET
The location of target backends on the host machine.

The **qconfig** utility sets these variables according to the version of QNX Momentics that you specified.

Conforming to standards

The header files supplied with the C library provide the proper declarations for the functions and for the number and types of arguments used with them. Constant values used in conjunction with the functions are also declared. The files can usually be included in any order, although individual function descriptions show the preferred order for specific headers.

When the **-ansi** option is used, **qcc** compiles strict ANSI code. Use this option when you're creating an application that must conform to the ANSI standard. The effect on the inclusion of ANSI- and POSIX-defined header files is that certain portions of the header files are omitted:

- for ANSI header files, these are the portions that go beyond the ANSI standard
- for POSIX header files, these are the portions that go beyond the POSIX standard

You can then use the **qcc -D** option to define *feature-test macros* to select those portions that are omitted. Here are the most commonly used feature-test macros:

_POSIX_C_SOURCE=199506

Include those portions of the header files that relate to the POSIX standard (*IEEE Standard Portable Operating System Interface for Computer Environments - POSIX 1003.1*, 1996)

_FILE_OFFSET_BITS=64

Make the libraries use 64-bit file offsets.

_LARGEFILE64_SOURCE

Include declarations for the functions that support large files (those whose names end with **64**).

_QNX_SOURCE

Include everything defined in the header files. This is the default.

Feature-test macros may be defined on the command line, or in the source file before any header files are included. The latter is illustrated in the following example, in which an ANSI- and POSIX-conforming application is being developed.

```
#define _POSIX_C_SOURCE=199506
#include <limits.h>
#include <stdio.h>
   .
   .
   .
#if defined(_QNX_SOURCE)
  #include "non_POSIX_header1.h"
  #include "non_POSIX_header2.h"
  #include "non_POSIX_header3.h"
#endif
```

The source code is then compiled using the **-ansi** option.

The following ANSI header files are affected by the _POSIX_C_SOURCE feature test macro:

- **<limits.h>**
- **<setjmp.h>**
- **<signal.h>**

- **<stdio.h>**
- **<stdlib.h>**
- **<time.h>**

The following ANSI and POSIX header files are affected by the _QNX_SOURCE feature test macro:

Header file	Type
<ctype.h>	ANSI
<fcntl.h>	POSIX
<float.h>	ANSI
<limits.h>	ANSI
<math.h>	ANSI
<process.h>	extension to POSIX
<setjmp.h>	ANSI
<signal.h>	ANSI
<sys/stat.h>	POSIX
<stdio.h>	ANSI
<stdlib.h>	ANSI
<string.h>	ANSI
<termios.h>	POSIX
<time.h>	ANSI
<sys/types.h>	POSIX
<unistd.h>	POSIX

Header files in /usr/include

The **${QNX_TARGET}/usr/include** directory includes at least the following subdirectories (in addition to the usual **sys**):

arpa ARPA header files concerning the Internet, FTP and TELNET.

hw Descriptions of various hardware devices.

arm, **mips**, **ppc**, **sh**, **x86**

CPU-specific header files. You typically don't need to include them directly — they're included automatically. There are some files that you might want to look at:

- Files ending in ***intr.h** describe interrupt vector numbers for use with *InterruptAttach()* and *InterruptAttachEvent()*.
- Files ending with ***cpu.h** describe the registers and other information about the processor.

malloc, **malloc_g**

Memory allocation; for more information, see the Heap Analysis: Making Memory Errors a Thing of the Past chapter in this guide.

net Network interface descriptions.

netinet, **netinet6**, **netkey**

Header files concerning TCP/IP.

photon Header files concerning the Photon microGUI; for more information, see the Photon documentation.

snmp Descriptions for the Simple Network Management Protocol (SNMP).

Self-hosted or cross-development

In the rest of this chapter, we'll describe how to compile and debug a Neutrino system. Your Neutrino system might be anything from a deeply embedded turnkey system to a powerful multiprocessor server. You'll develop the code to implement your system using development tools running on the Neutrino platform itself or on any other supported cross-development platform.

Neutrino supports both of these development types:

- *self-hosted* — you develop and debug on the same system
- *cross-development* — you develop on your host system, then transfer and debug the executable on your target hardware

This section describes the procedures for compiling and debugging for both types.

A simple example

We'll now go through the steps necessary to build a simple Neutrino system that runs on a standard PC and prints out the text "Hello, world!" — the classic first C program.

Let's look at the spectrum of methods available to you to run your executable:

If your environment is:	Then you can:
Self-hosted	Compile and link, then run on host
Cross-development, network filesystem link	Compile and link, load over network filesystem, then run on target

continued...

If your environment is:	Then you can:
Cross-development, debugger link	Compile and link, use debugger as a "network filesystem" to transfer executable over to target, then run on target
Cross-development, rebuilding the image	Compile and link, rebuild entire image, reboot target.

Which method you use depends on what's available to you. All the methods share the same initial step — write the code, then compile and link it for Neutrino on the platform that you wish to run the program on.

You can choose how you wish to compile and link your programs: you can use tools with a command-line interface (via the **qcc** command) or you can use an IDE (Integrated Development Environment) with a graphical user interface (GUI) environment. Our samples here illustrate the command-line method.

The "Hello, world!" program itself is very simple:

```
#include <stdio.h>

int
main (void)
{
    printf ("Hello, world!\n");
    return (0);
}
```

You compile it for PowerPC (big-endian) with the single line:

```
qcc -V gcc_ntoppcbe hello.c -o hello
```

This executes the C compiler with a special cross-compilation flag, **-V gcc_ntoppcbe**, that tells the compiler to use the **gcc** compiler, Neutrino-specific includes, libraries, and options to create a PowerPC (big-endian) executable using the GCC compiler.

To see a list of compilers and platforms supported, simply execute the command:

```
qcc -V
```

If you're using an IDE, refer to the documentation that came with the IDE software for more information.

At this point, you should have an executable called **hello**.

Self-hosted

If you're using a self-hosted development system, you're done. You don't even have to use the **-V** cross-compilation flag (as was shown above), because the **qcc** driver will default to the current platform. You can now run **hello** from the command line:

```
hello
```

Cross-development with network filesystem

If you're using a network filesystem, let's assume you've already set up the filesystem on both ends. For information on setting this up, see the Sample Buildfiles appendix in *Building Embedded Systems*.

Using a network filesystem is the richest cross-development method possible, because you have access to remotely mounted filesystems. This is ideal for a number of reasons:

- Your embedded system requires only a network connection; no disks (and disk controllers) are required.
- You can access all the shipped and custom-developed Neutrino utilities — they don't need to be present on your (limited) embedded system.
- Multiple developers can share the same filesystem server.

For a network filesystem, you'll need to ensure that the shell's **PATH** environment variable includes the path to your executable via the network-mounted filesystem. At this point, you can just type the name of the executable at the target's command-line prompt (if you're running a shell on the target):

```
hello
```

Cross-development with debugger

Once the debug agent is running, and you've established connectivity between the host and the target, you can use the debugger to download the executable to the target, and then run and interact with it.

Download/upload facility

When the debug agent is connected to the host debugger, you can transfer files between the host and target systems. Note that this is a general-purpose file transfer facility — it's not limited to transferring only executables to the target (although that's what we'll be describing here).

In order for Neutrino to execute a program on the target, the program must be available for loading from some type of filesystem. This means that when you transfer executables to the target, you must write them to a filesystem. Even if you don't have a conventional filesystem on your target, recall that there's a writable "filesystem" present under Neutrino — the **`/dev/shmem`** filesystem. This serves as a convenient RAM-disk for downloading the executables to.

Cross-development, deeply embedded

If your system is deeply embedded and you have no connectivity to the host system, or you wish to build a system "from scratch," you'll have to perform the following steps (in addition to the common step of creating the executable(s), as described above):

1. Build a Neutrino system image.

2. Transfer the system image to the target.
3. Boot the target.

Step 1: Build a Neutrino system image.

You use a *buildfile* to build a Neutrino system image that includes your program. The buildfile contains a list of files (or modules) to be included in the image, as well as information about the image. A buildfile lets you execute commands, specify command arguments, set environment variables, and so on. The buildfile will look like this:

```
[virtual=ppcbe,elf] .bootstrap = {
    startup-800fads
    PATH=/proc/boot procnto-800
}
[+script] .script = {
    devc-serppc800 -e -c20000000 -b9600 smc1 &
    reopen
    hello
}

[type=link] /dev/console=/dev/ser1
[type=link] /usr/lib/ldqnx.so.2=/proc/boot/libc.so
[perms=+r,+x]
libc.so

[data=copy]
[perms=+r,+x]
devc-serppc800
hello
```

The first part (the four lines starting with **`[virtual=ppcbe,elf]`**), contains information about the kind of image we're building.

The next part (the five lines starting with **`[+script]`**) is the startup script that indicates what executables (and their command-line parameters, if any) should be invoked.

The **`[type=link]`** lines set up symbolic links to specify the serial port and shared library file we want to use.

The runtime linker is expected to be found in a file called **ldqnx.so.2**, but the runtime linker is currently contained within the **libc.so** file, so we make a process manager symbolic link to it.

The **[perms=+r,+x]** lines assign permissions to the binaries that follow — in this case, we're setting them to be Readable and Executable.

Then we include the C shared library, **libc.so**.

Then the line **[data=copy]** specifies to the loader that the data segment should be copied. This applies to all programs that follow the **[data=copy]** attribute. The result is that we can run the executable multiple times.

Finally, the last part (the last two lines) is simply the list of files indicating which files should be included as part of the image. For more details on buildfile syntax, see the **mkifs** entry in the *Utilities* Reference.

Our sample buildfile indicates the following:

- A PowerPC 800 FADS board and ELF boot prefix code are being used to boot.
- The image should contain **devc-serppc800**, the serial communications manager for the PowerPC 80x family, as well as **hello** (our test program).
- **devc-serppc800** should be started in the background (specified by the **&** character). This manager will use a clock rate of 20 MHz, a baud rate of 9600, and an **smc1** device.
- Standard input, output, and error should be redirected to **/dev/ser1** (via the **reopen** command, which by default redirects to **/dev/console**, which we've linked to **/dev/ser1**).
- Finally, our **hello** program should run.

Let's assume that the above buildfile is called **hello.bld**. Using the **mkifs** utility, you could then build an image by typing:

```
mkifs hello.bld hello.ifs
```

Step 2: Transfer the system image to the target.

You now have to transfer the image **`hello.ifs`** to the target system. If your target is a PC, the most universal method of booting is to make a bootable floppy diskette.

If you're developing on a platform that has TCP/IP networking and connectivity to your target, you may be able to boot your Neutrino target system using a BOOTP server. For details, see the "BOOTP section" in the Customizing IPL Programs chapter in *Building Embedded Systems*.

If your development system is Neutrino, transfer your image to a floppy by issuing this command:

```
dinit -f hello.ifs /dev/fd0
```

If your development system is Windows NT or Windows 95/98, transfer your image to a floppy by issuing this command:

```
dinit -f hello.ifs a:
```

Step 3: Boot the target.

Place the floppy diskette into your target system and reboot your machine. The message "**`Hello, world!`**" should appear on your screen.

Using libraries

When you're developing code, you almost always make use of a *library* — a collection of code modules that you or someone else has already developed (and hopefully debugged). Under Neutrino, we have three different ways of using libraries:

- static linking
- dynamic linking
- runtime loading

Static linking

You can combine your modules with the modules from the library to form a single executable that's entirely self-contained. We call this *static linking*. The word "static" implies that it's not going to change — *all* the required modules are already combined into one executable.

Dynamic linking

Rather than build a self-contained executable ahead of time, you can take your modules and link them in such a way that the Process Manager will link them to the library modules before your program runs. We call this *dynamic linking*. The word "dynamic" here means that the association between your program and the library modules that it uses is done *at load time*, not at linktime (as was the case with the static version).

Runtime loading

There's a variation on the theme of dynamic linking called *runtime loading*. In this case, the program decides *while it's actually running* that it wishes to load a particular function from a library.

Static and dynamic libraries

To support the two major kinds of linking described above, Neutrino has two kinds of libraries: *static* and *dynamic*.

Static libraries

A static library is usually identified by a **`.a`** (for "archive") suffix (e.g. **`libc.a`**). The library contains the modules you want to include in your program and is formatted as a collection of ELF object modules

that the linker can then extract (as required by your program) and *bind* with your program at linktime.

This "binding" operation literally copies the object module from the library and incorporates it into your "finished" executable. The major advantage of this approach is that when the executable is created, it's entirely self-sufficient — it doesn't require any other object modules to be present on the target system. This advantage is usually outweighed by two principal disadvantages, however:

- *Every* executable created in this manner has its own private copy of the library's object modules, resulting in large executable sizes (and possibly slower loading times, depending on the medium).
- You must *relink the executable* in order to upgrade the library modules that it's using.

Dynamic libraries

A dynamic library is usually identified by a **`.so`** (for "shared object") suffix (e.g. **`libc.so`**). Like a static library, this kind of library also contains the modules that you want to include in your program, but these modules are *not* bound to your program at linktime. Instead, your program is linked in such a way that the Process Manager causes your program to be bound to the shared objects at load time.

The Process Manager performs this binding by looking at the program to see if it references any shared objects (**`.so`** files). If it does, then the Process Manager looks to see if those particular shared objects are already present in memory. If they're not, it loads them into memory. Then the Process Manager patches your program to be able to use the shared objects. Finally, the Process Manager starts your program.

Note that from your program's perspective, it isn't even aware that it's running with a shared object versus being statically linked — that happened before the first line of your program ran!

The main advantage of dynamic linking is that the programs in the system will reference only a particular set of objects — they don't contain them. As a result, programs are smaller. This also means that you can upgrade the shared objects *without relinking the programs*.

This is especially handy when you don't have access to the source code for some of the programs.

dlopen()

When a program decides at runtime that it wants to "augment" itself with additional code, it will issue the *dlopen()* function call. This function call tells the system that it should find the shared object referenced by the *dlopen()* function and create a binding between the program and the shared object. Again, if the shared object isn't present in memory already, the system will load it. The main advantage of this approach is that the program can determine, at runtime, which objects it needs to have access to.

Note that there's no *real* difference between a library of shared objects that you link against and a library of shared objects that you load at runtime. Both modules are of the exact same format. The only difference is in how they get used.

By convention, therefore, we place libraries that you link against (whether statically or dynamically) into the **`lib`** directory, and shared objects that you load at runtime into the **`lib/dll`** (for "dynamically loaded libraries") directory.

Note that this is just a convention — there's nothing stopping you from linking against a shared object in the **`lib/dll`** directory or from using the *dlopen()* function call on a shared object in the **`lib`** directory.

Platform-specific library locations

The development tools have been designed to work out of their processor directories (**`x86`**, **`ppcbe`**, etc.). This means you can use the same toolset for any target platform.

If you have development libraries for a certain platform, then put them into the platform-specific library directory (e.g. **`/x86/lib`**), which is where the compiler tools will look.

You can use the **-L** option to **qcc** to explicitly provide a library path.

Linking your modules

By default, the tool chain links dynamically. We do this because of all the benefits mentioned above.

If you want to link statically, then you should specify the **-static** option to **qcc**, which will cause the link stage to look in the library directory *only* for static libraries (identified by a **.a** extension).

For this release of Neutrino, you can't use the floating point emulator (**fpemu.so**) in statically linked executables.

Although we generally discourage linking statically, it does have this advantage: in an environment with tight configuration management and software QA, the very same executable can be regenerated at linktime and known to be complete at runtime.

To link dynamically (the default), you don't have to do anything.

To link statically *and* dynamically (some libraries linked one way, other libraries linked the other way), the two keywords **-Bstatic** and **-Bdynamic** are positional parameters that can be specified to **qcc**. All libraries specified after the particular **-B** option will be linked in the specified manner. You can have multiple **-B** options:

```
qcc ... -Bdynamic lib1 lib2 -Bstatic lib3 lib4 -Bdynamic lib5
```

This will cause libraries **lib1**, **lib2**, and **lib5** to be dynamically linked (i.e. will link against the files **lib1.so**, **lib2.so** and **lib5.so**), and libraries **lib3** and **lib4** to be statically linked (i.e. will link against the files **lib3.a** and **lib4.a**).

You may see the extension **.1** appended to the name of the shared object (e.g. **libc.so.1**). This is a version number. Use the extension **.1** for your first revision, and increment the revision number if required.

You may wish to use the above "mixed-mode" linking because some of the libraries you're using will be needed by only one executable or because the libraries are small (less than 4 KB), in which case you'd be wasting memory to use them as shared libraries. Note that shared libraries are typically mapped in 4-KB pages and will require at least one page for the "**text**" section and possibly one page for the "**data**" section.

When you specify **-Bstatic** or **-Bdynamic**, *all* subsequent libraries will be linked in the specified manner.

Creating shared objects

To create a shared object suitable for linking against:

1. Compile the source files for the library using the **-shared** option to **qcc**.
2. To create the library from the individual object modules, simply combine them with the linker (this is done via the **qcc** compiler driver as well, also using the **-shared** command-line option).

Make sure that all objects and "static" libs that are pulled into a **.so** are position-independent as well (i.e. also compiled with **-shared**).

If you make a shared library that has to static-link against an existing library, you can't static-link against the **.a** version (because those libraries themselves aren't compiled in a position-independent manner). Instead, there's a special version of the libraries that has a capital "S" just before the **.a** extension. For example, instead of linking against **libsocket.a**, you'd link against **libsocketS.a**. We recommend that you don't static-link, but rather link against the **.so** shared object version.

Specifying an internal name

When you're building a shared object, you can specify the following option to **qcc**:

"-Wl,-h*name***"**

(You might need the quotes to pass the option through to the linker intact, depending on the shell.)

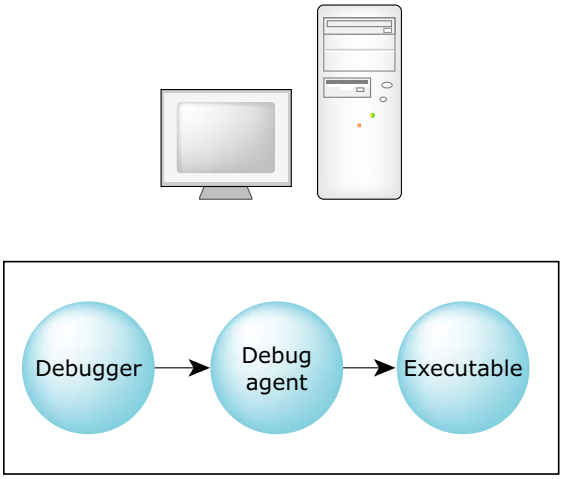
This option sets the internal name of the shared object to *name* instead of to the object's pathname, so you'd use *name* to access the object when dynamically linking. You might find this useful when doing cross-development (e.g. from a Windows NT system to a Neutrino target).

Debugging

Now let's look at the different options you have for debugging the executable. Just as you have two basic ways of developing (self-hosted and cross-development), you have similar options for debugging.

Debugging in a self-hosted environment

The debugger can run on the same platform as the executable being debugged:

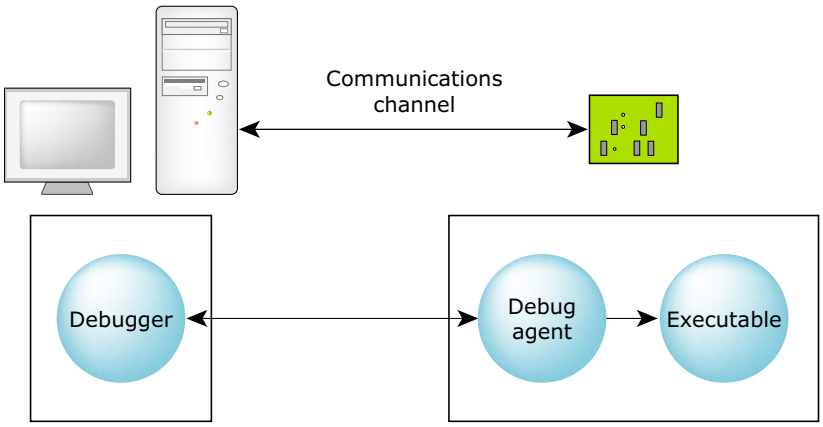


Debugging in a self-hosted environment.

In this case, the debugger starts the debug agent, and then establishes its own communications channel to the debug agent.

Debugging in a cross-development environment

The debugger can run on one platform to debug executables on another:



Debugging in a cross-development environment.

In a cross-development environment, the host and the target systems must be connected via some form of communications channel.

The two components, the debugger and the debug agent, perform different functions. The debugger is responsible for presenting a user interface and for communicating over some communications channel to the debug agent. The debug agent is responsible for controlling (via the **/proc** filesystem) the process being debugged.

All debug information and source remains on the host system. This combination of a small target agent and a full-featured host debugger allows for full symbolic debugging, even in the memory-constrained environments of small targets.

☞ In order to debug your programs with full source using the symbolic debugger, you'll need to tell the C compiler and linker to include symbolic information in the object and executable files. For details, see the **qcc** docs in the *Utilities* Reference. Without this symbolic information, the debugger can provide only assembly-language-level debugging.

The GNU debugger (gdb)

The GNU debugger is a command-line program that provides a very rich set of options. You'll find a tutorial-style doc called "Using GDB" as an appendix in this manual.

Starting gdb

You can invoke **gdb** by using the following variants, which correspond to your target platform:

For this target:	Use this command:
ARM	**ntoarm-gdb**
Intel	**ntox86-gdb**
MIPS	**ntomips-gdb**
PowerPC	**ntoppc-gdb**
SH4	**ntosh-gdb**

For more information, see the **gdb** entry in the *Utilities* Reference.

The process-level debug agent

When a breakpoint is encountered and the process-level debug agent (**pdebug**) is in control, the process being debugged and all its threads are stopped. All other processes continue to run and interrupts remain enabled.

To use the **pdebug** agent, you must set up pty support (via **devc-pty**) on your target.

When the process's threads are stopped and the debugger is in control, you may examine the state of any thread within the process. You may also "freeze" all or a subset of the stopped threads when you continue. For more info on examining thread states, see your debugger docs.

The **pdebug** agent may either be included in the image and started in the image startup script or started later from any available filesystem that contains **pdebug**.

The **pdebug** command-line invocation specifies which device will be used. (Note that for self-hosted debugging, **pdebug** is started automatically by the host debugger.)

You can start **pdebug** in one of three ways, reflecting the nature of the connection between the debugger and the debug agent:

- serial connection
- TCP/IP static port connection
- TCP/IP dynamic port connection

Serial connection

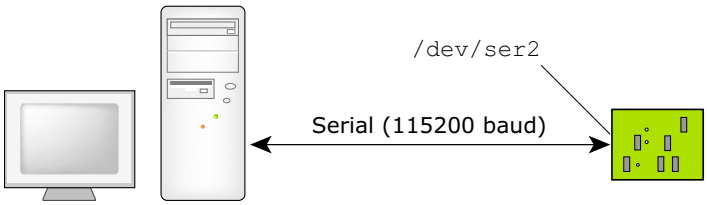
If the host and target systems are connected via a serial port, then the debug agent (**pdebug**) should be started with the following command:

pdebug *devicename*[,*baud*]

This indicates the target's communications channel (*devicename*) and specifies the baud rate (*baud*).

For example, if the target has a **/dev/ser2** connection to the host, and we want the link to be 115,200 baud, we would specify:

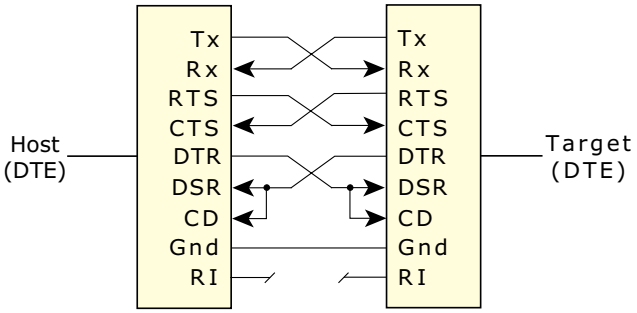
```
pdebug /dev/ser2,115200
```



Running the process debug agent with a serial link at 115200 baud.

The Neutrino target requires a supported serial port. The target is connected to the host using either a null-modem cable, which allows two identical serial ports to be directly connected, or a straight-through cable, depending on the particular serial port provided on the target.

The null-modem cable crosses the **Tx/Rx** data and handshaking lines. In our PowerPC FADS example, you'd use a a straight-through cable. Most computer stores stock both types of cables.



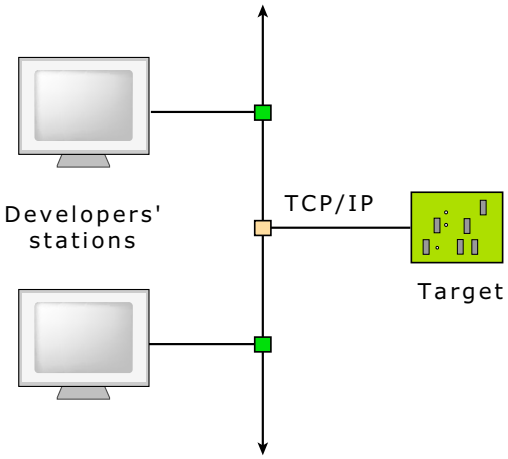
Null-modem cable pinout.

TCP/IP connection

If the host and the target are connected via some form of TCP/IP connection, the debugger and agent can use that connection as well. Two types of TCP/IP communications are possible with the debugger and agent: static port and dynamic port connections (see below).

The Neutrino target must have a supported Ethernet controller. Note that since the debug agent requires the TCP/IP manager to be running on the target, this requires more memory.

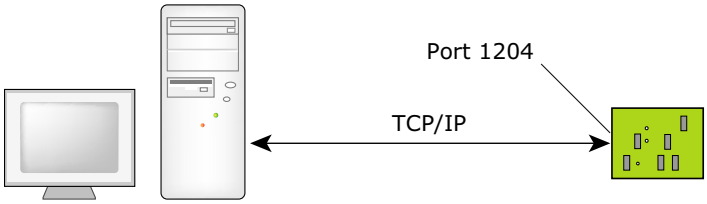
This need for extra memory is offset by the advantage of being able to run multiple debuggers with multiple debug sessions over the single network cable. In a networked development environment, developers on different network hosts could independently debug programs on a single common target.



Several developers can debug a single target system.

TCP/IP static port connection

For a static port connection, the debug agent is assigned a TCP/IP port number and will listen for communications on that port only. For example, the **`pdebug 1204`** command specifies TCP/IP port 1204:



Running the process debug agent with a TCP/IP static port.

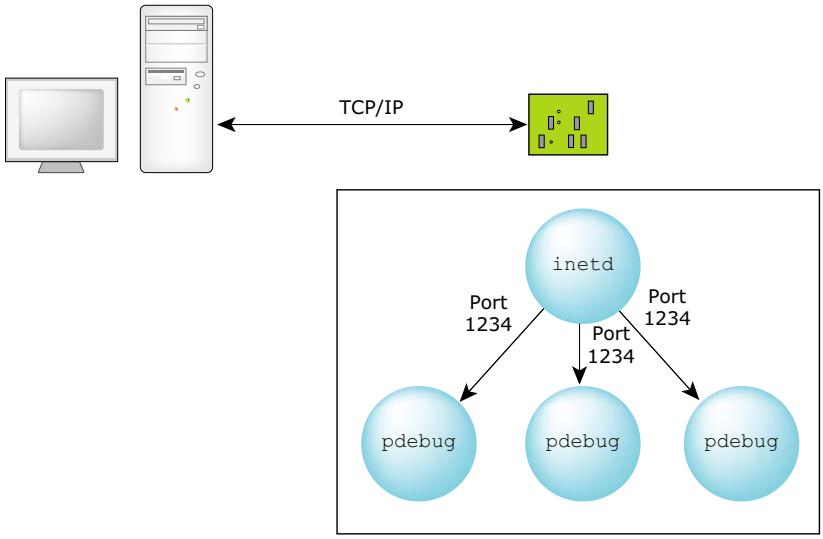
If you have multiple developers, each developer could be assigned a specific TCP/IP port number above the reserved ports **`0`** to **`1024`**.

TCP/IP dynamic port connection

For a dynamic port connection, the debug agent is started by **inetd** and communicates via standard input/output. The **inetd** process fetches the communications port from the configuration file (typically **/etc/services**). The host process debug agent connects to the port via **inetd** — the debug agent has no knowledge of the port.

The command to run the process debug agent in this case is simply as follows (from the **inetd.conf** file):

```
pdebug -
```



*For a TCP/IP dynamic port connection, the **inetd** process will manage the port.*

Note that this method is also suitable for one or more developers.

Sample boot script for dynamic port sessions

The following boot script supports multiple sessions specifying the same port. Although the port for each session on the **pdebug** side is

the same, **inetd** causes unique ports to be used on the debugger side. This ensures a unique socket pair for each session.

Note that **inetd** should be included and started in your boot image. The **pdebug** program should also be in your boot image (or available from a mounted filesystem).

The config files could be built into your boot image (as in this sample script) or linked in from a remote filesystem using the **[type=link]** command:

```
[type=link] /etc/services=/mount_point/services
[type=link] /etc/inetd.conf=/mount_point/inetd.conf
```

Here's the boot script:

```
[virtual=x86,bios +compress] boot = {
    startup-bios -N node428
    PATH=/proc/boot:/bin:/apk/bin_nto:./ procnto
}

[+script] startup-script = {
# explicitly running in edited mode for the console link
    devc-ser8250 -e -b115200 &
    reopen
    display_msg Welcome to Neutrino on a PC-compatible BIOS system
# tcp/ip with a NE2000 Ethernet adaptor
    io-net -dne2000 -pttcpip if=ndi0:10.0.1.172 &
    waitfor /dev/socket
    inetd &
    pipe &
# pdebug needs devc-pty and esh
    devc-pty &
# NFS mount of the Neutrino filesystem
    fs-nfs2 -r 10.89:/x86 /x86 -r 10.89:/home /home &
# CIFS mount of the NT filesystem
    fs-cifs -b //QA:10.0.1.181:/QARoot /QAc apkleywegt 123 &
# NT Hyperterm needs this to interpret backspaces correctly
    stty erase=08
    reopen /dev/console
    [+session] esh
}

[type=link] /usr/lib/ldqnx.so.2=/proc/boot/libc.so
[type=link] /lib=/x86/lib
[type=link] /tmp=/dev/shmem         # tmp points to shared memory
[type=link] /dev/console=/dev/ser2  # no local terminal
```

```
[type=link] /bin=/x86/bin           # executables in the path
[type=link] /apk=/home/apkleywegt   # home dir

[perms=+r,+x]           # Boot images made under MS-Windows
                        # need to be reminded of permissions.
devn-ne2000.so
npm-tcpip.so
libc.so
fpemu.so
libsocket.so

[data=copy]             # All executables that can be restarted
                        # go below.
devc-ser8250
io-net
pipe
devc-pty
fs-nfs2
fs-cifs
inetd
esh
stty
ping
ls
                        # Data files are created in the named
                        # directory.
/etc/hosts = {
127.0.0.1    localhost
10.89        node89
10.222       node222
10.326       node326
10.0.1.181   QA node437
10.241       APP_ENG_1
}

/etc/services = {
ftp           21/tcp
telnet        23/tcp
finger        79/tcp
pdebug        8000/tcp
}

/etc/inetd.conf = {
ftp     stream    tcp    nowait    root    /bin/fdtpd      fdtpd
telnet  stream    tcp    nowait    root    /bin/telnetd    telnetd
finger  stream    tcp    nowait    root    /bin            fingerd
pdebug  stream    tcp    nowait    root    /bin/pdebug     pdebug -
}
```

A simple debug session

In this example, we'll be debugging our "Hello, world!" program via a TCP/IP link. We go through the following steps:

- configuring the target
- compiling for debugging
- starting the debug session
- getting help

Configure the target

Let's assume an x86 target using a basic TCP/IP configuration. The following lines (from the sample boot file at the end of this chapter) show what's needed to host the sample session:

```
io-net -dne2000 -pttcpip if=ndi0:10.0.1.172 &
devc-pty &
[+session] pdebug 8000 &
```

The above specifies that the host IP address is 10.0.1.172 (or 10.428 for short). The **pdebug** program is configured to use port 8000.

Compile for debugging

We'll be using the x86 compiler. Note the **-g** option, which enables debugging information to be included:

```
$ qcc -V gcc_ntox86 -g -o hello hello.c
```

Start the debug session

For this simple example, the sources can be found in our working directory. The **gdb** debugger provides its own shell; by default its prompt is **(gdb)**. The following commands would be used to start the

session. To reduce document clutter, we'll run the debugger in quiet mode:

```
# Working from the source directory:
    (61) con1 /home/allan/src >ntox86-gdb -quiet

# Specifying the target IP address and the port
# used by pdebug:
    (gdb) target qnx 10.428:8000
    Remote debugging using 10.428:8000
    0x0 in ?? ()

# Uploading the debug executable to the target:
# (This can be a slow operation. If the executable
# is large, you may prefer to build the executable
# into your target image.)
# Note that the file has to be in the target system's namespace,
# so we can get the executable via a network filesystem, ftp,
# or, if no filesystem is present, via the upload command.

    (gdb) upload hello /tmp/hello

# Loading the symbolic debug information from the
# current working directory:
# (In this case, "hello" must reside on the host system.)

    (gdb) sym hello
    Reading symbols from hello...done.

# Starting the program:
    (gdb) run /tmp/hello
    Starting program:  /tmp/hello
    Trying to find symbol file for ldqnx.so.2
    Retrying dynamic interpreter in libc.so.1

# Setting the breakpoint on main():
    (gdb) break main
    Breakpoint 1 at 0x80483ae: file hello.c, line 8.

# Allowing the program to continue to the breakpoint
# found at main():
    (gdb) c
    Continuing.
    Breakpoint 1, main () at hello.c:8
    8       setprio (0,9);

# Ready to start the debug session.
(gdb)
```

Get help

While in a debug session, any of the following commands could be used as the next action for starting the actual debugging of the project:

`n`	Next instruction
`l`	List the next set of instructions
`help`	Get the help main menu
`help data`	Get the help data menu
`help inspect`	Get help for the **`inspect`** command
`inspect y`	Inspect the contents of variable *y*
`set y=3`	Assign a value to variable *y*
`bt`	Get a back trace.

Let's see how to use some of these basic commands.

```
# list command:
    (gdb) l
    3
    4   main () {
    5
    6       int x,y,z;
    7
    8       setprio (0,9);
    9       printf ("Hi ya!\n");
    10
    11      x=3;
    12      y=2;

# press <enter> repeat last command:
    (gdb) <enter>
    13      z=3*2;
    14
    15      exit (0);
```

```
    16
    17  }

# break on line 11:
   (gdb) break 11
   Breakpoint 2 at 0x80483c7: file hello.c, line 11.

# continue until the first break point:
    (gdb) c
    Continuing.
    Hi ya!

    Breakpoint 2, main () at hello.c:11
    11      x=3;

# Notice that the above command went past the
# printf statement at line 9. I/O from the
# printf statement is displayed on screen.

# inspect variable y, using short form of the
# inspect command.
    (gdb) ins y
    $1 = -1338755812

# get some help on step and next commands:
    (gdb) help s
    Step program until it reaches a different source line.
    Argument N means do this N times (or till program stops
    for another reason).
    (gdb) help n
    Step program, proceeding through subroutine calls.
    Like the "step" command as long as subroutine calls do not
    happen; when they do, the call is treated as one instruction.
    Argument N means do this N times (or till program stops
    for another reason).

# go to the next line of execution:
    (gdb) n
    12      y=2;
    (gdb) n
    13      z=3*2;
    (gdb) inspect z
    $2 = 1
    (gdb) n
    15      exit (0);
    (gdb) inspe z
    $3 = 6

# continue program execution:
    (gdb) continue
```

```
    Continuing.

    Program exited normally.

# quit the debugger session:
    (gdb) quit
    The program is running. Exit anyway? (y or n) y
    (61) con1 /home/allan/src >
```

Sample boot image

```
[virtual=x86,bios +compress] boot = {
    startup-bios -N node428
    PATH=/proc/boot:./ procnto
}

[+script] startup-script = {
# explicitly running in edited mode for the console link
    devc-ser8250 -e -b115200 &
    reopen
    display_msg Welcome to Neutrino on a PC-compatible BIOS system
# tcp/ip with a NE2000 Ethernet adaptor
    io-net -dne2000 -pttcpip if=ndi0:10.0.1.172 &
    waitfor /dev/socket
    pipe &
# pdebug needs devc-pty
    devc-pty &
# starting pdebug twice on separate ports
    [+session] pdebug 8000 &
}

[type=link] /usr/lib/ldqnx.so.2=/proc/boot/libc.so
[type=link] /lib=/x86/lib
[type=link] /tmp=/dev/shmem         # tmp points to shared memory
[type=link] /dev/console=/dev/ser2  # no local terminal

[perms=+r,+x]         # Boot images made under MS-Windows need
                      # to be reminded of permissions.
devn-ne2000.so
npm-tcpip.so
libc.so
fpemu.so
libsocket.so

[data=copy]            # All executables that can be restarted
                       # go below.
devc-ser8250
```

```
io-net
pipe
devc-pty
pdebug
esh
ping
ls
```

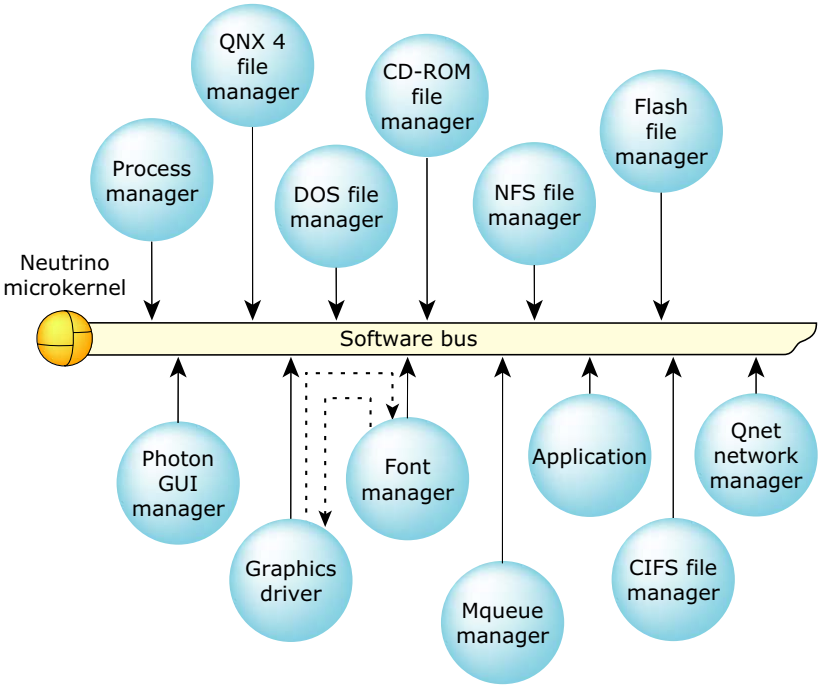
Chapter 2

Programming Overview

In this chapter. . .

Process model

The Neutrino OS architecture consists of the microkernel and some number of cooperating processes. These processes communicate with each other via various forms of interprocess communication (IPC). Message passing is the primary form of IPC in Neutrino.



The Neutrino architecture acts as a kind of "software bus" that lets you dynamically plug in/out OS modules. This picture shows the graphics driver sending a message to the font manager when it wants the bitmap for a font. The font manager responds with the bitmap.

The Photon microGUI windowing system is also made up of a number of cooperating processes: the GUI manager (**Photon**), a font manager (**phfontFA**), the graphics driver manager (**io-graphics**), and others. If the graphics driver needs to draw some text, it sends a message to the font manager asking for bitmaps in the desired font for

the text to be drawn in. The font manager responds with the requested bitmaps, and the graphics driver then draws the bitmaps on the screen.

An application as a set of processes

This idea of using a set of cooperating processes isn't limited to the OS "system processes." Your applications should be written in exactly the same way. You might have some driver process that gathers data from some hardware and then needs to pass that data on to other processes, which then act on that data.

Let's use the example of an application that's monitoring the level of water in a reservoir. Should the water level rise too high, then you'll want to alert an operator as well as open some flow-control valve.

In terms of hardware, you'll have some water-level sensor tied to an I/O board in a computer. If the sensor detects some water, it will cause the I/O board to generate an interrupt.

The software consists of a driver process that talks to the I/O board and contains an *interrupt handler* to deal with the board's interrupt. You'll also have a GUI process that will display an alarm window when told to do so by the driver, and finally, another driver process that will open/close the flow-control valve.

Why break this application into multiple processes? Why not have everything done in one process? There are several reasons:

1 Each process lives in its own *protected memory space*. If there's a bug such that a pointer has a value that isn't valid for the process, then when the pointer is next used, the hardware will generate a fault, which the kernel handles (the kernel will set the SIGSEGV signal on the process).

This approach has two benefits. The first is that a stray pointer won't cause one process to overwrite the memory of another process. The implications are that one process can go bad *while other processes keep running*.

The second benefit is that the fault will occur precisely when the pointer is used, not when it's overwriting some other

process's memory. If a pointer were allowed to overwrite another process's memory, then the problem wouldn't manifest itself until later and would therefore be much harder to debug.

2. It's very easy to add or remove processes from an application as need be. This implies that applications can be made scalable — adding new features is simply a matter of adding processes.

3. Processes can be started and stopped *on the fly*, which comes in handy for dynamic upgrading or simply for stopping an offending process.

4. Processing can be easily distributed across multiple processors in a networked environment.

5. The code for a process is much simpler if it concentrates on doing a single job. For example, a single process that acts as a driver, a GUI front-end, and a data logger would be fairly complex to build and maintain. This complexity would increase the chances of a bug, and any such bug would likely affect all the activities being done by the process.

6. Different programmers can work on different processes without fear of overwriting each other's work.

Processes and threads

Different operating systems often have different meanings for terms such as "process," "thread," "task," "program," and so on.

Some definitions

In the Neutrino OS, we typically use only the terms *process* and *thread*. An "application" typically means a collection of processes; the term "program" is usually equivalent to "process."

A *thread* is a single flow of execution or control. At the lowest level, this equates to the program counter or instruction pointer register advancing through some machine instructions. Each thread has its own current value for this register.

A *process* is a collection of one or more threads that share many things. Threads within a process share at least the following:

- variables that aren't on the stack
- signal handlers (although you typically have one thread that handles signals, and you block them in all the other threads)
- signal ignore mask
- channels
- connections

Threads don't share such things as stack, values for the various registers, SMP thread-affinity mask, and a few other things.

Two threads residing in two different processes don't share very much. About the only thing they do share is the CPU. You can have them share memory between them, but this takes a little setup (see *shm_open()* in the *Library Reference* for an example).

When you run a process, you're automatically running a thread. This thread is called the "main" thread, since the first programmer-provided function that runs in a C program is *main()*. The main thread can then create additional threads if need be.

Only a few things are special about the main thread. One is that if it returns normally, the code it returns to calls *exit()*. Calling *exit()* terminates the process, meaning that all threads in the process are terminated. So when you return normally from the main thread, the process is terminated. When other threads in the process return normally, the code they return to calls *pthread_exit()*, which terminates just that thread.

Another special thing about the main thread is that if it terminates in such a manner that the process is still around (e.g. it calls *pthread_exit()* and there are other threads in the process), then the memory for the main thread's stack is *not* freed up. This is because the command-line arguments are on that stack and other threads may need them. If any other thread terminates, then that thread's stack is freed.

Priorities and scheduling

Although there's a good discussion of priorities and scheduling policies in the *System Architecture* manual (see "Thread scheduling" in the chapter on the microkernel), it will help to go over that topic here in the context of a programmer's guide.

Neutrino provides a priority-driven preemptive architecture. *Priority-driven* means that each thread can be given a priority and will be able to access the CPU based on that priority. If a low-priority thread and a high-priority thread both want to run, then the high-priority thread will be the one that gets to run.

Preemptive means that if a low-priority thread is currently running and then a high-priority thread suddenly wants to run, then the high-priority thread will take over the CPU and run, thereby preempting the low-priority thread.

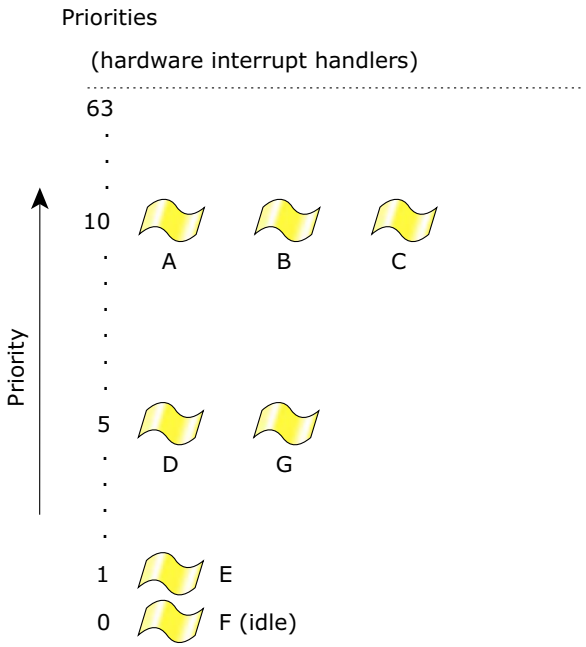
Priority range

Each thread can have a scheduling priority ranging from 1 to 63 (the highest priority), *independent of the scheduling policy*. The special *idle* thread (in the process manager) has priority 0 and is always ready to run. A thread inherits the priority of its parent thread by default.

A thread has both a *real priority* and an *effective priority*, and is scheduled in accordance with its effective priority. The thread itself can change both its real and effective priority together, but the effective priority may change because of priority inheritance or the scheduling policy. Normally, the effective priority is the same as the real priority.

Interrupt handlers are of higher priority than any thread, but they're not scheduled in the same way as threads. If an interrupt occurs, then:

1. Whatever thread was running loses the CPU handling the interrupt (SMP issues).
2. The hardware runs the kernel.
3. The kernel calls the appropriate interrupt handler.



Thread priorities range from 0 (lowest) to 63 (highest). Although interrupt handlers aren't scheduled in the same way as threads, they're considered to be of a higher priority because an interrupt handler will preempt any running thread.

BLOCKED and READY states

To fully understand how scheduling works, you must first understand what it means when we say a thread is BLOCKED and when a thread is in the READY state. You must also understand a particular data structure in the kernel called the *ready queue*.

A thread is BLOCKED if it doesn't want the CPU, which might happen for several reasons, such as:

- The thread is sleeping.
- The thread is waiting for a message from another thread.

- The thread is waiting on a mutex that some other thread owns.

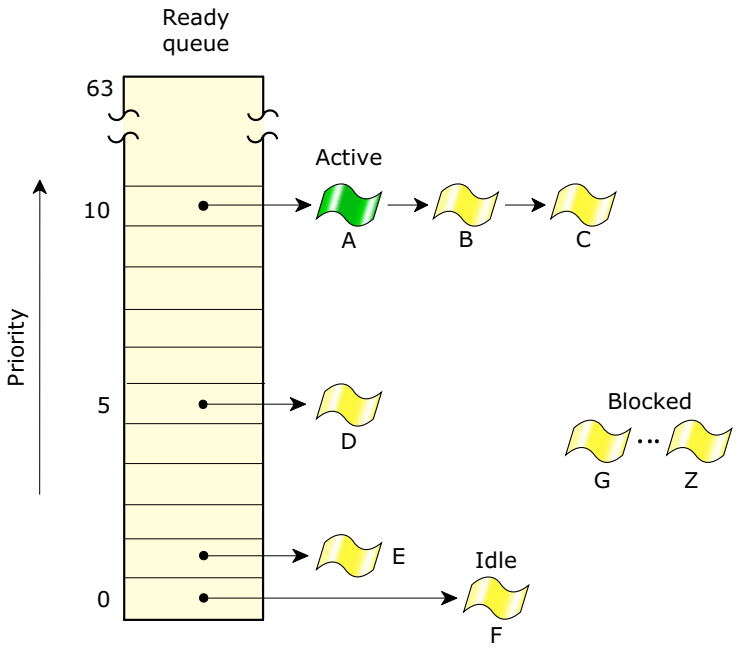
When designing an application, you always try to arrange it so that if any thread is waiting for something, make sure it *isn't spinning in a loop using up the CPU*. In general, try to avoid polling. If you do have to poll, then you should try to sleep for some period between polls, thereby giving lower-priority threads the CPU should they want it.

For each type of blocking there is a blocking state. We'll discuss these states briefly as they come up. Examples of some blocking states are REPLY-blocked, RECEIVE-blocked, MUTEX-blocked, INTERRUPT-blocked, and NANOSLEEP-blocked.

A thread is READY if it wants a CPU but something else currently has it. If a thread currently has a CPU, then it's actually in the RUNNING state, but for simplicity we'll just include it as one of the READY threads. Simply put, a thread that's either READY or RUNNING isn't blocked.

The ready queue

The ready queue is a simplified version of a kernel data structure consisting of a queue with one entry per priority. Each entry in turn consists of another queue of the threads that are READY at the priority. Any threads that aren't READY aren't in any of the queues — but they will be when they become READY.



The ready queue for six threads (A-F) that are READY. All other threads (G-Z) are BLOCKED. Thread A is currently running. Thread A, B, and C are at the highest priority, so they'll share the processor based on the running thread's scheduling algorithm.

The thread at the head of the highest-priority queue is the *active* thread (i.e. actually in the RUNNING state). In diagrams depicting the ready queue, the active thread is always shown in the left uppermost area in the diagram.

Every thread is assigned a priority. The scheduler selects the next thread to run by looking at the priority assigned to every thread in the READY state (i.e. capable of using the CPU). The thread with the highest priority that's at the head of its priority's queue is selected to run. In the above diagram, thread A is at the head of priority 10's queue, so thread A runs.

Suspending a running thread

The execution of a running thread is temporarily suspended whenever the microkernel is entered as the result of a kernel call, exception, or hardware interrupt. A scheduling decision is made whenever the execution state of any thread changes — it doesn't matter which processes the threads might reside within. *Threads are scheduled globally across all processes.*

Normally, the execution of the suspended thread will resume, but the scheduler will perform a context switch from one thread to another whenever the running thread:

- is blocked
- is preempted
- yields

When the thread is blocked

The running thread will block when it must wait for some event to occur (response to an IPC request, wait on a mutex, etc.). The blocked thread is removed from the ready queue, and the highest-priority ready thread that's at the head of its priority's queue is then allowed to run. When the blocked thread is subsequently unblocked, it's placed on the end of the ready queue for its priority level.

When the thread is preempted

The running thread will be preempted when a higher-priority thread is placed on the ready queue (it becomes READY as the result of its block condition being resolved). The preempted thread remains at the start of the ready queue for that priority, and the higher-priority thread runs. When it's time for a thread at that priority level to run again, that thread resumes execution — a preempted thread will not lose its place in the queue for its priority level.

When the thread yields

The running thread voluntarily yields the processor (via *sched_yield()*) and is placed on the end of the ready queue for that priority. The highest-priority thread then runs (which may still be the thread that just yielded).

Scheduling algorithms

To meet the needs of various applications, Neutrino provides these scheduling algorithms:

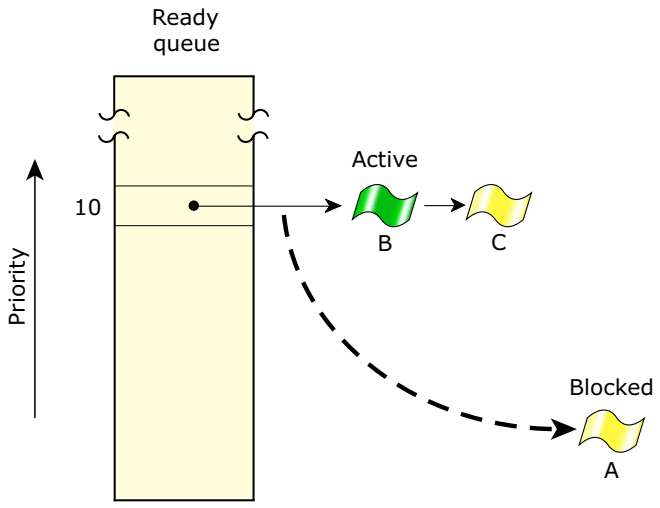
- FIFO scheduling — SCHED_FIFO
- Round-robin scheduling — SCHED_RR
- Sporadic scheduling — SCHED_SPORADIC

Another scheduling algorithm (called "other" — SCHED_OTHER) behaves in the same way as round-robin. We don't recommend using the "other" scheduling algorithm, because its behavior may change in the future.

Each thread in the system may run using any method. Scheduling methods are effective on a per-thread basis, not on a global basis for all threads and processes on a node.

Remember that these scheduling algorithms apply only when two or more threads that share the same priority are READY (i.e. the threads are directly competing with each other). If a higher-priority thread becomes READY, it immediately preempts all lower-priority threads.

In the following diagram, three threads of equal priority are READY. If Thread A blocks, Thread B will run.



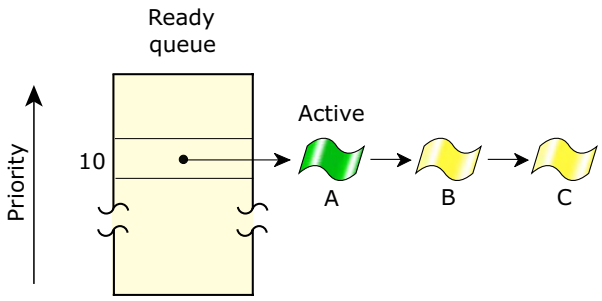
Thread A blocks, Thread B runs.

Although a thread inherits its scheduling algorithm from its parent thread, the thread can request to change the algorithm applied by the kernel.

FIFO scheduling

In FIFO (SCHED_FIFO) scheduling, a thread selected to run continues executing until it:

- voluntarily relinquishes control (e.g. it blocks)
- is preempted by a higher-priority thread

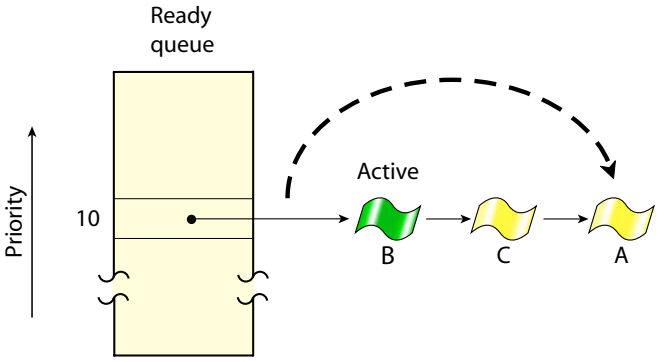


FIFO scheduling. Thread A runs until it blocks.

Round-robin scheduling

In round-robin (SCHED_RR) scheduling, a thread selected to run continues executing until it:

- voluntarily relinquishes control
- is preempted by a higher-priority thread
- consumes its timeslice



Round-robin scheduling. Thread A ran until it consumed its timeslice; the next READY thread (Thread B) now runs.

A *timeslice* is the unit of time assigned to every process. Once it consumes its timeslice, a thread is put at the end of its queue in the ready queue and the next READY thread at the same priority level is given control.

A timeslice is calculated as:

$4 \times$ *ticksize*

If your processor speed is greater than 40 MHz, then the ticksize defaults to 1 millisecond; otherwise, it defaults to 10 milliseconds. So, the default timeslice is either 4 milliseconds (the default for most CPUs) or 40 milliseconds (the default for slower hardware).

Apart from time-slicing, the round-robin scheduling method is identical to FIFO scheduling.

Why threads?

Now that we know more about priorities, we can talk about why you might want to use threads. We saw many good reasons for breaking things up into separate processes, but what's the purpose of a *multithreaded* process?

Let's take the example of a driver. A driver typically has two obligations: one is to talk to the hardware and the other is to talk to other processes. Generally, talking to the hardware is more time-critical than talking to other processes. When an interrupt comes in from the hardware, it needs to be serviced in a relatively small window of time — the driver shouldn't be busy at that moment talking to another process.

One way of fixing this problem is to choose a way of talking to other processes where this situation simply won't arise (e.g. don't send messages to another process such that you have to wait for acknowledgment, don't do any time-consuming processing on behalf of other processes, etc.).

Another way is to use two threads: a higher-priority thread that deals with the hardware and a lower-priority thread that talks to other processes. The lower-priority thread can be talking away to other

processes without affecting the time-critical job at all, because when the interrupt occurs, the *higher-priority thread will preempt the lower-priority thread* and then handle the interrupt.

Although this approach does add the complication of controlling access to any common data structures between the two threads, Neutrino provides synchronization tools such as *mutexes* (mutual exclusion locks), which can ensure exclusive access to any data shared between threads.

Summary

The modular architecture is apparent throughout the entire system: the Neutrino OS itself consists of a set of cooperating processes, as does an application. And each individual process can comprise several cooperating threads. What "keeps everything together" is the priority-based preemptive scheduling in Neutrino, which ensures that time-critical tasks are dealt with by the right thread or process at the right time.

Chapter 3

Processes

In this chapter. . .

As we stated in the Overview chapter, the Neutrino OS architecture consists of a small microkernel and some number of cooperating *processes*. We also pointed out that your applications should be written the same way — as a set of cooperating processes.

In this chapter, we'll see how to start processes (also known as *creating* processes) from code, how to terminate them, and how to detect their termination when it happens.

Starting processes — two methods

In embedded applications, there are two typical approaches to starting your processes at boot time. One approach is to run a *shell script* that contains the command lines for running the processes. There are some useful utilities such as **`exec`**, **`on`**, and **`nice`** for controlling how those processes are started.

The other approach is to have a *starter process* run at boot time. This starter process then starts up all your other processes. This approach has the advantage of giving you more control over how processes are started, whereas the script approach is easier for you (or anyone) to modify quickly.

Process creation

The process manager component of **`procnto`** is responsible for process creation. If a process wants to create another process, it makes a call to one of the process-creation functions, which then effectively sends a message to the process manager.

Here are the process-creation functions:

- *exec*()* family of functions
- *fork()*
- *forkpty()*
- *popen()*
- *spawn()*

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

For details on each of these functions, see their entries in the *Library Reference*. Here we'll mention some of the things common to many of them.

Concurrency

Three possibilities can happen to the creator during process creation:

1 The child process is created and runs concurrently with the parent. In this case, as soon as process creation is successful, the process manager replies to the parent, and the child is made READY. If it's the parent's turn to run, then the first thing it does is return from the process-creation function. This may not be the case if the child process was created at a higher priority than the parent (in which case the child will run before the parent gets to run again).

This is how *fork()*, *forkpty()*, *popen()*, and *spawn()* work. This is also how the *spawn*()* family of functions work when the mode is passed as P_NOWAIT or P_NOWAITO.

2 The child replaces the parent. In fact, they're not really parent and child, because the image of the given process simply replaces that of the caller. Many things will change, but those things that uniquely identify a process (such as the process ID) will remain the same. This is typically referred to as "execing," since usually the *exec*()* functions are used.

Many things will remain the same (including the process ID, parent process ID, and file descriptors) with the exception of file descriptors that had the FD_CLOEXEC flag set using *fcntl()*. See the *exec*()* functions for more on what will and will not be the same across the exec.

The **login** command serves as a good example of execing. Once the login is successful, the **login** command execs into a shell.

Functions you can use for this type of process creation are the *exec*()* and *spawn*()* families of functions, with mode passed as P_OVERLAY.

3 The parent waits until the child terminates. This can be done by passing the mode as P_WAIT for the *spawn*()* family of functions.

Note that what is going on underneath the covers in this case is that *spawn()* is called as in the first possibility above. Then, after it returns, *waitpid()* is called in order to wait for the child to terminate. This means that you can use any of the functions mentioned in our first possibility above to achieve the same thing if you follow them by a call to one of the *wait*()* functions (e.g. *wait()* or *waitpid()*).

Using *fork()* and *forkpty()*

As of this writing, you can't use *fork()* and *forkpty()* in a process that has threads. The *fork()* and *forkpty()* functions will simply return -1 and *errno* will contain **ENOSYS**.

Many programmers coming from the Unix world are familiar with the technique of using a call to *fork()* followed by a call to one of the *exec*()* functions in order to create a process that's different from the caller. In Neutrino, you can usually achieve the same thing in a single call to one of the *spawn*()* functions.

Inheriting file descriptors

The documentation in the *Library Reference* for each function describes in detail what the child inherits from the parent. One thing that we should talk about here, however, is file-descriptor inheritance.

With many of the process-creation functions, the child inherits the file descriptors of the parent. For example, if the parent had file descriptor

5 in use for a particular file when the parent creates the child, the child will also have file descriptor 5 in use for that same file. The child's file descriptor will have been duped from the parent's. This means that at the filesystem manager level, the parent and child have the same open control block (OCB) for the file, so if the child seeks to some position in the file, then that changes the parent's seek position as well. It also means that the child can do a **`write(5, buf, nbytes)`** without having previously called *open()*.

If you don't want the child to inherit a particular file descriptor, then you can use *fcntl()* to prevent it. Note that this won't prevent inheritance of a file descriptor during a *fork()*. The call to *fcntl()* would be:

```
fcntl(fd, F_SETFD, FD_CLOEXEC);
```

If you want the parent to set up exactly which files will be open for the child, then you can use the *fd_count* and *fd_map* parameters with *spawn()*. Note that in this case, only the file descriptors you specify will be inherited. This is especially useful for redirecting the child's standard input (file descriptor 0), standard output (file descriptor 1), and standard error (file descriptor 2) to places where the parent wants them to go.

Alternatively this file descriptor inheritance can also be done through use of *fork()*, one or more calls to *dup()*, *dup2()* and *close()*, and then *exec*()*. The call to *fork()* creates a child that inherits all the of the parent's file descriptors. *dup()*, *dup2()* and *close()* are then used by the child to rearrange its file descriptors. Lastly, *exec*()* is called to replace the child with the process to be created. Though more complicated, this method of setting up file descriptors is portable whereas the *spawn()* method is not.

Process termination

A process can terminate in one of two basic ways:

- normally (e.g. the process terminates itself)

- abnormally (e.g. the process terminates as the result of a signal's being set)

Normal process termination

A process can terminate itself by having any thread in the process call *exit()*. Returning from the main thread (i.e. *main()*) will also terminate the process, because the code that's returned to calls *exit()*. This isn't true of threads other than the main thread. Returning normally from one of them causes *pthread_exit()* to be called, which terminates only that thread. Of course, if that thread is the last one in the process, then the process is terminated.

The value passed to *exit()* or returned from *main()* is called the *exit status*.

Abnormal process termination

A process can be terminated abnormally for a number of reasons. Ultimately, all of these reasons will result in a *signal's being set on the process*. A signal is something that can interrupt the flow of your threads at any time. The default action for most signals is to terminate the process.

Note that what causes a particular signal to be generated is sometimes processor-dependent.

Here are some of the reasons that a process might be terminated abnormally:

- If any thread in the process tries to use a pointer that doesn't contain a valid virtual address for the process, then the hardware will generate a fault and the kernel will handle the fault by setting the SIGSEGV signal on the process. By default, this will terminate the process.
- A floating-point exception will cause the kernel to set the SIGFPE signal on the process. The default is to terminate the process.

- If you create a shared memory object and then map in more than the size of the object, when you try to write past the size of the object you'll be hit with SIGBUS. In this case, the virtual address used is valid (since the mapping succeeded), but the memory cannot be accessed.

To get the kernel to display some diagnostics whenever a process terminates abnormally, configure **procnto** with multiple **-v** options. If the process has fd 2 open, then the diagnostics are displayed using (*stderr*); otherwise; you can specify where the diagnostics get displayed by using the **-D** option to your startup. For example, the **-D** as used in this buildfile excerpt will cause the output to go to a serial port:

```
[virtual=x86,bios +compress] .bootstrap = {
    startup-bios -D 8250..115200
    procnto -vvvv
}
```

You can also have the current state of a terminated process written to a file so that you can later bring up the debugger and examine just what happened. This type of examination is called *postmortem* debugging. This happens only if the process is terminated due to one of these signals:

Signal	Description
SIGABRT	Program-called abort function
SIGBUS	Parity error
SIGEMT	EMT instruction
SIGFPE	Floating-point error or division by zero
SIGILL	Illegal instruction executed
SIGQUIT	Quit
SIGSEGV	Segmentation violation

continued...

Signal	Description
SIGSYS	Bad argument to a system call
SIGTRAP	Trace trap (not reset when caught)
SIGXCPU	Exceeded the CPU limit
SIGXFSZ	Exceeded the file size limit

The process that dumps the state to a file when the process terminates is called **`dumper`**, which must be running when the abnormal termination occurs. This is extremely useful, because embedded systems may run unassisted for days or even years before a crash occurs, making it impossible to reproduce the actual circumstances leading up to the crash.

Affect of parent termination

In some operating systems, if a parent process dies, then all of its child processes die too. This isn't the case in Neutrino.

Detecting process termination

In an embedded application, it's often important to detect if any process terminates prematurely and, if so, to handle it. Handling it may involve something as simple as restarting the process or as complex as:

1. Notifying other processes that they should put their systems into a safe state.
2. Resetting the hardware.

This is complicated by the fact that some Neutrino processes call *procmgr_daemon()*. Processes that call this function are referred to as *daemons*. The *procmgr_daemon()* function:

- detaches the caller from the controlling terminal
- puts it in session 1

- optionally, closes all file descriptors except *stdin*, *stdout*, and *stderr*
- optionally, redirects *stdin*, *stdout*, *stderr* to **`/dev/null`**

As a result of the above, their termination is hard to detect.

Another scenario is where a server process wants to know if any of its clients disappear so that it can clean up any resources it had set aside on their behalf.

Let's look at various ways of detecting process termination.

Using Critical Process Monitoring

The Critical Process Monitoring (CPM) Technology Development Kit provides components not only for detecting when processes terminate, but also for recovering from that termination.

The main component is a process called the High Availability Manager (HAM) that acts as a "smart watchdog". Your processes talk to the HAM using the HAM API. With this API you basically set up conditions that the HAM should watch for and take actions when these conditions occur. So the HAM can be told to detect when a process terminates and to automatically restart the process. It will even detect the termination of daemon processes.

In fact, the High Availability Manager can restart a number of processes, wait between restarts for a process to be ready, and notify the process that this is happening.

The HAM also does heartbeating. Processes can periodically notify the HAM that they are still functioning correctly. If a process specified amount of time goes by between these notifications then the HAM can take some action.

The above are just a sample of what is possible with Critical Process Monitoring. For more information, see the CPM *Developer's Guide*

Detecting termination from a starter process

If you've created a set of processes using a starter process as discussed at the beginning of this section, then all those processes are children of the starter process, with the exception of those that have

called *procmgr_daemon()*. If all you want to do is detect that one of those children has terminated, then a loop that blocks on *wait()* or *sigwaitinfo()* will suffice. Note that when a child process calls *procmgr_daemon()*, both *wait()* and *sigwaitinfo()* behave as if the child process died, although the child is still running.

The *wait()* function will block, waiting until any of the caller's child processes terminate. There's also *waitpid()*, which lets you wait for a specific child process, *wait3()*, and *wait4()*. Lastly, there is *waitid()*, which is the lower level of all the *wait*()* functions and returns the most information.

The *wait*()* functions won't always help, however. If a child process was created using one of the *spawn*()* family of functions with the mode passed as P_NOWAITO, then the *wait*()* functions won't be notified of its termination!

What if the child process terminates, but the parent hasn't yet called *wait*()*? This would be the case if one child had already terminated, so *wait*()* returned, but then before the parent got back to the *wait*()*, *a second child terminates*. In that case, some information would have to be stored away about the second child for when the parent does get around to its *wait*()*.

This is in fact the case. The second child's memory will have been freed up, its files will have been closed, and in general the child's resources will have been cleaned up with the exception of a few bytes of memory in the process manager that contain the child's exit status or other reason that it had terminated and its process ID. When the second child is in this state, it's referred to as a *zombie*. The child will remain a zombie until the parent either terminates or finds out about the child's termination (e.g. the parent calls *wait*()*).

What this means is that if a child has terminated and the parent is still alive but doesn't yet know about the terminated child (e.g. hasn't called *wait*()*), then the zombie will be hanging around. If the parent will never care, then you may as well not have the child become a zombie. To prevent the child from becoming a zombie when it terminates, create the child process using one of the *spawn*()* family of functions and pass P_NOWAITO for the *mode*.

The following sample illustrates the use of *wait()* for waiting for child processes to terminate.

Sample parent process using *wait()*

```
/*
 * waitchild.c
 *
 * This is an example of a parent process that creates some child
 * processes and then waits for them to terminate. The waiting is
 * done using wait(). When a child process terminates, the
 * wait() function returns.
*/

#include <spawn.h>
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/wait.h>

main(int argc, char **argv)
{
    char                *args[] = { "child", NULL };
    int                 i, status;
    pid_t               pid;
    struct inheritance  inherit;

    // create 3 child processes
    for (i = 0; i < 3; i++) {
        inherit.flags = 0;
        if ((pid = spawn("child", 0, NULL, &inherit, args, environ)) == -1)
            perror("spawn() failed");
        else
            printf("spawned child, pid = %d\n", pid);
    }

    while (1) {
        if ((pid = wait(&status)) == -1) {
            perror("wait() failed (no more child processes?)");
            exit(EXIT_FAILURE);
        }
        printf("a child terminated, pid = %d\n", pid);

        if (WIFEXITED(status)) {
            printf("child terminated normally, exit status = %d\n",
                WEXITSTATUS(status));
        } else if (WIFSIGNALED(status)) {
            printf("child terminated abnormally by signal = %X\n",
                WTERMSIG(status));
        } // else see documentation for wait() for more macros
    }
}
```

The following is a simple child process to try out with the above parent.

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

main(int argc, char **argv)
{
    printf("pausing, terminate me somehow\n");
    pause();
}
```

The *sigwaitinfo()* function will block, waiting until any signals that the caller tells it to wait for are set on the caller. If a child process terminates, then the SIGCHLD signal is set on the parent. So all the parent has to do is request that *sigwaitinfo()* return when SIGCHLD arrives.

Sample parent process using *sigwaitinfo()*

The following sample illustrates the use of *sigwaitinfo()* for waiting for child processes to terminate.

```
/*
 * sigwaitchild.c
 *
 * This is an example of a parent process that creates some child
 * processes and then waits for them to terminate.  The waiting is
 * done using sigwaitinfo().  When a child process terminates, the
 * SIGCHLD signal is set on the parent.  sigwaitinfo() will return
 * when the signal arrives.
*/

#include <errno.h>
#include <spawn.h>
#include <stdio.h>
#include <string.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/neutrino.h>

void
signal_handler(int signo)
{
    // do nothing
}

main(int argc, char **argv)
{
    char                *args[] = { "child", NULL };
    int                 i;
    pid_t               pid;
    sigset_t            mask;
    siginfo_t           info;
    struct inheritance  inherit;
```

```
    struct sigaction    action;

    // mask out the SIGCHLD signal so that it will not interrupt us,
    // (side note: the child inherits the parents mask)
    sigemptyset(&mask);
    sigaddset(&mask, SIGCHLD);
    sigprocmask(SIG_BLOCK, &mask, NULL);

    // by default, SIGCHLD is set to be ignored so unless we happen
    // to be blocked on sigwaitinfo() at the time that SIGCHLD
    // is set on us we will not get it.  To fix this, we simply
    // register a signal handler.  Since we've masked the signal
    // above, it will not affect us.  At the same time we will make
    // it a queued signal so that if more than one are set on us,
    // sigwaitinfo() will get them all.
    action.sa_handler = signal_handler;
    sigemptyset(&action.sa_mask);
    action.sa_flags = SA_SIGINFO; // make it a queued signal
    sigaction(SIGCHLD, &action, NULL);

    // create 3 child processes
    for (i = 0; i < 3; i++) {
        inherit.flags = 0;
        if ((pid = spawn("child", 0, NULL, &inherit, args, environ)) == -1)
            perror("spawn() failed");
        else
            printf("spawned child, pid = %d\n", pid);
    }

    while (1) {
        if (sigwaitinfo(&mask, &info) == -1) {
            perror("sigwaitinfo() failed");
            continue;
        }
        switch (info.si_signo) {
        case SIGCHLD:
            // info.si_pid is pid of terminated process, it is not POSIX
            printf("a child terminated, pid = %d\n", info.si_pid);
            break;
        default:
            // should not get here since we only asked for SIGCHLD
        }
    }
}
```

Detecting dumped processes

As mentioned above, you can run **`dumper`** so that when a process dies, **`dumper`** writes the state of the process to a file.

You can also write your own dumper-type process to run instead of, or as well as, **`dumper`**. This way the terminating process doesn't have to be a child of yours.

To do this, write a resource manager that registers the name, **/proc/dumper** with type _FTYPE_DUMPER. When a process dies due to one of the appropriate signals, the process manager will open **/proc/dumper** and write the pid of the process that died — then it'll wait until you reply to the write with success and then it'll finish terminating the process.

It's possible that more than one process will have **/proc/dumper** registered at the same time, however, the process manager notifies only the process that's at the beginning of its list for that name. Undoubtedly, you want both your resource manager and **dumper** to handle this termination. To do this, request the process manager to put you, instead of **dumper**, at the beginning of the **/proc/dumper** list by passing _RESMGR_FLAG_BEFORE to *resmgr_attach()*. You must also open **/proc/dumper** so that you can communicate with **dumper** if it's running. Whenever your io_write handler is called, write the pid to **dumper** and do your own handling. Of course this works only when **dumper** is run before your resource manager; otherwise, your open of **/proc/dumper** won't work.

The following is a sample process that demonstrates the above:

```
/*
 *  dumphandler.c
 *
 *  This demonstrates how you get notified whenever a process
 *  dies due to any of the following signals:
 *
 *  SIGABRT
 *  SIGBUS
 *  SIGEMT
 *  SIGFPE
 *  SIGILL
 *  SIGQUIT
 *  SIGSEGV
 *  SIGSYS
 *  SIGTRAP
 *  SIGXCPU
 *  SIGXFSZ
 *
 *  To do so, register the path, /proc/dumper with type
 *  _FTYPE_DUMPER. When a process dies due to one of the above
 *  signals, the process manager will open /proc/dumper, and
 *  write the pid of the process that died - it will wait until
 *  you reply to the write with success, and then it will finish
```

```
 *  terminating the process.
 *
 *  Note that while it is possible for more than one process to
 *  have /proc/dumper registered at the same time, the process
 *  manager will notify only the one that is at the beginning of
 *  its list for that name.
 *
 *  But we want both us and dumper to handle this termination.
 *  To do this, we make sure that we get notified instead of
 *  dumper by asking the process manager to put us at the
 *  beginning of its list for /proc/dumper (done by passing
 *  _RESMGR_FLAG_BEFORE to  resmgr_attach()).  We also open
 *  /proc/dumper so that we can communicate with dumper if it is
 *  running.  Whenever our io_write handler is called, we write
 *  the pid to dumper and do our own handling.  Of course, this
 *  works only if dumper is run before we are, or else our open
 *  will not work.
 *
*/

#include <errno.h>
#include <stdio.h>
#include <stdlib.h>
#include <fcntl.h>
#include <string.h>
#include <unistd.h>
#include <sys/iofunc.h>
#include <sys/dispatch.h>
#include <sys/neutrino.h>
#include <sys/procfs.h>
#include <sys/stat.h>

int io_write (resmgr_context_t *ctp, io_write_t  *msg,
              RESMGR_OCB_T *ocb);

static int  dumper_fd;

resmgr_connect_funcs_t  connect_funcs;
resmgr_io_funcs_t       io_funcs;
dispatch_t              *dpp;
resmgr_attr_t           rattr;
dispatch_context_t      *ctp;
iofunc_attr_t           ioattr;

char    *progname = "dumphandler";

main(int argc, char **argv)
{
    /* find dumper so that we can pass any pids on to it */
    dumper_fd = open("/proc/dumper", O_WRONLY);
```

```
    dpp = dispatch_create();

    memset(&rattr, 0, sizeof(rattr));
    rattr.msg_max_size = 2048;

    iofunc_func_init(_RESMGR_CONNECT_NFUNCS, &connect_funcs,
                     _RESMGR_IO_NFUNCS, &io_funcs);
    io_funcs.write = io_write;

    iofunc_attr_init(&ioattr, S_IFNAM | 0600, NULL, NULL);

    resmgr_attach(dpp, &rattr, "/proc/dumper", _FTYPE_DUMPER,
                  _RESMGR_FLAG_BEFORE, &connect_funcs,
                  &io_funcs, &ioattr);

    ctp = dispatch_context_alloc(dpp);

    while (1) {
        if ((ctp = dispatch_block(ctp)) == NULL) {
            fprintf(stderr, "%s:  dispatch_block failed: %s\n",
                            progname, strerror(errno));
            exit(1);
        }
        dispatch_handler(ctp);
    }
}

struct dinfo_s {
    procfs_debuginfo    info;
    char                pathbuffer[PATH_MAX]; /* 1st byte is
                                                 info.path[0] */
};

int
display_process_info(pid_t pid)
{
    char            buf[PATH_MAX + 1];
    int             fd, status;
    struct dinfo_s  dinfo;
    procfs_greg     reg;

    printf("%s: process %d died\n", progname, pid);

    sprintf(buf, "/proc/%d/as", pid);

    if ((fd = open(buf, O_RDONLY|O_NONBLOCK)) == -1)
        return errno;

    status = devctl(fd, DCMD_PROC_MAPDEBUG_BASE, &dinfo,
```

```
                    sizeof(dinfo), NULL);
    if (status != EOK) {
        close(fd);
        return status;
    }

    printf("%s: name is %s\n", progname, dinfo.info.path);

    /*
     * For getting other type of information, see sys/procfs.h,
     * sys/debug.h, and sys/dcmd_proc.h
     */

    close(fd);
    return EOK;
}

int
io_write(resmgr_context_t *ctp, io_write_t *msg,
         RESMGR_OCB_T *ocb)
{
    char    *pstr;
    int     status;

    if ((status = iofunc_write_verify(ctp, msg, ocb, NULL))
        != EOK)
        return status;

    if (msg->i.xtype & _IO_XTYPE_MASK != _IO_XTYPE_NONE)
        return ENOSYS;

    if (ctp->msg_max_size < msg->i.nbytes + 1)
        return ENOSPC; /* not all the message could fit in the
                          message buffer */

    pstr = (char *) (&msg->i) + sizeof(msg->i);
    pstr[msg->i.nbytes] = '\0';

    if (dumper_fd != -1) {
        /* pass it on to dumper so it can handle it too */
        if (write(dumper_fd, pstr, strlen(pstr)) == -1) {
            close(dumper_fd);
            dumper_fd = -1; /* something wrong, no sense in
                               doing it again later */
        }
    }

    if ((status = display_process_info(atoi(pstr))) == -1)
        return status;
```

```
    _IO_SET_WRITE_NBYTES(ctp, msg->i.nbytes);

    return EOK;
}
```

Detecting the termination of daemons

What would happen if you've created some processes that subsequently made themselves daemons (i.e. called *procmgr_daemon()*)? As we mentioned above, the *wait*()* functions and *sigwaitinfo()* won't help.

For these you can give the kernel an event, such as one containing a pulse, and have the kernel deliver that pulse to you whenever a daemon terminates. This request for notification is done by calling *procmgr_event_notify()* with PROCMGR_EVENT_DAEMON_DEATH in *flags*.

See the documentation for *procmgr_event_notify()* for an example that uses this function.

Detecting client termination

The last scenario is where a server process wants to be notified of any clients that terminate so that it can clean up any resources that it had set aside for them.

This is very easy to do if the server process is written as a *resource manager*, because the resource manager's *io_close_dup()* and *io_close_ocb()* handlers, as well as the *ocb_free()* function, will be called if a client is terminated for any reason.

Chapter 4

Writing a Resource Manager

In this chapter...

What is a resource manager?

This chapter assumes that you're familiar with message passing. If you're not, see the Neutrino Microkernel chapter in the *System Architecture* book as well as the *MsgSend(), MsgReceivev(),* and *MsgReply()* series of calls in the *Library Reference*.

A *resource manager* is a user-level server program that accepts messages from other programs and, optionally, communicates with hardware. It's a process that registers a pathname prefix in the pathname space (e.g. **`/dev/ser1`**), and when registered, other processes can open that name using the standard C library *open()* function, and then *read()* from, and *write()* to, the resulting file descriptor. When this happens, the resource manager receives an open request, followed by read and write requests.

A resource manager isn't restricted to handling just *open(), read(),* and *write()* calls — it can support any functions that are based on a file descriptor or file pointer, as well as other forms of IPC.

In Neutrino, resource managers are responsible for presenting an interface to various types of devices. In other operating systems, the managing of actual hardware devices (e.g. serial ports, parallel ports, network cards, and disk drives) or virtual devices (e.g. **`/dev/null`**, a network filesystem, and pseudo-ttys), is associated with *device drivers*. But unlike device drivers, the Neutrino resource managers execute as processes *separate from the kernel*.

A resource manager looks just like any other user-level program.

Adding resource managers in Neutrino won't affect any other part of the OS — the drivers are developed and debugged like any other application. And since the resource managers are in their own protected address space, a bug in a device driver won't cause the entire OS to shut down.

If you've written device drivers in most UNIX variants, you're used to being restricted in what you can do within a device driver; but since a device driver in Neutrino is just a regular process, you aren't

restricted in what you can do (except for the restrictions that exist inside an ISR).

In order to register a prefix in the pathname space, a resource manager must be run as **root**.

A few examples...

A serial port may be managed by a resource manager called **devc-ser8250**, although the actual resource may be called **/dev/ser1** in the pathname space. When a process requests serial port services, it does so by opening a serial port (in this case **/dev/ser1**).

```
fd = open("/dev/ser1", O_RDWR);
for (packet = 0; packet < npackets; packet++)
    write(fd, packets[packet], PACKET_SIZE);
close(fd);
```

Because resource managers execute as processes, their use isn't restricted to device drivers — any server can be written as a resource manager. For example, a server that's given DVD files to display in a GUI interface wouldn't be classified as a driver, yet it could be written as a resource manager. It can register the name **/dev/dvd** and as a result, clients can do the following:

```
fd = open("/dev/dvd", O_WRONLY);
while (data = get_dvd_data(handle, &nbytes)) {
    bytes_written = write(fd, data, nbytes);
    if (bytes_written != nbytes) {
        perror ("Error writing the DVD data");
    }
}
close(fd);
```

Why write a resource manager?

Here are a few reasons why you'd want to write a resource manager:

- The API is POSIX.

  The API for communicating with the resource manager is for the most part, POSIX. All C programmers are familiar with the *open()*, *read()*, and *write()* functions. Training costs are minimized, and so is the need to document the interface to your server.

- You can reduce the number of interface types.

  If you have many server processes, writing each server as a resource manager keeps the number of different interfaces that clients need to use to a minimum.

  An example of this is if you have a team of programmers building your overall application, and each programmer is writing one or more servers for that application. These programmers may work directly for your company, or they may belong to partner companies who are developing add-on hardware for your modular platform.

  If the servers are resource managers, then the interface to all of those servers is the POSIX functions: *open()*, *read()*, *write()*, and whatever else makes sense. For control-type messages that don't fit into a read/write model, there's *devctl()* (although *devctl()* isn't POSIX).

- Command-line utilities can communicate with resource managers.

  Since the API for communicating with a resource manager is the POSIX set of functions, and since standard POSIX utilities use this API, the utilities can be used for communicating with the resource managers.

  For instance, the tiny TCP/IP protocol module contains resource-manager code that registers the name **`/proc/ipstats`**. If you open this name and read from it, the resource manager code responds with a body of text that describes the statistics for IP.

The **cat** utility takes the name of a file and opens the file, reads from it, and displays whatever it reads to standard output (typically the screen). As a result, you can type:

```
cat /proc/ipstats
```

The resource manager code in the TCP/IP protocol module responds with text such as:

```
Ttcpip Sep  5 2000 08:56:16

verbosity level 0
ip checksum errors: 0
udp checksum errors: 0
tcp checksum errors: 0

packets sent: 82
packets received: 82

lo0   : addr 127.0.0.1       netmask 255.0.0.0       up

DST: 127.0.0.0       NETMASK: 255.0.0.0       GATEWAY: lo0

TCP 127.0.0.1.1227        > 127.0.0.1.6000        ESTABLISHED snd    0 rcv    0
TCP 127.0.0.1.6000        > 127.0.0.1.1227        ESTABLISHED snd    0 rcv    0
TCP 0.0.0.0.6000                                  LISTEN
```

You could also use command-line utilities for a robot-arm driver. The driver could register the name, **/dev/robot/arm/angle**, and any writes to this device are interpreted as the angle to set the robot arm to. To test the driver from the command line, you'd type:

```
echo 87 >/dev/robot/arm/angle
```

The **echo** utility opens **/dev/robot/arm/angle** and writes the string ("87") to it. The driver handles the write by setting the robot arm to 87 degrees. Note that this was accomplished without writing a special tester program.

Another example would be names such as **/dev/robot/registers/r1**, **r2**, ... Reading from these names returns the contents of the corresponding registers; writing to these names set the corresponding registers to the given values.

Even if all of your other IPC is done via some non-POSIX API, it's still worth having one thread written as a resource manager for responding to reads and writes for doing things as shown above.

Under the covers

Despite the fact that you'll be using a resource manager API that hides many details from you, it's still important to understand what's going on under the covers. For example, your resource manager is a server that contains a *MsgReceive()* loop, and clients send you messages using *MsgSend*()*. This means that you must reply either to your clients in a timely fashion, or leave your clients blocked but save the *rcvid* for use in a later reply.

To help you understand, we'll discuss the events that occur under the covers for both the client and the resource manager.

Under the client's covers

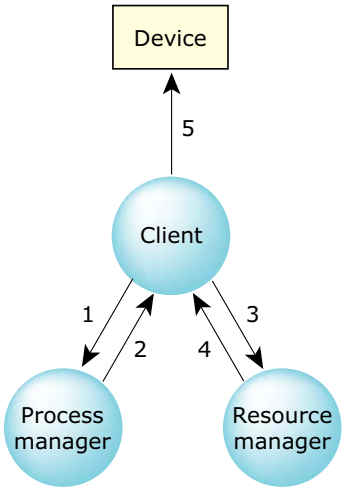
When a client calls a function that requires pathname resolution (e.g. *open(), rename(), stat(),* or *unlink()*), the function subsequently sends messages to both the process and the resource managers to obtain a file descriptor. Once the file descriptor is obtained, the client can use it to send messages directly to the device associated with the pathname.

In the following, the file descriptor is obtained and then the client writes directly to the device:

```
/*
 * In this stage, the client talks
 * to the process manager and the resource manager.
 */
fd = open("/dev/ser1", O_RDWR);

/*
 * In this stage, the client talks directly to the
 * resource manager.
 */
for (packet = 0; packet < npackets; packet++)
    write(fd, packets[packet], PACKET_SIZE);
close(fd);
```

For the above example, here's the description of what happened behind the scenes. We'll assume that a serial port is managed by a resource manager called **`devc-ser8250`**, that's been registered with the pathname prefix **`/dev/ser1`**:



Under-the-cover communication between the client, the process manager, and the resource manager.

1 The client's library sends a "query" message. The *open()* in the client's library sends a message to the process manager asking it to look up a name (e.g. **`/dev/ser1`**).

2 The process manager indicates who's responsible and it returns the *nd*, *pid*, *chid*, and *handle* that are associated with the pathname prefix.

Here's what went on behind the scenes...
When the **`devc-ser8250`** resource manager registered its name (**`/dev/ser1`**) in the namespace, it called the process manager. The process manager is responsible for maintaining information about pathname prefixes. During registration, it adds an entry to its table that looks similar to this:

```
0, 47167, 1, 0, 0, /dev/ser1
```

The table entries represent:

- Node descriptor (*nd*)
- Process ID of the resource manager (*pid*)

- Channel ID that the resource manager receives messages with (*chid*)
- Handle (*handle*)
- Open type (*open type*)
- Pathname prefix (*name*)

A resource manager is uniquely identified by a node descriptor, process ID, and a channel ID. The process manager's table entry associates the resource manager with a name, a handle (to distinguish multiple names when a resource manager registers more than one name), and an open type.

When the client's library issued the query call in step 1, the process manager looked through all of its tables for any registered pathname prefixes that match the name. Previously, had another resource manager registered the name **/**, more than one match would be found. So, in this case, both **/** and **/dev/ser1** match. The process manager will reply to the *open()* with the list of matched servers or resource managers. The servers are queried in turn about their handling of the path, with the longest match being asked first.

3 The client's library sends a "connect" message to the resource manager. To do so, it must create a connection to the resource manager's channel:

```
fd = ConnectAttach(nd, pid, chid, 0, 0);
```

The file descriptor that's returned by *ConnectAttach()* is also a connection ID and is used for sending messages directly to the resource manager. In this case, it's used to send a connect message (_IO_CONNECT defined in **<sys/iomsg.h>**) containing the handle to the resource manager requesting that it open **/dev/ser1**.

Typically, only functions such as *open()* call *ConnectAttach()* with an *index* argument of 0. Most of the time, you should OR _NTO_SIDE_CHANNEL into this argument, so that the connection is made via a *side channel*, resulting in a connection ID that's greater than any valid file descriptor.

When the resource manager gets the connect message, it performs validation using the access modes specified in the *open()* call (i.e. are you trying to write to a read-only device?, etc.)

4 The resource manager generally responds with a pass (and *open()* returns with the file descriptor) or fail (the next server is queried).

5 When the file descriptor is obtained, the client can use it to send messages directly to the device associated with the pathname.

In the sample code, it looks as if the client opens and writes directly to the device. In fact, the *write()* call sends an _IO_WRITE message to the resource manager requesting that the given data be written, and the resource manager responds that it either wrote some of all of the data, or that the write failed.

Eventually, the client calls *close()*, which sends an _IO_CLOSE_DUP message to the resource manager. The resource manager handles this by doing some cleanup.

Under the resource manager's covers

The resource manager is a server that uses the Neutrino send/receive/reply messaging protocol to receive and reply to messages. The following is pseudo-code for a resource manager:

```
initialize the resource manager
register the name with the process manager
DO forever
    receive a message
    SWITCH on the type of message
        CASE _IO_CONNECT:
            call io_open handler
```

```
            ENDCASE
        CASE _IO_READ:
            call io_read handler
            ENDCASE
        CASE _IO_WRITE:
            call io_write handler
            ENDCASE
        .   /* etc. handle all other messages */
        .   /* that may occur, performing     */
        .   /* processing as appropriate      */
    ENDSWITCH
ENDDO
```

Many of the details in the above pseudo-code are hidden from you by a resource manager library that you'll use. For example, you won't actually call a *MsgReceive*()* function — you'll call a library function, such as *resmgr_block()* or *dispatch_block()*, that does it for you. If you're writing a single-threaded resource manager, you might provide a message handling loop, but if you're writing a multi-threaded resource manager, the loop is hidden from you.

You don't need to know the format of all the possible messages, and you don't have to handle them all. Instead, you register "handler functions," and when a message of the appropriate type arrives, the library calls your handler. For example, suppose you want a client to get data from you using *read()* — you'll write a handler that's called whenever an _IO_READ message is received. Since your handler handles _IO_READ messages, we'll call it an "*io_read handler.*"

The resource manager library:

1. Receives the message.
2. Examines the message to verify that it's an _IO_READ message.
3. Calls your io_read handler.

However, it's still your responsibility to reply to the _IO_READ message. You can do that from within your io_read handler, or later on when data arrives (possibly as the result of an interrupt from some data-generating hardware).

The library does default handling for any messages that you don't want to handle. After all, most resource managers don't care about presenting proper POSIX filesystems to the clients. When writing them, you want to concentrate on the code for talking to the device you're controlling. You don't want to spend a lot of time worrying about the code for presenting a proper POSIX filesystem to the client.

The types of resource managers

In considering how much work you want to do yourself in order to present a proper POSIX filesystem to the client, you can break resource managers into two types:

- Device resource managers
- Filesystem resource managers

Device resource managers

Device resource managers create only single-file entries in the filesystem, each of which is registered with the process manager. Each name usually represents a single device. These resource managers typically rely on the resource-manager library to do most of the work in presenting a POSIX device to the user.

For example, a serial port driver registers names such as **`/dev/ser1`** and **`/dev/ser2`**. When the user does **`ls -l /dev`**, the library does the necessary handling to respond to the resulting _IO_STAT messages with the proper information. The person who writes the serial port driver is able to concentrate instead on the details of managing the serial port hardware.

Filesystem resource managers

Filesystem resource managers register a *mountpoint* with the process manager. A mountpoint is the portion of the path that's registered with the process manager. The remaining parts of the path are managed by the filesystem resource manager. For example, when a filesystem resource manager attaches a mountpoint at **`/mount`**, and the path **`/mount/home/thomasf`** is examined:

/mount/ Identifies the mountpoint that's managed by the process manager.

home/thomasf

Identifies the remaining part that's to be managed by the filesystem resource manager.

Examples of using filesystem resource managers are:

- flash filesystem drivers (although a flash driver toolkit is available that takes care of these details)
- a **tar** filesystem process that presents the contents of a **tar** file as a filesystem that the user can **cd** into and **ls** from
- a mailbox-management process that registers the name **/mailboxes** and manages individual mailboxes that look like directories, and files that contain the actual messages

Components of a resource manager

A resource manager is composed of some of the following layers:

- iofunc layer (the top layer)
- resmgr layer
- dispatch layer
- thread pool layer (the bottom layer)

iofunc layer

This top layer consists of a set of functions that take care of most of the POSIX filesystem details for you — they provide a POSIX-personality. If you're writing a device resource manager, you'll want to use this layer so that you don't have to worry too much about the details involved in presenting a POSIX filesystem to the world.

This layer consists of default handlers that the resource manager library uses if you don't provide a handler. For example, if you don't provide an io_open handler, *iofunc_open_default()* is called.

It also contains helper functions that the default handlers call. If you override the default handlers with your own, you can still call these helper functions. For example, if you provide your own io_read handler, you can call *iofunc_read_verify()* at the start of it to make sure that the client has access to the resource.

The names of the functions and structures for this layer have the form *iofunc_**. The header file is **<sys/iofunc.h>**. For more information, see the *Library Reference*.

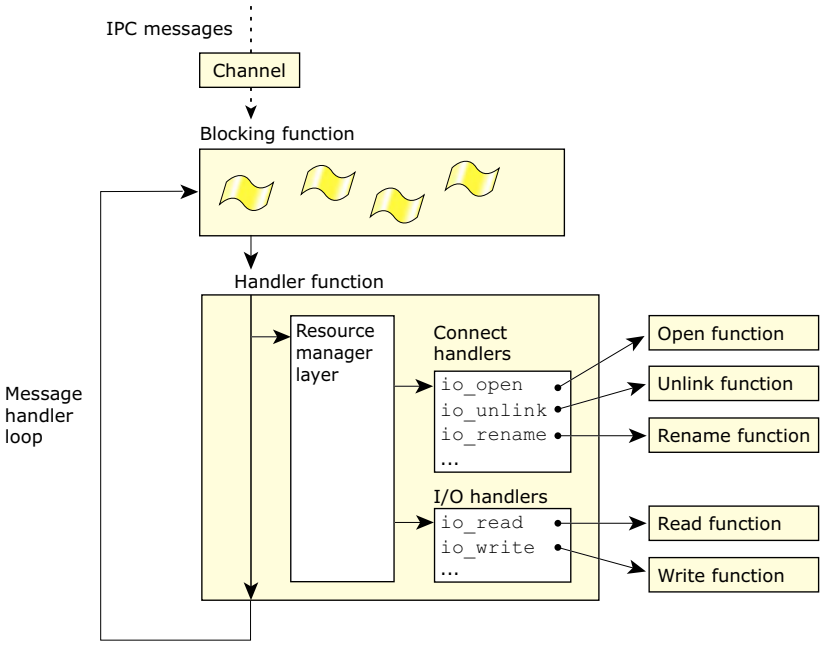
resmgr layer

This layer manages most of the resource manager library details. It:

- examines incoming messages
- calls the appropriate handler to process a message

If you don't use this layer, then you'll have to parse the messages yourself. Most resource managers use this layer.

The names of the functions and structures for this layer have the form *resmgr_**. The header file is **<sys/resmgr.h>**. For more information, see the *Library Reference*.



You can use the resmgr layer to handle _IO_* messages.

dispatch layer

This layer acts as a single blocking point for a number of different types of things. With this layer, you can handle:

_IO_* messages

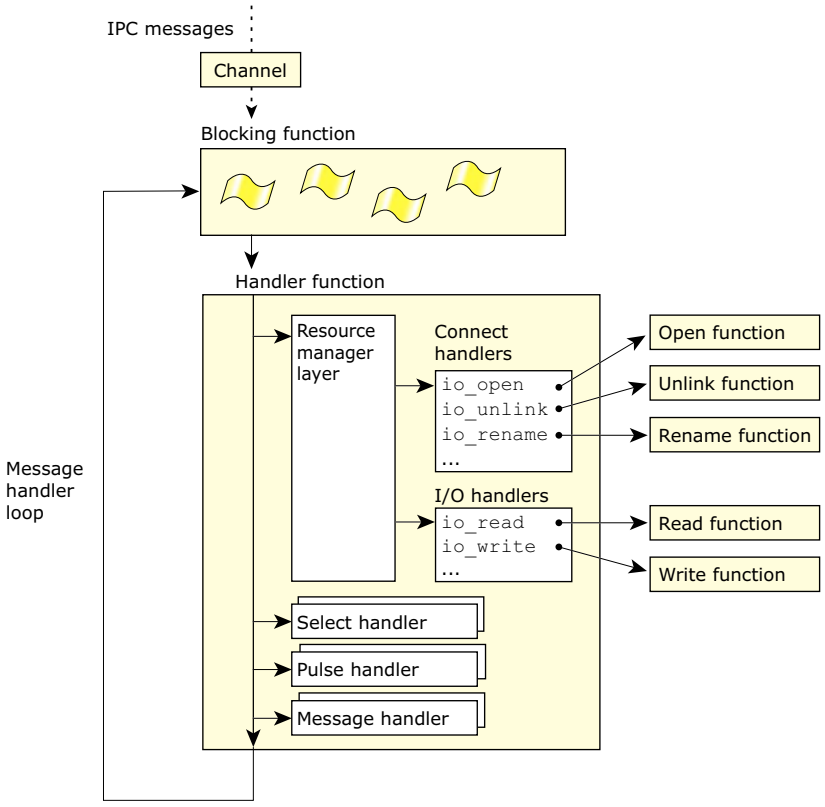
It uses the resmgr layer for this.

select

Processes that do TCP/IP often call *select()* to block while waiting for packets to arrive, or for there to be room for writing more data. With the dispatch layer, you register a handler function that's called when a packet arrives. The functions for this are the *select_*()* functions.

pulses
: As with the other layers, you register a handler function that's called when a specific pulse arrives. The functions for this are the *pulse_*()* functions.

other messages
: You can give the dispatch layer a range of message types that you make up, and a handler. So if a message arrives and the first few bytes of the message contain a type in the given range, the dispatch layer calls your handler. The functions for this are the *message_*()* functions.



You can use the dispatch layer to handle _IO_* messages, select, pulses, and other messages.

The following describes the manner in which messages are handled via the dispatch layer (or more precisely, through *dispatch_handler()*). Depending on the blocking type, the handler may call the *message_*()* subsystem. A search is made, based on the message type or pulse code, for a matching function that was attached using *message_attach()* or *pulse_attach()*. If a match is found, the attached function is called.

If the message type is in the range handled by the resource manager (I/O messages) and pathnames were attached using *resmgr_attach()*, the resource manager subsystem is called and handles the resource manager message.

If a pulse is received, it may be dispatched to the resource manager subsystem if it's one of the codes handled by a resource manager (UNBLOCK and DISCONNECT pulses). If a *select_attach()* is done and the pulse matches the one used by *select*, then the *select* subsystem is called and dispatches that event.

If a message is received and no matching handler is found for that message type, *MsgError*(ENOSYS) is returned to unblock the sender.

thread pool layer

This layer allows you to have a single- or multi-threaded resource manager. This means that one thread can be handling a *write()* while another thread handles a *read()*.

You provide the blocking function for the threads to use as well as the handler function that's to be called when the blocking function returns. Most often, you give it the dispatch layer's functions. However, you can also give it the resmgr layer's functions or your own.

You can use this layer independently of the resource manager layer.

Simple examples of device resource managers

The following are two complete but **simple** examples of a device resource manager:

- single-threaded device resource manager
- multi-threaded device resource manager

As you read through this chapter, you'll encounter many code snippets. Most of these code snippets have been written so that they can be combined with either of these simple resource managers.

Both of these simple device resource managers model their functionality after that provided by **`/dev/null`**:

- an *open()* always works
- *read()* returns zero bytes (indicating EOF)
- a *write()* of any size "works" (with the data being discarded)
- lots of other POSIX functions work (e.g. *chown()*, *chmod()*, *lseek()*, etc.)

Single-threaded device resource manager example

Here's the complete code for a simple single-threaded device resource manager:

```
#include <errno.h>
#include <stdio.h>
#include <stddef.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/iofunc.h>
#include <sys/dispatch.h>

static resmgr_connect_funcs_t    connect_funcs;
static resmgr_io_funcs_t         io_funcs;
static iofunc_attr_t             attr;
```

```
main(int argc, char **argv)
{
    /* declare variables we'll be using */
    resmgr_attr_t        resmgr_attr;
    dispatch_t           *dpp;
    dispatch_context_t   *ctp;
    int                  id;

    /* initialize dispatch interface */
    if((dpp = dispatch_create()) == NULL) {
        fprintf(stderr,
                "%s: Unable to allocate dispatch handle.\n",
                argv[0]);
        return EXIT_FAILURE;
    }

    /* initialize resource manager attributes */
    memset(&resmgr_attr, 0, sizeof resmgr_attr);
    resmgr_attr.nparts_max = 1;
    resmgr_attr.msg_max_size = 2048;

    /* initialize functions for handling messages */
    iofunc_func_init(_RESMGR_CONNECT_NFUNCS, &connect_funcs,
                     _RESMGR_IO_NFUNCS, &io_funcs);

    /* initialize attribute structure used by the device */
    iofunc_attr_init(&attr, S_IFNAM | 0666, 0, 0);

    /* attach our device name */
    id = resmgr_attach(
            dpp,            /* dispatch handle        */
            &resmgr_attr,   /* resource manager attrs */
            "/dev/sample",  /* device name            */
            _FTYPE_ANY,     /* open type              */
            0,              /* flags                  */
            &connect_funcs, /* connect routines       */
            &io_funcs,      /* I/O routines           */
            &attr);         /* handle                 */
    if(id == -1) {
        fprintf(stderr, "%s: Unable to attach name.\n", argv[0]);
        return EXIT_FAILURE;
    }

    /* allocate a context structure */
    ctp = dispatch_context_alloc(dpp);

    /* start the resource manager message loop */
    while(1) {
        if((ctp = dispatch_block(ctp)) == NULL) {
```

```
            fprintf(stderr, "block error\n");
            return EXIT_FAILURE;
        }
        dispatch_handler(ctp);
    }
}
```

Include **<sys/dispatch.h>** *after* **<sys/iofunc.h>** to avoid warnings about redefining the members of some functions.

Let's examine the sample code step-by-step.

Initialize the dispatch interface

```
/* initialize dispatch interface */
if((dpp = dispatch_create()) == NULL) {
    fprintf(stderr, "%s: Unable to allocate dispatch handle.\n",
            argv[0]);
    return EXIT_FAILURE;
}
```

We need to set up a mechanism so that clients can send messages to the resource manager. This is done via the *dispatch_create()* function which creates and returns the dispatch structure. This structure contains the channel ID. Note that the channel ID isn't actually created until you attach something, as in *resmgr_attach()*, *message_attach()*, and *pulse_attach()*.

The dispatch structure (of type **dispatch_t**) is opaque; you can't access its contents directly. Use *message_connect()* to create a connection using this hidden channel ID.

Initialize the resource manager attributes

```
/* initialize resource manager attributes */
memset(&resmgr_attr, 0, sizeof resmgr_attr);
resmgr_attr.nparts_max = 1;
resmgr_attr.msg_max_size = 2048;
```

The resource manager attribute structure is used to configure:

- how many IOV structures are available for server replies (*nparts_max*)
- the minimum receive buffer size (*msg_max_size*)

For more information, see *resmgr_attach()* in the *Library Reference*.

Initialize functions used to handle messages

```
/* initialize functions for handling messages */
iofunc_func_init(_RESMGR_CONNECT_NFUNCS, &connect_funcs,
                 _RESMGR_IO_NFUNCS, &io_funcs);
```

Here we supply two tables that specify which function to call when a particular message arrives:

- *connect functions* table
- *I/O functions* table

Instead of filling in these tables manually, we call *iofunc_func_init()* to place the *iofunc_*_default()* handler functions into the appropriate spots.

Initialize the attribute structure used by the device

```
/* initialize attribute structure used by the device */
iofunc_attr_init(&attr, S_IFNAM | 0666, 0, 0);
```

The attribute structure contains information about our particular device associated with the name **`/dev/sample`**. It contains at least the following information:

- permissions and type of device
- owner and group ID

Effectively, this is a *per-name* data structure. Later on, we'll see how you could extend the structure to include your own *per-device* information.

Put a name into the namespace

```
/* attach our device name */
id = resmgr_attach(dpp,            /* dispatch handle        */
                   &resmgr_attr,   /* resource manager attrs */
                   "/dev/sample",  /* device name            */
                   _FTYPE_ANY,     /* open type              */
                   0,              /* flags                  */
                   &connect_funcs, /* connect routines       */
                   &io_funcs,      /* I/O routines           */
                   &attr);         /* handle                 */
if(id == -1) {
    fprintf(stderr, "%s: Unable to attach name.\n", argv[0]);
    return EXIT_FAILURE;
}
```

Before a resource manager can receive messages from other programs, it needs to inform the other programs (via the process manager) that it's the one responsible for a particular pathname prefix. This is done via pathname registration. When registered, other processes can find and connect to this process using the registered name.

In this example, a serial port may be managed by a resource manager called **`devc-xxx`**, but the actual resource is registered as **`/dev/sample`** in the pathname space. Therefore, when a program requests serial port services, it opens the **`/dev/sample`** serial port.

We'll look at the parameters in turn, skipping the ones we've already discussed.

device name
: Name associated with our device (i.e. **`/dev/sample`**).

open type
: Specifies the constant value of _FTYPE_ANY. This tells the process manager that our resource manager will accept *any* type of open request — we're not limiting the kinds of connections we're going to be handling.

  Some resource managers legitimately limit the types of open requests they handle. For instance, the POSIX message queue resource manager accepts only open messages of type _FTYPE_MQUEUE.

flags — Controls the process manager's pathname resolution behavior. By specifying a value of zero, we'll only accept requests for the name "**/dev/sample**".

Allocate the context structure

```
/* allocate a context structure */
ctp = dispatch_context_alloc(dpp);
```

The context structure contains a buffer where messages will be received. The size of the buffer was set when we initialized the resource manager attribute structure. The context structure also contains a buffer of IOVs that the library can use for replying to messages. The number of IOVs was set when we initialized the resource manager attribute structure.

For more information, see *dispatch_context_alloc()* in the *Library Reference*.

Start the resource manager message loop

```
/* start the resource manager message loop */
while(1) {
    if((ctp = dispatch_block(ctp)) == NULL) {
        fprintf(stderr, "block error\n");
        return EXIT_FAILURE;
    }
    dispatch_handler(ctp);
}
```

Once the resource manager establishes its name, it receives messages when any client program tries to perform an operation (e.g. *open()*, *read()*, *write()*) on that name.

In our example, once **/dev/sample** is registered, and a client program executes:

```
fd = open ("/dev/sample", O_RDONLY);
```

the client's C library constructs an _IO_CONNECT message which it sends to our resource manager. Our resource manager receives the

message within the *dispatch_block()* function. We then call *dispatch_handler()* which decodes the message and calls the appropriate handler function based on the connect and I/O function tables that we passed in previously. After *dispatch_handler()* returns, we go back to the *dispatch_block()* function to wait for another message.

At some later time, when the client program executes:

```
read (fd, buf, BUFSIZ);
```

the client's C library constructs an _IO_READ message, which is then sent directly to our resource manager, and the decoding cycle repeats.

Multi-threaded device resource manager example

Here's the complete code for a simple multi-threaded device resource manager:

```
#include <errno.h>
#include <stdio.h>
#include <stddef.h>
#include <stdlib.h>
#include <unistd.h>

/*
 * define THREAD_POOL_PARAM_T such that we can avoid a compiler
 * warning when we use the dispatch_*() functions below
 */
#define THREAD_POOL_PARAM_T dispatch_context_t

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

static resmgr_connect_funcs_t    connect_funcs;
static resmgr_io_funcs_t         io_funcs;
static iofunc_attr_t             attr;

main(int argc, char **argv)
{
    /* declare variables we'll be using */
    thread_pool_attr_t   pool_attr;
    resmgr_attr_t        resmgr_attr;
    dispatch_t           *dpp;
    thread_pool_t        *tpp;
    dispatch_context_t   *ctp;
    int                  id;

    /* initialize dispatch interface */
    if((dpp = dispatch_create()) == NULL) {
        fprintf(stderr, "%s: Unable to allocate dispatch handle.\n",
```

```
            argv[0]);
        return EXIT_FAILURE;
    }

    /* initialize resource manager attributes */
    memset(&resmgr_attr, 0, sizeof resmgr_attr);
    resmgr_attr.nparts_max = 1;
    resmgr_attr.msg_max_size = 2048;

    /* initialize functions for handling messages */
    iofunc_func_init(_RESMGR_CONNECT_NFUNCS, &connect_funcs,
                     _RESMGR_IO_NFUNCS, &io_funcs);

    /* initialize attribute structure used by the device */
    iofunc_attr_init(&attr, S_IFNAM | 0666, 0, 0);

    /* attach our device name */
    id = resmgr_attach(dpp,            /* dispatch handle        */
                       &resmgr_attr,   /* resource manager attrs */
                       "/dev/sample",  /* device name            */
                       _FTYPE_ANY,     /* open type              */
                       0,              /* flags                  */
                       &connect_funcs, /* connect routines       */
                       &io_funcs,      /* I/O routines           */
                       &attr);         /* handle                 */
    if(id == -1) {
        fprintf(stderr, "%s: Unable to attach name.\n", argv[0]);
        return EXIT_FAILURE;
    }

    /* initialize thread pool attributes */
    memset(&pool_attr, 0, sizeof pool_attr);
    pool_attr.handle = dpp;
    pool_attr.context_alloc = dispatch_context_alloc;
    pool_attr.block_func = dispatch_block;
    pool_attr.unblock_func = dispatch_unblock;
    pool_attr.handler_func = dispatch_handler;
    pool_attr.context_free = dispatch_context_free;
    pool_attr.lo_water = 2;
    pool_attr.hi_water = 4;
    pool_attr.increment = 1;
    pool_attr.maximum = 50;

    /* allocate a thread pool handle */
    if((tpp = thread_pool_create(&pool_attr,
                                 POOL_FLAG_EXIT_SELF)) == NULL) {
        fprintf(stderr, "%s: Unable to initialize thread pool.\n",
                argv[0]);
        return EXIT_FAILURE;
    }

    /* start the threads, will not return */
    thread_pool_start(tpp);
}
```

Most of the code is the same as in the single-threaded example, so we will cover only those parts that not are described above. Also, we'll

go into more detail on multi-threaded resource managers later in this chapter, so we'll keep the details here to a minimum.

For this code sample, the threads are using the *dispatch_*()* functions (i.e. the dispatch layer) for their blocking loops.

Define THREAD_POOL_PARAM_T

```
/*
 * define THREAD_POOL_PARAM_T such that we can avoid a compiler
 * warning when we use the dispatch_*() functions below
 */
#define THREAD_POOL_PARAM_T dispatch_context_t

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

The THREAD_POOL_PARAM_T manifest tells the compiler what type of parameter is passed between the various blocking/handling functions that the threads will be using. This parameter should be the context structure used for passing context information between the functions. By default it is defined as a **`resmgr_context_t`** but since this sample is using the dispatch layer, we need it to be a **`dispatch_context_t`**. We define it prior to doing the includes above since the header files refer to it.

Initialize thread pool attributes

```
/* initialize thread pool attributes */
memset(&pool_attr, 0, sizeof pool_attr);
pool_attr.handle = dpp;
pool_attr.context_alloc = dispatch_context_alloc;
pool_attr.block_func = dispatch_block;
pool_attr.unblock_func = dispatch_unblock;
pool_attr.handler_func = dispatch_handler;
pool_attr.context_free = dispatch_context_free;
pool_attr.lo_water = 2;
pool_attr.hi_water = 4;
pool_attr.increment = 1;
pool_attr.maximum = 50;
```

The thread pool attributes tell the threads which functions to use for their blocking loop and control how many threads should be in existence at any time. We go into more detail on these attributes when

we talk about multi-threaded resource managers in more detail later in this chapter.

Allocate a thread pool handle

```
/* allocate a thread pool handle */
if((tpp = thread_pool_create(&pool_attr,
                             POOL_FLAG_EXIT_SELF)) == NULL) {
    fprintf(stderr, "%s: Unable to initialize thread pool.\n",
            argv[0]);
    return EXIT_FAILURE;
}
```

The thread pool handle is used to control the thread pool. Amongst other things, it contains the given attributes and flags. The *thread_pool_create()* function allocates and fills in this handle.

Start the threads

```
/* start the threads, will not return */
thread_pool_start(tpp);
```

The *thread_pool_start()* function starts up the thread pool. Each newly created thread allocates a context structure of the type defined by THREAD_POOL_PARAM_T using the *context_alloc* function we gave above in the attribute structure. They'll then block on the *block_func* and when the *block_func* returns, they'll call the *handler_func*, both of which were also given through the attributes structure. Each thread essentially does the same thing that the single-threaded resource manager above does for its message loop. THREAD_POOL_PARAM_T

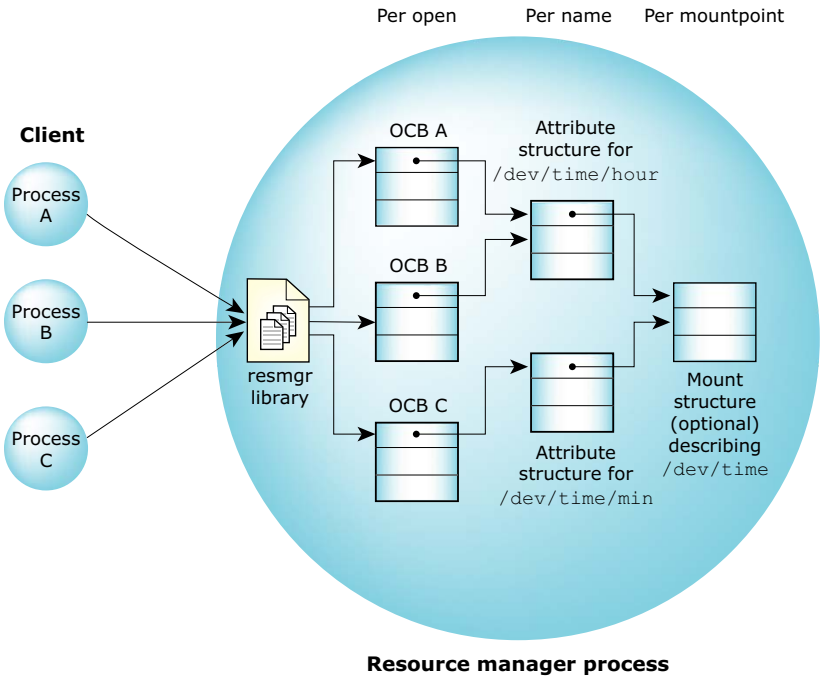
From this point on, your resource manager is ready to handle messages. Since we gave the POOL_FLAG_EXIT_SELF flag to *thread_pool_create()*, once the threads have been started up, *pthread_exit()* will be called and this calling thread will exit.

Data carrying structures

The resource manager library defines several key structures for carrying data:

- Open Control Block (OCB) structure contains per-*open* data.
- attribute structure contains per-*name* data.
- mount structure contains per-*mountpoint* data. (A device resource manager typically won't have a mount structure.)

This picture may help explain their interrelationships:



Multiple clients with multiple OCBs, all linked to one mount structure.

The Open Control Block (OCB) structure

The Open Control Block (OCB) maintains the state information about a particular session involving a client and a resource manager. It's created during open handling and exists until a close is performed.

This structure is used by the iofunc layer helper functions. (Later on, we'll show you how to extend this to include your own data).

The OCB structure contains at least the following:

```
typedef struct _iofunc_ocb {
    IOFUNC_ATTR_T   *attr;
    int32_t         ioflag;
    off_t           offset;
    uint16_t        sflag;
    uint16_t        flags;
} iofunc_ocb_t;
```

where the values represent:

attr A pointer to the attribute structure (see below).

ioflag Contains the mode (e.g. reading, writing, blocking) that the resource was opened with. This information is inherited from the **`io_connect_t`** structure that's available in the message passed to the open handler.

offset User-modifiable. Defines the read/write offset into the resource (e.g. our current *lseek()* position within a file).

sflag Defines the sharing mode. This information is inherited from the **`io_connect_t`** structure that's available in the message passed to the open handler.

flags User-modifiable. When the IOFUNC_OCB_PRIVILEGED bit is set, a privileged process (i.e. **`root`**) performed the *open()*. Additionally, you can use flags in the range IOFUNC_OCB_FLAGS_PRIVATE (see **`<sys/iofunc.h>`**) for your own purposes.

The attribute structure

The **`iofunc_attr_t`** structure defines the characteristics of the device that you're supplying the resource manager for. This is used in conjunction with the OCB structure.

The attribute structure contains at least the following:

```
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;
    off_t                     nbytes;
    ino_t                     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;
```

where the values represent:

**mount* A pointer to the *mount structure*.

flags The bit-mapped *flags* member contains the following flags:

IOFUNC_ATTR_ATIME

The access time is no longer valid. Typically set on a read from the resource.

IOFUNC_ATTR_CTIME

The change of status time is no longer valid. Typically set on a file info change.

IOFUNC_ATTR_DIRTY_NLINK

The number of links has changed.

IOFUNC_ATTR_DIRTY_MODE

The mode has changed.

IOFUNC_ATTR_DIRTY_OWNER

The uid or the gid has changed.

IOFUNC_ATTR_DIRTY_RDEV

The *rdev* member has changed, e.g. *mknod()*.

IOFUNC_ATTR_DIRTY_SIZE

The size has changed.

IOFUNC_ATTR_DIRTY_TIME

One or more of *mtime*, *atime*, or *ctime* has changed.

IOFUNC_ATTR_MTIME

The modification time is no longer valid. Typically set on a write to the resource.

Since your resource manager uses these flags, you can tell right away which fields of the attribute structure have been modified by the various iofunc-layer helper routines. That way, if you need to write the entries to some medium, you can write just those that have changed. The user-defined area for flags is IOFUNC_ATTR_PRIVATE (see **<sys/iofunc.h>**).

For details on updating your attribute structure, see the section on "Updating the time for reads and writes" below.

lock_tid and *lock_count*

To support multiple threads in your resource manager, you'll need to lock the attribute structure so that only one thread at a time is allowed to change it. The resource manager layer automatically locks the attribute (using *iofunc_attr_lock()*) for you when certain handler functions are called (i.e. IO_*). The *lock_tid* member holds the thread ID; the *lock_count* member holds the number of times the thread has locked the attribute structure. (For more information,

see the *iofunc_attr_lock()* and *iofunc_attr_unlock()* functions in the *Library Reference*.)

count, *rcount*, *wcount*, *rlocks* and *wlocks*

Several counters are stored in the attribute structure and are incremented/decremented by some of the iofunc layer helper functions. Both the functionality and the actual contents of the message received from the client determine which specific members are affected.

This counter:	tracks the number of:
count	OCBs using this attribute in any manner. When this count goes to zero, it means that no one is using this attribute.
rcount	OCBs using this attribute for reading.
wcount	OCBs using this attribute for writing.
rlocks	read locks currently registered on the attribute.
wlocks	write locks currently registered on the attribute.

These counts aren't exclusive. For example, if an OCB has specified that the resource is opened for reading and writing, then *count*, *rcount*, and *wcount* will *all* be incremented. (See the *iofunc_attr_init()*, *iofunc_lock_default()*, *iofunc_lock()*, *iofunc_ocb_attach()*, and *iofunc_ocb_detach()* functions.)

mmap_list and *lock_list*

To manage their particular functionality on the resource, the *mmap_list* member is used by the *iofunc_mmap()* and *iofunc_mmap_default()* functions; the *lock_list* member is used by the *iofunc_lock_default()* function. Generally, you shouldn't need to modify or examine these members.

list Reserved for future use.

list_size Size of reserved area; reserved for future use.

nbytes User-modifiable. The number of bytes in the resource. For a file, this would contain the file's size. For special devices (e.g. **`/dev/null`**) that don't support *lseek()* or have a radically different interpretation for *lseek()*, this field isn't used (because you wouldn't use any of the helper functions, but would supply your own instead.) In these cases, we recommend that you set this field to zero, unless there's a meaningful interpretation that you care to put to it.

inode This is a mountpoint-specific inode that must be unique per mountpoint. You can specify your own value, or 0 to have the process manager fill it in for you. For filesystem type of applications, this may correspond to some on-disk structure. In any case, the interpretation of this field is up to you.

uid and *gid* The user ID and group ID of the owner of this resource. These fields are updated automatically by the *chown()* helper functions (e.g. *iofunc_chown_default()*) and are referenced in conjunction with the *mode* member for access-granting purposes by the *open()* help functions (e.g. *iofunc_open_default()*).

mtime, *atime*, and *ctime*

The three POSIX time members:

- *mtime* — modification time (*write()* updates this)
- *atime* — access time (*read()* updates this)
- *ctime* — change of status time (*write()*, *chmod()* and *chown()* update this)

One or more of the three time members may be *invalidated* as a result of calling an iofunc-layer function. This is to avoid having each and every I/O message handler go to the kernel and request the current time of day, just to fill in the attribute structure's time member(s).

POSIX states that these times must be *valid* when the *fstat()* is performed, but they don't have to reflect the *actual* time that the associated change occurred. Also, the times must change between *fstat()* invocations *if* the associated change occurred between *fstat()* invocations. If the associated change never occurred between *fstat()* invocations, then the time returned should be the same as returned last time. Furthermore, if the associated change occurred multiple times between *fstat()* invocations, then the time need only be different from the previously returned time.

There's a helper function that fills the members with the correct time; you may wish to call it in the appropriate handlers to keep the time up-to-date on the device — see the *iofunc_time_update()* function.

mode

Contains the resource's mode (e.g. type, permissions). Valid modes may be selected from the S_* series of constants in **<sys/stat.h>**.

nlink

User-modifiable. Number of links to this particular name. For names that represent a directory, this value must be greater than 2.

rdev Contains the device number for a character special device and the **rdev** number for a named special device.

The mount structure

The members of the mount structure, specifically the *conf* and *flags* members, modify the behavior of some of the iofunc layer functions. This *optional* structure contains at least the following:

```
typedef struct _iofunc_mount {
    uint32_t            flags;
    uint32_t            conf;
    dev_t               dev;
    int32_t             blocksize;
    iofunc_funcs_t      *funcs;
} iofunc_mount_t;
```

The variables are:

flags Contains one relevant bit (manifest constant IOFUNC_MOUNT_32BIT), which indicates that the offsets used by this resource manager are 32-bit (as opposed to the extended 64-bit offsets). The user-modifiable mount flags are defined as IOFUNC_MOUNT_FLAGS_PRIVATE (see **<sys/iofunc.h>**).

conf Contains several bits:

IOFUNC_PC_CHOWN_RESTRICTED

Causes the default handler for the _IO_CHOWN message to behave in a manner defined by POSIX as "**chown**-restricted".

IOFUNC_PC_NO_TRUNC

Has no effect on the iofunc layer libraries, but is returned by the iofunc layer's default _IO_PATHCONF handler.

IOFUNC_PC_SYNC_IO

If not set, causes the default iofunc layer _IO_OPEN handler to fail if the client specified any one of O_DSYNC, O_RSYNC, or O_SYNC.

IOFUNC_PC_LINK_DIR

Controls whether or not **root** is allowed to link and unlink directories.

Note that the options mentioned above for the *conf* member are returned by the iofunc layer _IO_PATHCONF default handler.

dev Contains the device number for the filesystem. This number is returned to the client's *stat()* function in the **struct stat** *st_dev* member.

blocksize Contains the block size of the device. On filesystem types of resource managers, this indicates the native blocksize of the disk, e.g. 512 bytes.

funcs Contains the following structure:

```
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);
};
```

where:

nfuncs Indicates the number of functions present in the structure; it should be filled with the manifest constant _IOFUNC_NFUNCS.

ocb_calloc() and *ocb_free()*

Allows you to override the OCBs on a per-mountpoint basis. (See the section titled "Extending the OCB and attribute structures.")

If these members are NULL, then the default library versions are used. You must specify either *both* or *neither* of these functions — they operate as a matched pair.

Handling the _IO_READ message

The io_read handler is responsible for returning data bytes to the client after receiving an _IO_READ message. Examples of functions that send this message are *read()*, *readdir()*, *fread()*, and *fgetc()*. Let's start by looking at the format of the message itself:

```
struct _io_read {
    uint16_t            type;
    uint16_t            combine_len;
    int32_t             nbytes;
    uint32_t            xtype;
};

typedef union {
    struct _io_read     i;
    /* unsigned char    data[nbytes];    */
    /* nbytes is returned with MsgReply  */
} io_read_t;
```

As with all resource manager messages, we've defined **union** that contains the input (coming into the resource manager) structure and a reply or output (going back to the client) structure. The *io_read()* function is prototyped with an argument of **io_read_t *** *msg* — that's the pointer to the union containing the message.

Since this is a *read()*, the *type* member has the value _IO_READ. The items of interest in the input structure are:

combine_len — This field has meaning for a combine message — see the "Combine messages" section in this chapter.

nbytes — How many bytes the client is expecting.

xtype — A per-message override, if your resource manager supports it. Even if your resource manager doesn't

support it, you should still examine this member. More on the *xtype* later (see the section "*xtype*").

We'll create an *io_read()* function that will serve as our handler that actually returns some data (the fixed string **"Hello, world\n"**). We'll use the OCB to keep track of our position within the buffer that we're returning to the client.

When we get the _IO_READ message, the *nbytes* member tells us exactly how many bytes the client wants to read. Suppose that the client issues:

```
read (fd, buf, 4096);
```

In this case, it's a simple matter to return our entire **"Hello, world\n"** string in the output buffer and tell the client that we're returning 13 bytes, i.e. the size of the string.

However, consider the case where the client is performing the following:

```
while (read (fd, &character, 1) != EOF) {
    printf ("Got a character \"%c\"\n", character);
}
```

Granted, this isn't a terribly efficient way for the client to perform reads! In this case, we would get **msg->i.nbytes** set to 1 (the size of the buffer that the client wants to get). We can't simply return the entire string all at once to the client — we have to hand it out one character at a time. This is where the OCB's *offset* member comes into play.

Sample code for handling _IO_READ messages

Here's a complete *io_read()* function that correctly handles these cases:

```
#include <errno.h>
#include <stdio.h>
#include <stddef.h>
#include <stdlib.h>
```

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

int io_read (resmgr_context_t *ctp, io_read_t *msg, RESMGR_OCB_T *ocb);

static char                     *buffer = "Hello world\n";

static resmgr_connect_funcs_t   connect_funcs;
static resmgr_io_funcs_t        io_funcs;
static iofunc_attr_t            attr;

main(int argc, char **argv)
{
    /* declare variables we'll be using */
    resmgr_attr_t        resmgr_attr;
    dispatch_t           *dpp;
    dispatch_context_t   *ctp;
    int                  id;

    /* initialize dispatch interface */
    if((dpp = dispatch_create()) == NULL) {
        fprintf(stderr, "%s: Unable to allocate dispatch handle.\n",
                argv[0]);
        return EXIT_FAILURE;
    }

    /* initialize resource manager attributes */
    memset(&resmgr_attr, 0, sizeof resmgr_attr);
    resmgr_attr.nparts_max = 1;
    resmgr_attr.msg_max_size = 2048;

    /* initialize functions for handling messages */
    iofunc_func_init(_RESMGR_CONNECT_NFUNCS, &connect_funcs,
                     _RESMGR_IO_NFUNCS, &io_funcs);
    io_funcs.read = io_read;

    /* initialize attribute structure used by the device */
    iofunc_attr_init(&attr, S_IFNAM | 0666, 0, 0);
    attr.nbytes = strlen(buffer)+1;

    /* attach our device name */
    if((id = resmgr_attach(dpp, &resmgr_attr, "/dev/sample", _FTYPE_ANY, 0,
                &connect_funcs, &io_funcs, &attr)) == -1) {
        fprintf(stderr, "%s: Unable to attach name.\n", argv[0]);
        return EXIT_FAILURE;
    }

    /* allocate a context structure */
    ctp = dispatch_context_alloc(dpp);

    /* start the resource manager message loop */
    while(1) {
        if((ctp = dispatch_block(ctp)) == NULL) {
            fprintf(stderr, "block error\n");
            return EXIT_FAILURE;
        }
        dispatch_handler(ctp);
    }
}
```

```
int
io_read (resmgr_context_t *ctp, io_read_t *msg, RESMGR_OCB_T *ocb)
{
    int         nleft;
    int         nbytes;
    int         nparts;
    int         status;

    if ((status = iofunc_read_verify (ctp, msg, ocb, NULL)) != EOK)
        return (status);

    if ((msg->i.xtype & _IO_XTYPE_MASK) != _IO_XTYPE_NONE)
        return (ENOSYS);

    /*
     *  On all reads (first and subsequent), calculate
     *  how many bytes we can return to the client,
     *  based upon the number of bytes available (nleft)
     *  and the client's buffer size
     */

    nleft = ocb->attr->nbytes - ocb->offset;
    nbytes = min (msg->i.nbytes, nleft);

    if (nbytes > 0) {
        /* set up the return data IOV */
        SETIOV (ctp->iov, buffer + ocb->offset, nbytes);

        /* set up the number of bytes (returned by client's read()) */
        _IO_SET_READ_NBYTES (ctp, nbytes);

        /*
         * advance the offset by the number of bytes
         * returned to the client.
         */

        ocb->offset += nbytes;

        nparts = 1;
    } else {
        /*
         * they've asked for zero bytes or they've already previously
         * read everything
         */

        _IO_SET_READ_NBYTES (ctp, 0);

        nparts = 0;
    }

    /* mark the access time as invalid (we just accessed it) */

    if (msg->i.nbytes > 0)
        ocb->attr->flags |= IOFUNC_ATTR_ATIME;

    return (_RESMGR_NPARTS (nparts));
}
```

The *ocb* maintains our context for us by storing the *offset* field, which gives us the position within the *buffer*, and by having a pointer to the attribute structure *attr*, which tells us how big the buffer actually is via its *nbytes* member.

Of course, we had to give the resource manager library the address of our *io_read()* handler function so that it knew to call it. So the code in *main()* where we had called *iofunc_func_init()* became:

```
/* initialize functions for handling messages */
iofunc_func_init(_RESMGR_CONNECT_NFUNCS, &connect_funcs,
                 _RESMGR_IO_NFUNCS, &io_funcs);
io_funcs.read = io_read;
```

We also needed to add the following to the area above *main()*:

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

int io_read (resmgr_context_t *ctp, io_read_t *msg, RESMGR_OCB_T *ocb);

static char *buffer = "Hello world\n";"
```

Where did the attribute structure's *nbytes* member get filled in? In *main()*, just after we did the *iofunc_attr_init()*. We modified *main()* slightly:

After this line:

```
iofunc_attr_init (&attr, S_IFNAM | 0666, 0, 0);
```

We added this one:

```
attr.nbytes = strlen (buffer)+1;
```

At this point, if you were to run the resource manager (our simple resource manager used the name **`/dev/sample`**), you could do:

```
# cat /dev/sample
Hello, world
```

The return line **`(_RESMGR_NPARTS(nparts))`** tells the resource manager library to:

- reply to the client for us
- reply with *nparts* IOVs

Where does it get the IOV array? It's using **`ctp->iov`**. That's why we first used the *SETIOV()* macro to make **`ctp->iov`** point to the data to reply with.

If we had no data, as would be the case of a read of zero bytes, then we'd do a return **`(_RESMGR_NPARTS(0))`**. But *read()* returns with the number of bytes successfully read. Where did we give it this information? That's what the *_IO_SET_READ_NBYTES()* macro was for. It takes the *nbytes* that we give it and stores it in the context structure (*ctp*). Then when we return to the library, the library takes this *nbytes* and passes it as the second parameter to the *MsgReplyv()*. The second parameter tells the kernel what the *MsgSend()* should return. And since the *read()* function is calling *MsgSend()*, that's where it finds out how many bytes were read.

We also update the access time for this device in the read handler. For details on updating the access time, see the section on "Updating the time for reads and writes" below.

Ways of adding functionality to the resource manager

You can add functionality to the resource manager you're writing in these fundamental ways:

- Use the default functions encapsulated within your own.
- Use the helper functions within your own.
- Write the entire function yourself.

The first two are almost identical, because the default functions really don't do that much by themselves — they rely on the POSIX helper functions. The third approach has advantages and disadvantages.

Using the default functions

Since the default functions (e.g. *iofunc_open_default()*) can be installed in the jump table directly, there's no reason you couldn't embed them within your own functions.

Here's an example of how you would do that with your own *io_open()* handler:

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

    /* install all of the default functions */
    iofunc_func_init (_RESMGR_CONNECT_NFUNCS, &connect_funcs,
                      _RESMGR_IO_NFUNCS, &io_funcs);

    /* take over the open function */
    connect_funcs.open = io_open;
    ...
}

int
io_open (resmgr_context_t *ctp, io_open_t *msg,
         RESMGR_HANDLE_T *handle, void *extra)
{
    return (iofunc_open_default (ctp, msg, handle, extra));
}
```

Obviously, this is just an incremental step that lets you gain control in your *io_open()* when the message arrives from the client. You may wish to do something before or after the default function does its thing:

```
/* example of doing something before */

extern int accepting_opens_now;

int
io_open (resmgr_context_t *ctp, io_open_t *msg,
         RESMGR_HANDLE_T *handle, void *extra)
{
    if (!accepting_opens_now) {
        return (EBUSY);
    }

    /*
```

```
     *  at this point, we're okay to let the open happen,
     *  so let the default function do the "work".
     */

    return (iofunc_open_default (ctp, msg, handle, extra));
}
```

Or:

```
/* example of doing something after */

int
io_open (resmgr_context_t *ctp, io_open_t *msg,
         RESMGR_HANDLE_T *handle, void *extra)
{
    int     sts;

    /*
     * have the default function do the checking
     * and the work for us
     */

    sts = iofunc_open_default (ctp, msg, handle, extra);

    /*
     *  if the default function says it's okay to let the open
     *  happen, we want to log the request
     */

    if (sts == EOK) {
        log_open_request (ctp, msg);
    }
    return (sts);
}
```

It goes without saying that you can do something before *and* after the standard default POSIX handler.

The principal advantage of this approach is that you can add to the functionality of the standard default POSIX handlers with very little effort.

Using the helper functions

The default functions make use of *helper* functions — these functions can't be placed directly into the connect or I/O jump tables, but they do perform the bulk of the work.

Here's the source for the two functions *iofunc_chmod_default()* and *iofunc_stat_default()*:

```
int
iofunc_chmod_default (resmgr_context_t *ctp, io_chmod_t *msg,
                      iofunc_ocb_t *ocb)
{
    return (iofunc_chmod (ctp, msg, ocb, ocb -> attr));
}

int
iofunc_stat_default (resmgr_context_t *ctp, io_stat_t *msg,
                     iofunc_ocb_t *ocb)
{
    iofunc_time_update (ocb -> attr);
    iofunc_stat (ocb -> attr, &msg -> o);
    return (_RESMGR_PTR (ctp, &msg -> o,
                         sizeof (msg -> o)));
}
```

Notice how the *iofunc_chmod()* handler performs all the work for the *iofunc_chmod_default()* default handler. This is typical for the simple functions.

The more interesting case is the *iofunc_stat_default()* default handler, which calls two helper routines. First it calls *iofunc_time_update()* to ensure that all of the time fields (*atime*, *ctime* and *mtime*) are up to date. Then it calls *iofunc_stat()*, which builds the reply. Finally, the default function builds a pointer in the *ctp* structure and returns it.

The most complicated handling is done by the *iofunc_open_default()* handler:

```
int
iofunc_open_default (resmgr_context_t *ctp, io_open_t *msg,
                     iofunc_attr_t *attr, void *extra)
{
    int     status;

    iofunc_attr_lock (attr);
```

```
    if ((status = iofunc_open (ctp, msg, attr, 0, 0)) != EOK) {
        iofunc_attr_unlock (attr);
        return (status);
    }

    if ((status = iofunc_ocb_attach (ctp, msg, 0, attr, 0))
        != EOK) {
        iofunc_attr_unlock (attr);
        return (status);
    }

    iofunc_attr_unlock (attr);
    return (EOK);
}
```

This handler calls four helper functions:

1. It calls *iofunc_attr_lock()* to lock the attribute structure so that it has exclusive access to it (it's going to be updating things like the counters, so we need to make sure no one else is doing that at the same time).
2. It then calls the helper function *iofunc_open()*, which does the actual verification of the permissions.
3. Next it calls *iofunc_ocb_attach()* to bind an OCB to this request, so that it will get automatically passed to all of the I/O functions later.
4. Finally, it calls *iofunc_attr_unlock()* to release the lock on the attribute structure.

Writing the entire function yourself

Sometimes a default function will be of no help for your particular resource manager. For example, *iofunc_read_default()* and *iofunc_write_default()* functions implement **`/dev/null`** — they do all the work of returning 0 bytes (EOF) or swallowing all the message bytes (respectively).

You'll want to do something in those handlers (unless your resource manager doesn't support the _IO_READ or _IO_WRITE messages).

Note that even in such cases, there are still helper functions you can use: *iofunc_read_verify()* and *iofunc_write_verify()*.

Handling the _IO_WRITE message

The io_write handler is responsible for writing data bytes to the media after receiving a client's _IO_WRITE message. Examples of functions that send this message are *write()* and *fflush()*. Here's the message:

```
struct _io_write {
    uint16_t            type;
    uint16_t            combine_len;
    int32_t             nbytes;
    uint32_t            xtype;
    /* unsigned char    data[nbytes]; */
};

typedef union {
    struct _io_write    i;
    /*  nbytes is returned with MsgReply  */
} io_write_t;
```

As with the **`io_read_t`**, we have a union of an input and an output message, with the output message being empty (the number of bytes actually written is returned by the resource manager library directly to the client's *MsgSend()*).

The data being written by the client almost always follows the header message stored in **`struct _io_write`**. The exception is if the write was done using *pwrite()* or *pwrite64()*. More on this when we discuss the *xtype* member.

To access the data, we recommend that you reread it into your own buffer. Let's say you had a buffer called *inbuf* that was "big enough" to hold all the data you expected to read from the client (if it isn't big enough, you'll have to read the data piecemeal).

Sample code for handling _IO_WRITE messages

The following is a code snippet that can be added to one of the simple resource manager examples. It prints out whatever it's given (making the assumption that it's given only character text):

```
int
io_write (resmgr_context_t *ctp, io_write_t *msg, RESMGR_OCB_T *ocb)
{
    int     status;
    char    *buf;

    if ((status = iofunc_write_verify(ctp, msg, ocb, NULL)) != EOK)
        return (status);

    if ((msg->i.xtype & _IO_XTYPE_MASK) != _IO_XTYPE_NONE)
        return(ENOSYS);

    /* set up the number of bytes (returned by client's write()) */

    _IO_SET_WRITE_NBYTES (ctp, msg->i.nbytes);

    buf = (char *) malloc(msg->i.nbytes + 1);
    if (buf == NULL)
        return(ENOMEM);

    /*
     *  Reread the data from the sender's message buffer.
     *  We're not assuming that all of the data fit into the
     *  resource manager library's receive buffer.
     */

    resmgr_msgread(ctp, buf, msg->i.nbytes, sizeof(msg->i));
    buf [msg->i.nbytes] = '\0'; /* just in case the text is not NULL terminated */
    printf ("Received %d bytes = '%s'\n", msg -> i.nbytes, buf);
    free(buf);

    if (msg->i.nbytes > 0)
        ocb->attr->flags |= IOFUNC_ATTR_MTIME | IOFUNC_ATTR_CTIME;

    return (_RESMGR_NPARTS (0));
}
```

Of course, we'll have to give the resource manager library the address of our io_write handler so that it'll know to call it. In the code for *main()* where we called *iofunc_func_init()*, we'll add a line to register our io_write handler:

```
/* initialize functions for handling messages */
iofunc_func_init(_RESMGR_CONNECT_NFUNCS, &connect_funcs,
                 _RESMGR_IO_NFUNCS, &io_funcs);
io_funcs.write = io_write;
```

You may also need to add the following prototype:

```
int io_write (resmgr_context_t *ctp, io_write_t *msg,
              RESMGR_OCB_T *ocb);
```

At this point, if you were to run the resource manager (our simple resource manager used the name **/dev/sample**), you could write to it by doing **echo Hello > /dev/sample** as follows:

```
# echo Hello > /dev/sample
Received 6 bytes = 'Hello'
```

Notice how we passed the last argument to *resmgr_msgread()* (the *offset* argument) as the size of the input message buffer. This effectively skips over the header and gets to the data component.

If the buffer you supplied wasn't big enough to contain the entire message from the client (e.g. you had a 4 KB buffer and the client wanted to write 1 megabyte), you'd have to read the buffer in stages, using a **for** loop, advancing the offset passed to *resmgr_msgread()* by the amount read each time.

Unlike the io_read handler sample, this time we didn't do anything with **ocb->offset**. In this case there's no reason to. The **ocb->offset** would make more sense if we were managing things that had advancing positions such as a file position.

The reply is simpler than with the io_read handler, since a *write()* call doesn't expect any data back. Instead, it just wants to know if the write succeeded and if so, how many bytes were written. To tell it how many bytes were written we used the *_IO_SET_WRITE_NBYTES()* macro. It takes the *nbytes* that we give it and stores it in the context structure (*ctp*). Then when we return to the library, the library takes this *nbytes* and passes it as the second parameter to the *MsgReplyv()*. The second parameter tells the kernel what the *MsgSend()* should return. And since the *write()* function is calling *MsgSend()*, that's where it finds out how many bytes were written.

Since we're writing to the device, we should also update the modification, and potentially, the creation time. For details on updating the modification and change of file status times, see the section on "Updating the time for reads and writes" below.

Methods of returning and replying

You can return to the resource manager library from your handler functions in various ways. This is complicated by the fact that the resource manager library can reply for you if you want it to, but you must tell it to do so and put the information that it'll use in all the right places.

In this section, we'll discuss the following ways of returning to the resource manager library:

- Returning with an error
- Returning using an IOV array that points to your data
- Returning with a single buffer containing data
- Returning success but with no data
- Getting the resource manager library to do the reply
- Performing the reply in the server
- Returning and telling the library to do the default action

Returning with an error

To reply to the client such that the function the client is calling (e.g. *read()*) will return with an error, you simply return with an appropriate *errno* value (from **<errno.h>**).

```
return (ENOMEM);
```

You may occasionally see another form in use (historical and deprecated) that works out to exactly the same thing:

```
return (_RESMGR_ERRNO(ENOMEM));
```

In the case of a *read()*, both of the above cause the read to return -1 with *errno* set to ENOMEM.

Returning using an IOV array that points to your data

Sometimes you'll want to reply with a header followed by one of *N* buffers, where the buffer used will differ each time you reply. To do this, you can set up an IOV array whose elements point to the header and to a buffer.

The context structure already has an IOV array. If you want the resource manager library to do your reply for you, then you must use this array. But the array must contain enough elements for your needs. To ensure that this is the case, you'd set the *nparts_max* member of the **resmgr_attr_t** structure that you passed to *resmgr_attach()* when you registered your name in the pathname space.

The following example assumes that the variable *i* contains the offset into the array of buffers of the desired buffer to reply with. The **2** in **_RESMGR_NPARTS(2)** tells the library how many elements in **ctp->iov** to reply with.

```
my_header_t     header;
a_buffer_t      buffers[N];

...

SETIOV(&ctp->iov[0], &header, sizeof(header));
SETIOV(&ctp->iov[1], &buffers[i], sizeof(buffers[i]));
return (_RESMGR_NPARTS(2));
```

Returning with a single buffer containing data

An example of this would be replying to a *read()* where all the data existed in a single buffer. You'll typically see this done in two ways:

```
return (_RESMGR_PTR(ctp, buffer, nbytes));
```

And:

```
SETIOV (ctp->iov, buffer, nbytes);
return (_RESMGR_NPARTS(1));
```

The first method, using the *_RESMGR_PTR()* macro, is just a convenience for the second method where a single IOV is returned.

Returning success but with no data

This can be done in a few ways. The most simple would be:

```
return (EOK);
```

But you'll often see:

```
return (_RESMGR_NPARTS(0));
```

Note that in neither case are you causing the *MsgSend()* to return with a 0. The value that the *MsgSend()* returns is the value passed to the *_IO_SET_READ_NBYTES()*, *_IO_SET_WRITE_NBYTES()*, and other similar macros. These two were used in the read and write samples above.

Getting the resource manager library to do the reply

In this case, you give the client the data and get the resource manager library to do the reply for you. However, the reply data won't be valid by that time. For example, if the reply data was in a buffer that you wanted to free before returning, you could use the following:

```
resmgr_msgwrite (ctp, buffer, nbytes, 0);
free (buffer);
return (EOK);
```

The *resmgr_msgwrite()* copies the contents of buffer into the client's reply buffer immediately. Note that a reply is still required in order to unblock the client so it can examine the data. Next we free the buffer. Finally, we return to the resource manager library such that it does a reply with zero-length data. Since the reply is of zero length, it doesn't overwrite the data already written into the client's reply buffer. When the client returns from its send call, the data is there waiting for it.

Performing the reply in the server

In all of the previous examples, it's the resource manager library that calls *MsgReply*()* or *MsgError()* to unblock the client. In some cases, you may not want the library to reply for you. For instance, you might have already done the reply yourself, or you'll reply later. In either case, you'd return as follows:

```
return (_RESMGR_NOREPLY);
```

Leaving the client blocked, replying later

An example of a resource manager that would reply to clients later is a pipe resource manager. If the client is doing a read of your pipe but you have no data for the client, then you have a choice:

- You can reply back with an error (EAGAIN).

  Or:

- You can leave the client blocked and later, when your write handler function is called, you can reply to the client with the new data.

Another example might be if the client wants you to write out to some device but doesn't want to get a reply until the data has been fully written out. Here are the sequence of events that might follow:

1. Your resource manager does some I/O out to the hardware to tell it that data is available.
2. The hardware generates an interrupt when it's ready for a packet of data.
3. You handle the interrupt by writing data out to the hardware.
4. Many interrupts may occur before all the data is written — only then would you reply to the client.

The first issue, though, is whether the client wants to be left blocked. If the client doesn't want to be left blocked, then it opens with the O_NONBLOCK flag:

```
fd = open("/dev/sample", O_RDWR | O_NONBLOCK);
```

The default is to allow you to block it.

One of the first things done in the read and write samples above was to call some POSIX verification functions: *iofunc_read_verify()* and *iofunc_write_verify()*. If we pass the address of an **int** as the last parameter, then on return the functions will stuff that **int** with nonzero if the client doesn't want to be blocked (O_NONBLOCK flag was set) or with zero if the client wants to be blocked.

```
int    nonblock;

if ((status = iofunc_read_verify (ctp, msg, ocb,
                                  &nonblock)) != EOK)
    return (status);

...

int    nonblock;

if ((status = iofunc_write_verify (ctp, msg, ocb,
                                   &nonblock)) != EOK)
    return (status);
```

When it then comes time to decide if we should reply with an error or reply later, we do:

```
if (nonblock) {
    /* client doesn't want to be blocked */
    return (EAGAIN);
} else {
    /*
    *  The client is willing to be blocked.
    *  Save at least the ctp->rcvid so that you can
    *  reply to it later.
    */
    ...
    return (_RESMGR_NOREPLY);
}
```

The question remains: How do you do the reply yourself? The only detail to be aware of is that the *rcvid* to reply to is **ctp->rcvid**. If you're replying later, then you'd save **ctp->rcvid** and use the saved value in your reply.

```
MsgReply(saved_rcvid, 0, buffer, nbytes);
```

Or:

```
iov_t    iov[2];

SETIOV(&iov[0], &header, sizeof(header));
SETIOV(&iov[1], &buffers[i], sizeof(buffers[i]));
MsgReplyv(saved_rcvid, 0, iov, 2);
```

Note that you can fill up the client's reply buffer as data becomes available by using *resmgr_msgwrite()* and *resmgr_msgwritev()*. Just remember to do the *MsgReply*()* at some time to unblock the client.

If you're replying to an _IO_READ or _IO_WRITE message, the *status* argument for *MsgReply*()* must be the number of bytes read or written.

Returning and telling the library to do the default action

The default action in most cases is for the library to cause the client's function to fail with ENOSYS:

```
return (_RESMGR_DEFAULT);
```

Handling other read/write details

Topics in this session include:

- Handling the *xtype* member
- Handling *pread*()* and *pwrite*()*
- Handling *readcond()*.

Handling the *xtype* member

The *io_read*, *io_write*, and *io_openfd* message structures contain a member called *xtype*. From **`struct _io_read`**:

```
struct _io_read {
    ...
    uint32_t            xtype;
    ...
}
```

Basically, the *xtype* contains extended type information that can be used to adjust the behavior of a standard I/O function. Most resource managers care about only a few values:

_IO_XTYPE_NONE

No extended type information is being provided.

_IO_XTYPE_OFFSET

If clients are calling *pread()*, *pread64()*, *pwrite()*, or *pwrite64()*, then they don't want you to use the offset in the OCB. Instead, they're providing a one-shot offset. That offset follows the **`struct _io_read`** or **`struct _io_write`** headers that reside at the beginning of the message buffers.

For example:

```
struct myread_offset {
    struct _io_read         read;
    struct _xtype_offset    offset;
}
```

Some resource managers can be sure that their clients will never call *pread*()* or *pwrite*()*. (For example, a resource manager that's controlling a robot arm probably wouldn't care.) In this case, you can treat this type of message as an error.

_IO_XTYPE_READCOND

If a client is calling *readcond()*, they want to impose timing and return buffer size constraints on the read. Those constraints

follow the **struct _io_read** or **struct _io_write** headers at the beginning of the message buffers. For example:

```
struct myreadcond {
    struct _io_read        read;
    struct _xtype_readcond cond;
}
```

As with _IO_XTYPE_OFFSET, if your resource manager isn't prepared to handle *readcond()*, you can treat this type of message as an error.

If you aren't expecting extended types (*xtype*)

The following code sample demonstrates how to handle the case where you're not expecting any extended types. In this case, if you get a message that contains an *xtype*, you should reply with ENOSYS. The example can be used in either an io_read or io_write handler.

```
int
io_read (resmgr_context_t *ctp, io_read_t *msg,
         RESMGR_OCB_T *ocb)
{
    int    status;

    if ((status = iofunc_read_verify(ctp, msg, ocb, NULL))
         != EOK) {
        return (_RESMGR_ERRNO(status));
    }

    /* No special xtypes */
    if ((msg->i.xtype & _IO_XTYPE_MASK) != _IO_XTYPE_NONE)
        return (_RESMGR_ERRNO(ENOSYS));

    ...
}
```

Handling *pread*()* and *pwrite*()*

Here are code examples that demonstrate how to handle an _IO_READ or _IO_WRITE message when a client calls:

- *pread*()*
- *pwrite*()*

Sample code for handling _IO_READ messages in *pread*()*

The following sample code demonstrates how to handle _IO_READ for the case where the client calls one of the *pread*()* functions.

```
/* we are defining io_pread_t here to make the code below
   simple */
typedef struct {
    struct _io_read         read;
    struct _xtype_offset    offset;
} io_pread_t;

int
io_read (resmgr_context_t *ctp, io_read_t *msg,
         RESMGR_OCB_T *ocb)
{
    off64_t offset; /* where to read from */
    int     status;

    if ((status = iofunc_read_verify(ctp, msg, ocb, NULL))
         != EOK) {
        return(_RESMGR_ERRNO(status));
    }

    switch(msg->i.xtype & _IO_XTYPE_MASK) {
    case _IO_XTYPE_NONE:
        offset = ocb->offset;
        break;
    case _IO_XTYPE_OFFSET:
        /*
         *  io_pread_t is defined above.
         *  Client is doing a one-shot read to this offset by
         *  calling one of the pread*() functions
         */
        offset = ((io_pread_t *) msg)->offset.offset;
        break;
    default:
        return(_RESMGR_ERRNO(ENOSYS));
    }
```

```
    ...
}
```

Sample code for handling _IO_WRITE messages in *pwrite*()*

The following sample code demonstrates how to handle _IO_WRITE for the case where the client calls one of the *pwrite*()* functions. Keep in mind that the **struct _xtype_offset** information follows the **struct _io_write** in the sender's message buffer. This means that the data to be written follows the **struct _xtype_offset** information (instead of the normal case where it follows the **struct _io_write**). So, you must take this into account when doing the *resmgr_msgread()* call in order to get the data from the sender's message buffer.

```
/* we are defining io_pwrite_t here to make the code below
   simple */
typedef struct {
    struct _io_write        write;
    struct _xtype_offset    offset;
} io_pwrite_t;

int
io_write (resmgr_context_t *ctp, io_write_t *msg,
          RESMGR_OCB_T *ocb)
{
    off64_t offset; /* where to write */
    int     status;
    size_t  skip;   /* offset into msg to where the data
                       resides */

    if ((status = iofunc_write_verify(ctp, msg, ocb, NULL))
         != EOK) {
        return(_RESMGR_ERRNO(status));
    }

    switch(msg->i.xtype & _IO_XTYPE_MASK) {
    case _IO_XTYPE_NONE:
        offset = ocb->offset;
        skip = sizeof(io_write_t);
        break;
    case _IO_XTYPE_OFFSET:
        /*
         *  io_pwrite_t is defined above
         *  client is doing a one-shot write to this offset by
```

```
             *  calling one of the pwrite*() functions
             */
            offset = ((io_pwrite_t *) msg)->offset.offset;
            skip = sizeof(io_pwrite_t);
            break;
        default:
            return(_RESMGR_ERRNO(ENOSYS));
        }

        ...

        /*
         *  get the data from the sender's message buffer,
         *  skipping all possible header information
         */
        resmgr_msgreadv(ctp, iovs, niovs, skip);

        ...
    }
```

Handling *readcond()*

The same type of operation that was done to handle the *pread()*/_IO_XTYPE_OFFSET case can be used for handling the client's *readcond()* call:

```
typedef struct {
    struct _io_read        read;
    struct _xtype_readcond cond;
} io_readcond_t
```

Then:

```
struct _xtype_readcond *cond
...
    CASE _IO_XTYPE_READCOND:
        cond = &((io_readcond_t *)msg)->cond
        break;
}
```

Then your manager has to properly interpret and deal with the arguments to *readcond()*. For more information, see the *Library Reference*.

Attribute handling

Updating the time for reads and writes

In the read sample above we did:

```
if (msg->i.nbytes > 0)
    ocb->attr->flags |= IOFUNC_ATTR_ATIME;
```

According to POSIX, if the read succeeds and the reader had asked for more than zero bytes, then the access time must be marked for update. But POSIX doesn't say that it must be updated right away. If you're doing many reads, you may not want to read the time from the kernel for every read. In the code above, we mark the time only as needing to be updated. When the next _IO_STAT or _IO_CLOSE_OCB message is processed, the resource manager library will see that the time needs to be updated and will get it from the kernel then. This of course has the disadvantage that the time is not the time of the read.

Similarly for the write sample above, we did:

```
if (msg->i.nbytes > 0)
    ocb->attr->flags |= IOFUNC_ATTR_MTIME | IOFUNC_ATTR_CTIME;
```

so the same thing will happen.

If you *do* want to have the times represent the read or write times, then after setting the flags you need only call the *iofunc_time_update()* helper function. So the read lines become:

```
if (msg->i.nbytes > 0) {
    ocb->attr->flags |= IOFUNC_ATTR_ATIME;
    iofunc_time_update(ocb->attr);
}
```

and the write lines become:

```
if (msg->i.nbytes > 0) {
    ocb->attr->flags |= IOFUNC_ATTR_MTIME | IOFUNC_ATTR_CTIME;
    iofunc_time_update(ocb->attr);
}
```

You should call *iofunc_time_update()* before you flush out any cached attributes. As a result of changing the time fields, the attribute structure will have the IOFUNC_ATTR_DIRTY_TIME bit set in the flags field, indicating that this field of the attribute must be updated when the attribute is flushed from the cache.

Combine messages

In this section:

- Where combine messages are used
- The library's combine-message handling

Where combine messages are used

In order to conserve network bandwidth and to provide support for atomic operations, *combine messages* are supported. A combine message is constructed by the client's C library and consists of a number of I/O and/or connect messages packaged together into one. Let's see how they're used.

Atomic operations

Consider a case where two threads are executing the following code, trying to read from the same file descriptor:

```
a_thread ()
{
    char buf [BUFSIZ];

    lseek (fd, position, SEEK_SET);
    read (fd, buf, BUFSIZ);
    ...
}
```

The first thread performs the *lseek()* and then gets preempted by the second thread. When the first thread resumes executing, its offset into the file will be at the end of where the second thread read from, *not* the position that it had *lseek()*'d to.

This can be solved in one of three ways:

- The two threads can use a *mutex* to ensure that only one thread at a time is using the file descriptor.
- Each thread can open the file itself, thus generating a unique file descriptor that won't be affected by any other threads.
- The threads can use the *readblock()* function, which performs an atomic *lseek()* and *read()*.

Let's look at these three methods.

Using a mutex

In the first approach, if the two threads use a mutex between themselves, the following issue arises: every *read()*, *lseek()*, and *write()* operation *must* use the mutex.

If this practice isn't enforced, then you still have the exact same problem. For example, suppose one thread that's obeying the convention locks the mutex and does the *lseek()*, thinking that it's protected. However, another thread (that's not obeying the convention) can preempt it and move the offset to somewhere else. When the first thread resumes, we again encounter the problem where the offset is at a different (unexpected) location. Generally, using a mutex will be successful only in very tightly managed projects, where a code review will *ensure* that each and every thread's file functions obey the convention.

Per-thread files

The second approach — of using different file descriptors — is a good general-purpose solution, *unless* you explicitly wanted the file descriptor to be shared.

The *readblock()* function

In order for the *readblock()* function to be able to effect an atomic seek/read operation, it must ensure that the requests it sends to the resource manager will all be processed at the same time. This is done by combining the _IO_LSEEK and _IO_READ messages into one

message. Thus, when the base layer performs the *MsgReceive()*, it will receive the entire *readblock()* request in one atomic message.

Bandwidth considerations

Another place where combine messages are useful is in the *stat()* function, which can be implemented by calling *open()*, *fstat()*, and *close()* in sequence.

Rather than generate three separate messages (one for each of the functions), the C library combines them into one contiguous message. This boosts performance, especially over a networked connection, and also simplifies the resource manager, because it's not forced to have a connect function to handle *stat()*.

The library's combine-message handling

The resource manager library handles combine messages by presenting each component of the message to the appropriate handler routines. For example, if we get a combine message that has an _IO_LSEEK and _IO_READ in it (e.g. *readblock()*), the library will call our *io_lseek()* and *io_read()* functions for us in turn.

But let's see what happens in the resource manager when it's handling these messages. With multiple threads, both of the client's threads may very well have sent in their "atomic" combine messages. Two threads in the resource manager will now attempt to service those two messages. We again run into the same synchronization problem as we originally had on the client end — one thread can be part way through processing the message and can then be preempted by the other thread.

The solution? The resource manager library provides callouts to lock the OCB while processing any message (except _IO_CLOSE and _IO_UNBLOCK — we'll return to these). As an example, when processing the *readblock()* combine message, the resource manager library performs callouts in this order:

1. *lock_ocb* handler
2. _IO_LSEEK message handler

3 _IO_READ message handler

4 *unlock_ocb* handler

Therefore, in our scenario, the two threads within the resource manager would be mutually exclusive to each other by virtue of the lock — the first thread to acquire the lock would completely process the combine message, unlock the lock, and then the second thread would perform its processing.

Let's examine several of the issues that are associated with handling combine messages:

- Component responses
- Component data access
- Locking and unlocking the attribute structure
- Various styles of connect messages
- _IO_CONNECT_COMBINE_CLOSE
- _IO_CONNECT_COMBINE

Component responses

As we've seen, a combine message really consists of a number of "regular" resource manager messages combined into one large contiguous message. The resource manager library handles each component in the combine message separately by extracting the individual components and then out calling to the handlers you've specified in the connect and I/O function tables, as appropriate, for each component.

This generally doesn't present any new wrinkles for the message handlers themselves, except in one case. Consider the *readblock()* combine message:

Client call: *readblock()*

Message(s): _IO_LSEEK , _IO_READ

Callouts: *io_lock_ocb()*
io_lseek()
io_read()
io_unlock_ocb()

Ordinarily, after processing the _IO_LSEEK message, your handler would return the current position within the file. However, the next message (the _IO_READ) also returns data. By convention, only the last data-returning message within a combine message will actually return data. The intermediate messages are allowed to return only a pass/fail indication.

The impact of this is that the _IO_LSEEK message handler has to be aware of whether or not it's being invoked as part of combine message handling. If it is, it should only return either an EOK (indicating that the *lseek()* operation succeeded) or an error indication to indicate some form of failure.

But if the _IO_LSEEK handler isn't being invoked as part of combine message handling, it should return the EOK *and* the new offset (or, in case of error, an error indication only).

Here's a sample of the code for the default iofunc-layer *lseek()* handler:

```
int
iofunc_lseek_default (resmgr_context_t *ctp,
                      io_lseek_t *msg,
                      iofunc_ocb_t *ocb)
{
    /*
     *  performs the lseek processing here
     *  may "early-out" on error conditions
     */
     . . .

    /* decision re: combine messages done here */
    if (msg -> i.combine_len & _IO_COMBINE_FLAG) {
        return (EOK);
    }

    msg -> o = offset;
    return (_RESMGR_PTR (ctp, &msg -> o, sizeof (msg -> o)));
}
```

The relevant decision is made in this statement:

```
if (msg -> i.combine_len & _IO_COMBINE_FLAG)
```

If the _IO_COMBINE_FLAG bit is set in the *combine_len* member, this indicates that the message is being processed as part of a combine message.

When the resource manager library is processing the individual components of the combine message, it looks at the error return from the individual message handlers. If a handler returns anything other than EOK, then processing of further combine message components is aborted. The error that was returned from the failing component's handler is returned to the client.

Component data access

The second issue associated with handling combine messages is how to access the data area for subsequent message components.

For example, the *writeblock()* combine message format has an *lseek()* message first, followed by the *write()* message. This means that the data associated with the *write()* request is further in the received message buffer than would be the case for just a simple _IO_WRITE message:

Client call:	*writeblock()*
Message(s):	_IO_LSEEK , _IO_WRITE , data
Callouts:	*io_lock_ocb()* *io_lseek()* *io_write()* *io_unlock_ocb()*

This issue is easy to work around. There's a resource manager library function called *resmgr_msgread()* that knows how to get the data corresponding to the correct message component. Therefore, in the

io_write handler, if you used *resmgr_msgread()* instead of *MsgRead()*, this would be transparent to you.

Resource managers should always use *resmgr_msg*()* cover functions.

For reference, here's the source for *resmgr_msgread()*:

```
int resmgr_msgread( resmgr_context_t *ctp,
                    void *msg,
                    int nbytes,
                    int offset)
{
    return MsgRead(ctp->rcvid, msg, nbytes, ctp->offset + offset);
}
```

As you can see, *resmgr_msgread()* simply calls *MsgRead()* with the offset of the component message from the beginning of the combine message buffer. For completeness, there's also a *resmgr_msgwrite()* that works in an identical manner to *MsgWrite()*, except that it dereferences the passed *ctp* to obtain the *rcvid*.

Locking and unlocking the attribute structure

As mentioned above, another facet of the operation of the *readblock()* function from the client's perspective is that it's atomic. In order to process the requests for a particular OCB in an atomic manner, we must lock and unlock the attribute structure pointed to by the OCB, thus ensuring that only one resource manager thread has access to the OCB at a time.

The resource manager library provides two callouts for doing this:

- *lock_ocb*
- *unlock_ocb*

These are members of the I/O functions structure. The handlers that you provide for those callouts should lock and unlock the attribute structure pointed to by the OCB by calling *iofunc_attr_lock()* and *iofunc_attr_unlock()*. Therefore, if you're locking the attribute

structure, there's a possibility that the *lock_ocb* callout will block for a period of time. This is normal and expected behavior. Note also that the attributes structure is automatically locked for you when your I/O function is called.

Connect message types

Let's take a look at the general case for the io_open handler — it doesn't always correspond to the client's *open()* call!

For example, consider the *stat()* and *access()* client function calls.

_IO_CONNECT_COMBINE_CLOSE

For a *stat()* client call, we essentially perform the sequence *open()*/*fstat()*/*close()*. Note that if we actually did that, three messages would be required. For performance reasons, we implement the *stat()* function as one single combine message:

Client call:	*stat()*
Message(s):	_IO_CONNECT_COMBINE_CLOSE , _IO_STAT
Callouts:	*io_open()* *io_lock_ocb()* *io_stat()* *io_unlock_ocb()* *io_close()*

The _IO_CONNECT_COMBINE_CLOSE message causes the io_open handler to be called. It then implicitly (at the end of processing for the combine message) causes the *io_close_ocb* handler to be called.

_IO_CONNECT_COMBINE

For the *access()* function, the client's C library will open a connection to the resource manager and perform a *stat()* call. Then, based on the results of the *stat()* call, the client's C library *access()* may perform an optional *devctl()* to get more information. In any event, because *access()* opened the device, it must also call *close()* to close it:

Client call:	*access()*
Message(s):	_IO_CONNECT_COMBINE , _IO_STAT _IO_DEVCTL (optional) _IO_CLOSE
Callouts:	*io_open()* *io_lock_ocb()* *io_stat()* *io_unlock_ocb()* *io_lock_ocb()* (optional) *io_devctl()* (optional) *io_unlock_ocb()* (optional) *io_close()*

Notice how the *access()* function opened the pathname/device — it sent it an _IO_CONNECT_COMBINE message along with the _IO_STAT message. This creates an OCB (when the io_open handler is called), locks the associated attribute structure (via *io_lock_ocb()*), performs the stat (*io_stat()*), and then unlocks the attributes structure (*io_unlock_ocb()*). Note that we don't implicitly close the OCB — this is left for a later, explicit, message. Contrast this handling with that of the plain *stat()* above.

Extending Data Control Structures (DCS)

This section contains:

- Extending the OCB and attribute structures
- Extending the mount structures

Extending the OCB and attribute structures

In our **`/dev/sample`** example, we had a static buffer associated with the entire resource. Sometimes you may want to keep a pointer to a buffer associated with the resource, rather than in a global area. To maintain the pointer with the resource, we would have to store it in

the attribute structure. Since the attribute structure doesn't have any spare fields, we would have to extend it to contain that pointer.

Sometimes you may want to add extra entries to the standard *iofunc_*()* OCB (**iofunc_ocb_t**).

Let's see how we can extend both of these structures. The basic strategy used is to encapsulate the existing attributes and OCB structures within a newly defined superstructure that also contains our extensions. Here's the code (see the text following the listing for comments):

```
/* Define our overrides before including <sys/iofunc.h>  */
struct device;
#define IOFUNC_ATTR_T       struct device  /* see note 1 */
struct ocb;
#define IOFUNC_OCB_T        struct ocb     /* see note 1 */

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

struct ocb {                               /* see note 2 */
    iofunc_ocb_t            hdr;           /* see note 4; must always be first */
    struct ocb              *next;
    struct ocb              **prev;        /* see note 3 */
};

struct device {                            /* see note 2 */
    iofunc_attr_t           attr;          /* must always be first */
    struct ocb              *list;         /* waiting for write */
};

/* Prototypes, needed since we refer to them a few lines down */

struct ocb *ocb_calloc (resmgr_context_t *ctp, struct device *device);
void ocb_free (struct ocb *ocb);

iofunc_funcs_t ocb_funcs = { /* our ocb allocating & freeing functions */
    _IOFUNC_NFUNCS,
    ocb_calloc,
    ocb_free
};

/* The mount structure.  We have only one, so we statically declare it */

iofunc_mount_t          mountpoint = { 0, 0, 0, 0, &ocb_funcs };

/* One struct device per attached name (there's only one name in this
   example) */

struct device           deviceattr;

main()
{
    ...
```

```
    /*
     *  deviceattr will indirectly contain the addresses
     *  of the OCB allocating and freeing functions
     */

    deviceattr.attr.mount = &mountpoint;
    resmgr_attach (..., &deviceattr);

    ...
}

/*
 * ocb_calloc
 *
 *  The purpose of this is to give us a place to allocate our own OCB.
 *  It is called as a result of the open being done
 *  (e.g. iofunc_open_default causes it to be called). We
 *  registered it through the mount structure.
 */
IOFUNC_OCB_T
ocb_calloc (resmgr_context_t *ctp, IOFUNC_ATTR_T *device)
{
    struct ocb *ocb;

    if (!(ocb = calloc (1, sizeof (*ocb)))) {
        return 0;
    }

    /* see note 3 */
    ocb -> prev = &device -> list;
    if (ocb -> next = device -> list) {
        device -> list -> prev = &ocb -> next;
    }
    device -> list = ocb;

    return (ocb);
}

/*
 * ocb_free
 *
 * The purpose of this is to give us a place to free our OCB.
 * It is called as a result of the close being done
 * (e.g. iofunc_close_ocb_default causes it to be called). We
 * registered it through the mount structure.
 */
void
ocb_free (IOFUNC_OCB_T *ocb)
{
    /* see note 3 */
    if (*ocb -> prev = ocb -> next) {
        ocb -> next -> prev = ocb -> prev;
        }
        free (ocb);
}
```

Here are the notes for the above code:

1. We place the definitions for our enhanced structures *before* including the standard I/O functions header file. Because the standard I/O functions header file checks to see if the two manifest constants are already defined, this allows a convenient way for us to semantically override the structures.
2. Define our new enhanced data structures, being sure to place the encapsulated members first.
3. The *ocb_calloc()* and *ocb_free()* sample functions shown here cause the newly allocated OCBs to be maintained in a linked list. Note the use of dual indirection on the **`struct ocb **prev;`** member.
4. You ***must always*** place the **`iofunc`** structure that you're overriding as the first member of the new extended structure. This lets the common library work properly in the default cases.

Extending the mount structure

You can also extend the **`iofunc_mount_t`** structure in the same manner as the attribute and OCB structures. In this case, you'd define:

```
#define IOFUNC_MOUNT_T       struct newmount
```

then declare the new structure:

```
struct newmount {
    iofunc_mount_t          mount;
    int                    ourflag;
};
```

Handling *devctl()* messages

The *devctl()* function is a general-purpose mechanism for communicating with a resource manager. Clients can send data to, receive data from, or both send and receive data from a resource manager. The format of the client *devctl()* call is:

```
devctl( int fd,
        int dcmd,
        void * data,
        size_t nbytes,
        int * return_info);
```

The following values (described in detail in the *devctl()* documentation in the *Library Reference*) map directly to the _IO_DEVCTL message itself:

```
struct _io_devctl {
        uint16_t                type;
        uint16_t                combine_len;
        int32_t                 dcmd;
        int32_t                 nbytes;
        int32_t                 zero;
/*      char                    data[nbytes]; */
};

struct _io_devctl_reply {
        uint32_t                zero;
        int32_t                 ret_val;
        int32_t                 nbytes;
        int32_t                 zero2;
/*      char                    data[nbytes]; */
    } ;

typedef union {
        struct _io_devctl       i;
        struct _io_devctl_reply o;
} io_devctl_t;
```

As with most resource manager messages, we've defined a **union** that contains the input structure (coming into the resource manager), and a reply or output structure (going back to the client). The io_devctl resource manager handler is prototyped with the argument:

**io_devctl_t ***msg*

which is the pointer to the union containing the message.

The *type* member has the value _IO_DEVCTL.

The *combine_len* field has meaning for a combine message; see the "Combine messages" section in this chapter.

The *nbytes* value is the *nbytes* that's passed to the *devctl()* function. The value contains the size of the data to be sent to the device driver, or the maximum size of the data to be received from the device driver.

The most interesting item of the input structure is the **dcmd**. that's passed to the *devctl()* function. This command is formed using the macros defined in **<devctl.h>**:

```
#define _POSIX_DEVDIR_NONE        0
#define _POSIX_DEVDIR_TO          0x80000000
#define _POSIX_DEVDIR_FROM        0x40000000
#define __DIOF(class, cmd, data)  ((sizeof(data)<<16) + ((class)<<8) + (cmd) + _POSIX_DEVDIR_FROM)
#define __DIOT(class, cmd, data)  ((sizeof(data)<<16) + ((class)<<8) + (cmd) + _POSIX_DEVDIR_TO)
#define __DIOTF(class, cmd, data) ((sizeof(data)<<16) + ((class)<<8) + (cmd) + _POSIX_DEVDIR_TOFROM)
#define __DION(class, cmd)        (((class)<<8) + (cmd) + _POSIX_DEVDIR_NONE)
```

It's important to understand how these macros pack data to create a command. An 8-bit class (defined in **<devctl.h>**) is combined with an 8-bit subtype that's manager-specific, and put together in the lower 16 bits of the integer.

The upper 16 bits contain the direction (TO, FROM) as well as a hint about the size of the data structure being passed. This size is only a hint put in to uniquely identify messages that may use the same class and code but pass different data structures.

In the following example, a *cmd* is generated to indicate that the client is sending data to the server (TO), but not receiving anything in return. The only bits that the library or the resource manager layer look at are the TO and FROM bits to determine which arguments are to be passed to *MsgSend()*.

```
struct _my_devctl_msg {
    ...
}

#define MYDCMD  __DIOT(_DCMD_MISC, 0x54, struct _my_devctl_msg)
```

The size of the structure that's passed as the last field to the *__DIO** macros **must** be less than 2^{14} == 16 KB. Anything larger than this interferes with the upper two directional bits.

The data directly follows this message structure, as indicated by the **`/* char data[nbytes] */`** comment in the **`_io_devctl`** structure.

Sample code for handling _IO_DEVCTL messages

You can add the following code samples to either of the examples provided in the "Simple device resource manager examples" section. Both of those code samples provided the name **`/dev/sample`**. With the changes indicated below, the client can use *devctl()* to set and retrieve a global value (an integer in this case) that's maintained in the resource manager.

The first addition defines what the *devctl()* commands are going to be. This is generally put in a common or shared header file:

```
typedef union _my_devctl_msg {
        int tx;             //Filled by client on send
        int rx;             //Filled by server on reply
} data_t;

#define MY_CMD_CODE      1
#define MY_DEVCTL_GETVAL __DIOF(_DCMD_MISC,  MY_CMD_CODE + 0, int)
#define MY_DEVCTL_SETVAL __DIOT(_DCMD_MISC,  MY_CMD_CODE + 1, int)
#define MY_DEVCTL_SETGET __DIOTF(_DCMD_MISC, MY_CMD_CODE + 2, union _my_devctl_msg)
```

In the above code, we defined three commands that the client can use:

MY_DEVCTL_SETVAL

Sets the server global to the integer the client provides.

MY_DEVCTL_GETVAL

Gets the server global and puts that value into the client's buffer.

MY_DEVCTL_SETGET

Sets the server global to the integer the client provides and returns the previous value of the server global in the client's buffer.

Add this code to the *main()* function:

```
io_funcs.devctl = io_devctl;  /* For handling _IO_DEVCTL, sent by devctl() */
```

And the following code gets added before the *main()* function:

```
int io_devctl(resmgr_context_t *ctp, io_devctl_t *msg, RESMGR_OCB_T *ocb);

int global_integer = 0;
```

Now, you need to include the new handler function to handle the _IO_DEVCTL message:

```
int io_devctl(resmgr_context_t *ctp, io_devctl_t *msg, RESMGR_OCB_T *ocb) {
    int     nbytes, status, previous;
    union {
        data_t  data;
        int     data32;
        // ... other devctl types you can receive
    } *rx_data;


    /*
     Let common code handle DCMD_ALL_* cases.
     You can do this before or after you intercept devctl's depending
     on your intentions.  Here we aren't using any pre-defined values
     so let the system ones be handled first.
    */
    if ((status = iofunc_devctl_default(ctp, msg, ocb)) != _RESMGR_DEFAULT) {
        return(status);
    }
    status = nbytes = 0;

    /*
     Note this assumes that you can fit the entire data portion of
     the devctl into one message.  In reality you should probably
     perform a MsgReadv() once you know the type of message you
     have received to suck all of the data in rather than assuming
     it all fits in the message.  We have set in our main routine
     that we'll accept a total message size of up to 2k so we
     don't worry about it in this example where we deal with ints.
    */
    rx_data = _DEVCTL_DATA(msg->i);

    /*
     Three examples of devctl operations.
```

```
     SET: Setting a value (int) in the server
     GET: Getting a value (int) from the server
     SETGET: Setting a new value and returning with the previous value
    */
    switch (msg->i.dcmd) {
    case MY_DEVCTL_SETVAL:
        global_integer = rx_data->data32;
        nbytes = 0;
        break;

    case MY_DEVCTL_GETVAL:
        rx_data->data32 = global_integer;
        nbytes = sizeof(rx_data->data32);
        break;

    case MY_DEVCTL_SETGET:
        previous = global_integer;
        global_integer = rx_data->data.tx;
        rx_data->data.rx = previous;        //Overwrites tx data
        nbytes = sizeof(rx_data->data.rx);
        break;

    default:
        return(ENOSYS);
    }

    /* Clear the return message ... note we saved our data _after_ this */
    memset(&msg->o, 0, sizeof(msg->o));

    /*
     If you wanted to pass something different to the return
     field of the devctl() you could do it through this member.
    */
    msg->o.ret_val = status;

    /* Indicate the number of bytes and return the message */
    msg->o.nbytes = nbytes;
    return(_RESMGR_PTR(ctp, &msg->o, sizeof(msg->o) + nbytes));
}
```

When working with *devctl()* handler code, you should be familiar with the following:

- The default *devctl()* handler is called before we begin to service our messages. This allows normal system messages to be processed. If the message isn't handled by the default handler, then it returns _RESMGR_DEFAULT to indicate that the message might be a custom message. This means that we should check the incoming command against commands that our resource manager understands.
- The data to be passed follows directly after the **`io_devctl_t`** structure. You can get a pointer to this location by using the

_DEVCTL_DATA(*msg***->i)** macro defined in **<devctl.h>**. The argument to this macro **must** be the input message structure — if it's the union message structure or a pointer to the input message structure, the pointer won't point to the right location.

For your convenience, we've defined a union of all of the messages that this server can receive. However, this won't work with large data messages. In this case, you'd use *resmgr_msgread()* to read the message from the client. Our messages are never larger than **sizeof(int)** and this comfortably fits into the minimum receive buffer size.

- The last argument to the *devctl()* function is a pointer to an integer. If this pointer is provided, then the integer is filled with the value stored in the **msg->o.ret_val** reply message. This is a convenient way for a resource manager to return simple status information without affecting the core *devctl()* operation. It's not used in this example.

- The data being returned to the client is placed at the end of the reply message. This is the same mechanism used for the input data so we can use the *_DEVCTL_DATA()* function to get a pointer to this location. With large replies that wouldn't necessarily fit into the server's receive buffer, you should use one of the reply mechanisms described in the "Methods of returning and replying" section. Again, in this example, we're only returning an integer that fits into the receive buffer without any problem.

If you add the following handler code, a client should be able to open **/dev/sample** and subsequently set and retrieve the global integer value:

```
int main(int argc, char **argv) {
    int     fd, ret, val;
    data_t  data;

    if ((fd = open("/dev/sample", O_RDONLY)) == -1) {
            return(1);
    }

    /* Find out what the value is set to initially */
    val = -1;
    ret = devctl(fd, MY_DEVCTL_GETVAL, &val, sizeof(val), NULL);
    printf("GET returned %d w/ server value %d \n", ret, val);
```

```
    /* Set the value to something else */
    val = 25;
    ret = devctl(fd, MY_DEVCTL_SETVAL, &val, sizeof(val), NULL);
    printf("SET returned %d \n", ret);

    /* Verify we actually did set the value */
    val = -1;
    ret = devctl(fd, MY_DEVCTL_GETVAL, &val, sizeof(val), NULL);
    printf("GET returned %d w/ server value %d == 25? \n", ret, val);

    /* Now do a set/get combination */
    memset(&data, 0, sizeof(data));
    data.tx = 50;
    ret = devctl(fd, MY_DEVCTL_SETGET, &data, sizeof(data), NULL);
    printf("SETGET returned with %d w/ server value %d == 25?\n", ret, data.rx);

    /* Check set/get worked */
    val = -1;
    ret = devctl(fd, MY_DEVCTL_GETVAL, &val, sizeof(val), NULL);
    printf("GET returned %d w/ server value %d == 50? \n", ret, val);

    return(0);
}
```

Handling *ionotify()* and *select()*

A client uses *ionotify()* and *select()* to ask a resource manager about the status of certain conditions (e.g. whether input data is available). The conditions may or may not have been met. The resource manager can be asked to:

- check the status of the conditions immediately, and return if any have been met
- deliver an event later on when a condition is met (this is referred to as arming the resource manager)

The *select()* function differs from *ionotify()* in that most of the work is done in the library. For example, the client code would be unaware that any event is involved, nor would it be aware of the blocking function that waits for the event. This is all hidden in the library code for *select()*.

However, from a resource manager's point of view, there's no difference between *ionotify()* and *select()*; they're handled with the same code.

For more information on the *ionotify()* and *select()* functions, see the *Library Reference*.

Currently, the API for notification handling from your resource manager doesn't support multithreaded client processes very well. Problems may arise when a thread in a client process requests notification and other threads in the same client process are also dealing with the resource manager. This is not a problem when the threads are from different processes.

Since *ionotify()* and *select()* require the resource manager to do the same work, they both send the _IO_NOTIFY message to the resource manager. The *io_notify* handler is responsible for handling this message. Let's start by looking at the format of the message itself:

```
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                    flags;
};

typedef union {
    struct _io_notify           i;
    struct _io_notify_reply     o;
} io_notify_t;
```

As with all resource manager messages, we've defined a **union** that contains the input structure (coming into the resource manager), and a reply or output structure (going back to the client). The *io_notify* handler is prototyped with the argument:

io_notify_t * *msg*

which is the pointer to the union containing the message.

The items in the input structure are:

- *type*
- *combine_len*
- *action*
- *flags*
- *event*

The *type* member has the value _IO_NOTIFY.

The *combine_len* field has meaning for a combine message; see the "Combine messages" section in this chapter.

The *action* member is used by the *iofunc_notify()* helper function to tell it whether it should:

- just check for conditions now
- check for conditions now, and if none are met, arm them
- just arm for transitions

Since *iofunc_notify()* looks at this, you don't have to worry about it.

The *flags* member contains the conditions that the client is interested in and can be any mixture of the following:

_NOTIFY_COND_INPUT

This condition is met when there are one or more units of input data available (i.e. clients can now issue reads). The number of units defaults to 1, but you can change it. The definition of a unit is up to you: for a character device such as a serial port, it would be a character; for a POSIX message queue, it would be a message. Each resource manager selects an appropriate object.

_NOTIFY_COND_OUTPUT

This condition is met when there's room in the output buffer for one or more units of data (i.e. clients can now issue writes). The number of units defaults to 1, but you can change it. The definition of a unit is up to you — some resource managers may

default to an empty output buffer while others may choose some percentage of the buffer empty.

_NOTIFY_COND_OBAND

The condition is met when one or more units of out-of-band data are available. The number of units defaults to 1, but you can change it. The definition of out-of-band data is specific to the resource manager.

The *event* member is what the resource manager delivers once a condition is met.

A resource manager needs to keep a list of clients that want to be notified as conditions are met, along with the events to use to do the notifying. When a condition is met, the resource manager must traverse the list to look for clients that are interested in that condition, and then deliver the appropriate event. As well, if a client closes its file descriptor, then any notification entries for that client must be removed from the list.

To make all this easier, the following structure and helper functions are provided for you to use in a resource manager:

`iofunc_notify_t` structure

Contains the three notification lists, one for each possible condition. Each is a list of the clients to be notified for that condition.

iofunc_notify() Adds or removes notification entries; also polls for conditions. Call this function inside of your io_notify handler function.

iofunc_notify_trigger()

Sends notifications to queued clients. Call this function when one or more conditions have been met.

iofunc_notify_remove()

Removes notification entries from the list. Call this function when the client closes its file descriptor.

Sample code for handling _IO_NOTIFY messages

You can add the following code samples to either of the examples provided in the "Simple device resource manager examples" section. Both of those code samples provided the name **`/dev/sample`**. With the changes indicated below, clients can use writes to send it data, which it'll store as discrete messages. Other clients can use either *ionotify()* or *select()* to request notification when that data arrives. When clients receive notification, they can issue reads to get the data.

You'll need to replace this code that's located above the *main()* function:

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

static resmgr_connect_funcs_t    connect_funcs;
static resmgr_io_funcs_t         io_funcs;
static iofunc_attr_t             attr;
```

with the following:

```
struct device_attr_s;
#define IOFUNC_ATTR_T   struct device_attr_s

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

/*
 * define structure and variables for storing the data that is received.
 * When clients write data to us, we store it here.  When clients do
 * reads, we get the data from here.  Result ... a simple message queue.
*/
typedef struct item_s {
    struct item_s   *next;
    char            *data;
} item_t;

/* the extended attributes structure */
typedef struct device_attr_s {
    iofunc_attr_t   attr;
    iofunc_notify_t notify[3];  /* notification list used by iofunc_notify*() */
    item_t          *firstitem; /* the queue of items */
    int             nitems;     /* number of items in the queue */
} device_attr_t;
```

```
/* We only have one device; device_attr is its attribute structure */

static device_attr_t    device_attr;

int io_read(resmgr_context_t *ctp, io_read_t  *msg, RESMGR_OCB_T *ocb);
int io_write(resmgr_context_t *ctp, io_write_t *msg, RESMGR_OCB_T *ocb);
int io_notify(resmgr_context_t *ctp, io_notify_t *msg, RESMGR_OCB_T *ocb);
int io_close_ocb(resmgr_context_t *ctp, void *reserved, RESMGR_OCB_T *ocb);

static resmgr_connect_funcs_t  connect_funcs;
static resmgr_io_funcs_t       io_funcs;
```

We need a place to keep data that's specific to our device. A good place for this is in an attribute structure that we can associate with the name we registered: **`/dev/sample`**. So, in the code above, we defined **`device_attr_t`** and **`IOFUNC_ATTR_T`** for this purpose. We talk more about this type of device-specific attribute structure in the section, "Extending Data Control Structures (DCS)."

We need two types of device-specific data:

- an array of three notification lists — one for each possible condition that a client can ask to be notified about. In **`device_attr_t`**, we called this *notify*.
- a queue to keep the data that gets written to us, and that we use to reply to a client. For this, we defined **`item_t`**; it's a type that contains data for a single item, as well as a pointer to the next **`item_t`**. In **`device_attr_t`** we use *firstitem* (points to the first item in the queue), and *nitems* (number of items).

Note that we removed the definition of *attr*, since we use *device_attr* instead.

Of course, we have to give the resource manager library the address of our handlers so that it'll know to call them. In the code for *main()* where we called *iofunc_func_init()*, we'll add the following code to register our handlers:

```
/* initialize functions for handling messages */
iofunc_func_init(_RESMGR_CONNECT_NFUNCS, &connect_funcs,
                 _RESMGR_IO_NFUNCS, &io_funcs);
io_funcs.notify = io_notify; /* for handling _IO_NOTIFY, sent as
                                a result of client calls to ionotify()
                                and select() */
```

```
io_funcs.write = io_write;
io_funcs.read = io_read;
io_funcs.close_ocb = io_close_ocb;
```

And, since we're using *device_attr* in place of *attr*, we need to change the code wherever we use it in *main()*. So, you'll need to replace this code:

```
/* initialize attribute structure used by the device */
iofunc_attr_init(&attr, S_IFNAM | 0666, 0, 0);

/* attach our device name */
id = resmgr_attach(dpp,            /* dispatch handle        */
                   &resmgr_attr,   /* resource manager attrs */
                   "/dev/sample",  /* device name            */
                   _FTYPE_ANY,     /* open type              */
                   0,              /* flags                  */
                   &connect_funcs, /* connect routines       */
                   &io_funcs,      /* I/O routines           */
                   &attr);         /* handle                 */
```

with the following:

```
/* initialize attribute structure used by the device */
iofunc_attr_init(&device_attr.attr, S_IFNAM | 0666, 0, 0);
IOFUNC_NOTIFY_INIT(device_attr.notify);
device_attr.firstitem = NULL;
device_attr.nitems = 0;

/* attach our device name */
id = resmgr_attach(dpp,            /* dispatch handle        */
                   &resmgr_attr,   /* resource manager attrs */
                   "/dev/sample",  /* device name            */
                   _FTYPE_ANY,     /* open type              */
                   0,              /* flags                  */
                   &connect_funcs, /* connect routines       */
                   &io_funcs,      /* I/O routines           */
                   &device_attr);  /* handle                 */
```

Note that we set up our device-specific data in *device_attr*. And, in the call to *resmgr_attach()*, we passed **`&device_attr`** (instead of **`&attr`**) for the handle parameter.

Now, you need to include the new handler function to handle the _IO_NOTIFY message:

```
int
io_notify(resmgr_context_t *ctp, io_notify_t *msg, RESMGR_OCB_T *ocb)
{
    device_attr_t   *dattr = (device_attr_t *) ocb->attr;
    int             trig;
```

```
    /*
     * 'trig' will tell iofunc_notify() which conditions are currently
     * satisfied.  'dattr->nitems' is the number of messages in our list of
     * stored messages.
    */

    trig = _NOTIFY_COND_OUTPUT;         /* clients can always give us data */
    if (dattr->nitems > 0)
        trig |= _NOTIFY_COND_INPUT;      /* we have some data available */

    /*
     * iofunc_notify() will do any necessary handling, including adding
     * the client to the notification list is need be.
    */

    return (iofunc_notify(ctp, msg, dattr->notify, trig, NULL, NULL));
}
```

As stated above, our io_notify handler will be called when a client calls *ionotify()* or *select()*. In our handler, we're expected to remember who those clients are, and what conditions they want to be notified about. We should also be able to respond immediately with conditions that are already true. The *iofunc_notify()* helper function makes this easy.

The first thing we do is to figure out which of the conditions we handle have currently been met. In this example, we're always able to accept writes, so in the code above we set the *_NOTIFY_COND_OUTPUT* bit in *trig*. We also check *nitems* to see if we have data and set the _NOTIFY_COND_INPUT if we do.

We then call *iofunc_notify()*, passing it the message that was received (*msg*), the notification lists (*notify*), and which conditions have been met (*trig*). If one of the conditions that the client is asking about has been met, and the client wants us to poll for the condition before arming, then *iofunc_notify()* will return with a value that indicates what condition has been met and the condition will not be armed. Otherwise, the condition will be armed. In either case, we'll return from the handler with the return value from *iofunc_notify()*.

Earlier, when we talked about the three possible conditions, we mentioned that if you specify _NOTIFY_COND_INPUT, the client is notified when there's one or more units of input data available and that the number of units is up to you. We said a similar thing about

_NOTIFY_COND_OUTPUT and _NOTIFY_COND_OBAND. In the code above, we let the number of units for all these default to 1. If you want to use something different, then you must declare an array such as:

```
int notifycounts[3] =  { 10, 2, 1 };
```

This sets the units for: _NOTIFY_COND_INPUT to 10; _NOTIFY_COND_OUTPUT to 2; and _NOTIFY_COND_OBAND to 1. We would pass *notifycounts* to *iofunc_notify()* as the second to last parameter.

Then, as data arrives, we notify whichever clients have asked for notification. In this sample, data arrives through clients sending us _IO_WRITE messages and we handle it using an io_write handler.

```
int
io_write(resmgr_context_t *ctp, io_write_t *msg,
         RESMGR_OCB_T *ocb)
{
    device_attr_t   *dattr = (device_attr_t *) ocb->attr;
    int             i;
    char            *p;
    int             status;
    char            *buf;
    item_t          *newitem;

    if ((status = iofunc_write_verify(ctp, msg, ocb, NULL))
         != EOK)
        return (status);

    if ((msg->i.xtype & _IO_XTYPE_MASK) != _IO_XTYPE_NONE)
        return (ENOSYS);

    if (msg->i.nbytes > 0) {

        /* Get and store the data */

        if ((newitem = malloc(sizeof(item_t))) == NULL)
            return (errno);
        if ((newitem->data = malloc(msg->i.nbytes+1)) ==
            NULL) {
            free(newitem);
            return (errno);
        }
        /* reread the data from the sender's message buffer */
        resmgr_msgread(ctp, newitem->data, msg->i.nbytes,
```

```
                    sizeof(msg->i));
        newitem->data[msg->i.nbytes] = NULL;

        if (dattr->firstitem)
            newitem->next = dattr->firstitem;
        else
            newitem->next = NULL;
        dattr->firstitem = newitem;
        dattr->nitems++;

        /*
         * notify clients who may have asked to be notified
         * when there is data
         */

        if (IOFUNC_NOTIFY_INPUT_CHECK(dattr->notify,
            dattr->nitems, 0))
            iofunc_notify_trigger(dattr->notify, dattr->nitems,
                                  IOFUNC_NOTIFY_INPUT);
    }

    /* set up the number of bytes (returned by client's
       write()) */

    _IO_SET_WRITE_NBYTES(ctp, msg->i.nbytes);

    if (msg->i.nbytes > 0)
        ocb->attr->attr.flags |= IOFUNC_ATTR_MTIME |
                                 IOFUNC_ATTR_CTIME;

    return (_RESMGR_NPARTS(0));
}
```

The important part of the above *io_write()* handler is the code within the following section:

```
if (msg->i.nbytes > 0) {
    ....
}
```

Here we first allocate space for the incoming data, and then use *resmgr_msgread()* to copy the data from the client's send buffer into the allocated space. Then, we add the data to our queue.

Next, we pass the number of input units that are available to *IOFUNC_NOTIFY_INPUT_CHECK()* to see if there are enough units to notify clients about. This is checked against the *notifycounts* that

we mentioned above when talking about the io_notify handler. If there are enough units available then we call *iofunc_notify_trigger()* telling it that *nitems* of data are available (IOFUNC_NOTIFY_INPUT means input is available). The *iofunc_notify_trigger()* function checks the lists of clients asking for notification (*notify*) and notifies any that asked about data being available.

Any client that gets notified will then perform a read to get the data. In our sample, we handle this with the following io_read handler:

```
int
io_read(resmgr_context_t *ctp, io_read_t *msg, RESMGR_OCB_T *ocb)
{
    device_attr_t   *dattr = (device_attr_t *) ocb->attr;
    int             status;

    if ((status = iofunc_read_verify(ctp, msg, ocb, NULL)) != EOK)
        return (status);

    if ((msg->i.xtype & _IO_XTYPE_MASK) != _IO_XTYPE_NONE)
        return (ENOSYS);

    if (dattr->firstitem) {
        int     nbytes;
        item_t  *item, *prev;

        /* get last item */
        item = dattr->firstitem;
        prev = NULL;
        while (item->next != NULL) {
            prev = item;
            item = item->next;
        }

        /*
         * figure out number of bytes to give, write the data to the
         * client's reply buffer, even if we have more bytes than they
         * are asking for, we remove the item from our list
        */
        nbytes = min (strlen (item->data), msg->i.nbytes);

        /* set up the number of bytes (returned by client's read()) */
        _IO_SET_READ_NBYTES (ctp, nbytes);

        /*
         * write the bytes to the client's reply buffer now since we
         * are about to free the data
        */
        resmgr_msgwrite (ctp, item->data, nbytes, 0);

        /* remove the data from the queue */
        if (prev)
            prev->next = item->next;
        else
            dattr->firstitem = NULL;
        free(item->data);
```

```
        free(item);
        dattr->nitems--;
    } else {
        /* the read() will return with 0 bytes */
        _IO_SET_READ_NBYTES (ctp, 0);
    }

    /* mark the access time as invalid (we just accessed it) */

    if (msg->i.nbytes > 0)
        ocb->attr->attr.flags |= IOFUNC_ATTR_ATIME;

    return (EOK);
}
```

The important part of the above io_read handler is the code within this section:

```
if (firstitem) {
     ....
}
```

We first walk through the queue looking for the oldest item. Then we use *resmgr_msgwrite()* to write the data to the client's reply buffer. We do this now because the next step is to free the memory that we're using to store that data. We also remove the item from our queue.

Lastly, if a client closes their file descriptor, we must remove them from our list of clients. This is done using a io_close_ocb handler:

```
int
io_close_ocb(resmgr_context_t *ctp, void *reserved, RESMGR_OCB_T *ocb)
{
    device_attr_t   *dattr = (device_attr_t *) ocb->attr;

    /*
     * a client has closed their file descriptor or has terminated.
     * Remove them from the notification list.
    */

    iofunc_notify_remove(ctp, dattr->notify);

    return (iofunc_close_ocb_default(ctp, reserved, ocb));
}
```

In the io_close_ocb handler, we called *iofunc_notify_remove()* and passed it *ctp* (contains the information that identifies the client) and *notify* (contains the list of clients) to remove the client from the lists.

Handling private messages and pulses

A resource manager may need to receive and handle pulses, perhaps because an interrupt handler has returned a pulse or some other thread or process has sent a pulse.

The main issue with pulses is that they have to be received as a *message* — this means that a thread has to explicitly perform a *MsgReceive()* in order to get the pulse. But unless this pulse is sent to a different channel than the one that the resource manager is using for its main messaging interface, it will be received *by the library*. Therefore, we need to see how a resource manager can associate a pulse code with a handler routine and communicate that information to the library.

The *pulse_attach()* function can be used to associate a pulse code with a handler function. Therefore, when the dispatch layer receives a pulse, it will look up the pulse code and see which associated handler to call to handle the pulse message.

You may also want to define your own private message range to communicate with your resource manager. Note that the range **0x0** to **0x1FF** is reserved for the OS. To attach a range, you use the *message_attach()* function.

In this example, we create the same resource manager, but this time we also attach to a private message range and attach a pulse, which is then used as a timer event:

```
#include <stdio.h>
#include <stddef.h>
#include <stdlib.h>

#define THREAD_POOL_PARAM_T     dispatch_context_t
#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
timer_tick(message_context_t *ctp, int code, unsigned flags, void *handle) {

    union sigval             value = ctp->msg->pulse.value;
    /*
     *  Do some useful work on every timer firing
```

```
     *  ....
     */
    printf("received timer event, value %d\n", value.sival_int);
    return 0;
}

int
message_handler(message_context_t *ctp, int code, unsigned flags, void *handle) {
    printf("received private message, type %d\n", code);
    return 0;
}

int
main(int argc, char **argv) {
    thread_pool_attr_t    pool_attr;
    resmgr_attr_t         resmgr_attr;
    struct sigevent       event;
    struct _itimer        itime;
    dispatch_t            *dpp;
    thread_pool_t         *tpp;
    resmgr_context_t      *ctp;
    int                   timer_id;
    int                   id;


    if((dpp = dispatch_create()) == NULL) {
        fprintf(stderr,
                "%s: Unable to allocate dispatch handle.\n",
                argv[0]);
        return EXIT_FAILURE;
    }

    memset(&pool_attr, 0, sizeof pool_attr);
    pool_attr.handle = dpp;
    /*  We are doing resmgr and pulse-type attaches.
     *
     *  If you're going to use custom messages or pulses with
     *  the message_attach() or pulse_attach() functions,
     *  then you MUST use the dispatch functions
     *  (i.e. dispatch_block(),  dispatch_handler(), ...),
     *  NOT the resmgr functions (resmgr_block(), resmgr_handler()).
     */
    pool_attr.context_alloc = dispatch_context_alloc;
    pool_attr.block_func = dispatch_block;
    pool_attr.unblock_func = dispatch_unblock;
    pool_attr.handler_func = dispatch_handler;
    pool_attr.context_free = dispatch_context_free;
    pool_attr.lo_water = 2;
    pool_attr.hi_water = 4;
    pool_attr.increment = 1;
    pool_attr.maximum = 50;

    if((tpp = thread_pool_create(&pool_attr, POOL_FLAG_EXIT_SELF)) == NULL) {
        fprintf(stderr, "%s: Unable to initialize thread pool.\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 | 0666, 0, 0);
```

```
    memset(&resmgr_attr, 0, sizeof resmgr_attr);
    resmgr_attr.nparts_max = 1;
    resmgr_attr.msg_max_size = 2048;

    if((id = resmgr_attach(dpp, &resmgr_attr, "/dev/sample", _FTYPE_ANY, 0,
                &connect_func, &io_func, &attr)) == -1) {
        fprintf(stderr, "%s: Unable to attach name.\n", argv[0]);
        return EXIT_FAILURE;
    }

    /* We want to handle our own private messages, of type 0x5000 to 0x5fff */
    if(message_attach(dpp, NULL, 0x5000, 0x5fff, &message_handler, NULL) == -1) {
        fprintf(stderr, "Unable to attach to private message range.\n");
         return EXIT_FAILURE;
    }

    /* Initialize an event structure, and attach a pulse to it */
    if((event.sigev_code = pulse_attach(dpp, MSG_FLAG_ALLOC_PULSE, 0, &timer_tick,
                                        NULL)) == -1) {
        fprintf(stderr, "Unable to attach timer pulse.\n");
         return EXIT_FAILURE;
    }

    /* Connect to our channel */
    if((event.sigev_coid = message_connect(dpp, MSG_FLAG_SIDE_CHANNEL)) == -1) {
        fprintf(stderr, "Unable to attach to channel.\n");
        return EXIT_FAILURE;
    }

    event.sigev_notify = SIGEV_PULSE;
    event.sigev_priority = -1;
    /* We could create several timers and use different sigev values for each */
    event.sigev_value.sival_int = 0;

    if((timer_id = TimerCreate(CLOCK_REALTIME, &event)) == -1) {;
        fprintf(stderr, "Unable to attach channel and connection.\n");
        return EXIT_FAILURE;
    }

    /* And now set up our timer to fire every second */
    itime.nsec = 1000000000;
    itime.interval_nsec = 1000000000;
    TimerSettime(timer_id, 0, &itime, NULL);

    /* Never returns */
    thread_pool_start(tpp);
}
```

We can either define our own pulse code (e.g. **`#define OurPulseCode 57`**), or we can ask the *pulse_attach()* function to dynamically generate one for us (and return the pulse code value as the return code from *pulse_attach()*) by specifying the pulse code as _RESMGR_PULSE_ALLOC.

See the *pulse_attach()*, *MsgSendPulse()*, *MsgDeliverEvent()*, and *MsgReceive()* functions in the *Library Reference* for more information on receiving and generating pulses.

Handling *open()*, *dup()*, and *close()* messages

The resource manager library provides another convenient service for us: it knows how to handle *dup()* messages.

Suppose that the client executed code that eventually ended up performing:

```
fd = open ("/dev/sample", O_RDONLY);
...
fd2 = dup (fd);
...
fd3 = dup (fd);
...
close (fd3);
...
close (fd2);
...
close (fd);
```

Our resource manager would get an _IO_CONNECT message for the first *open()*, followed by two _IO_DUP messages for the two *dup()* calls. Then, when the client executed the *close()* calls, we would get three _IO_CLOSE messages.

Since the *dup()* functions generate duplicates of the file descriptors, we don't want to allocate new OCBs for each one. And since we're not allocating new OCBs for each *dup()*, we don't want to *release* the memory in each _IO_CLOSE message when the _IO_CLOSE messages arrive! If we did that, the first close would wipe out the OCB.

The resource manager library knows how to manage this for us; it keeps count of the number of _IO_DUP and _IO_CLOSE messages sent by the client. Only on the *last* _IO_CLOSE message will the library synthesize a call to our _IO_CLOSE_OCB handler.

Most users of the library will want to have the default functions manage the _IO_DUP and _IO_CLOSE messages; you'll most likely *never* override the default actions.

Handling client unblocking due to signals or timeouts

Another convenient service that the resource manager library does for us is *unblocking*.

When a client issues a request (e.g. *read()*), this translates (via the client's C library) into a *MsgSend()* to our resource manager. The *MsgSend()* is a blocking call. If the client receives a signal during the time that the *MsgSend()* is outstanding, our resource manager needs to have some indication of this so that it can abort the request.

Because the library set the _NTO_CHF_UNBLOCK flag when it called *ChannelCreate()*, we'll receive a pulse whenever the client tries to unblock from a *MsgSend()* that we have *MsgReceive()*'d.

As an aside, recall that in the Neutrino messaging model the client can be in one of two states as a result of calling *MsgSend()*. If the server hasn't yet received the message (via the server's *MsgReceive()*), the client is in a *SEND-blocked* state — the client is waiting for the server to receive the message. When the server has actually received the message, the client transits to a *REPLY-blocked* state — the client is now waiting for the server to reply to the message (via *MsgReply()*).

When this happens and the pulse is generated, the resource manager library handles the pulse message and synthesizes an _IO_UNBLOCK message.

Looking through the **`resmgr_io_funcs_t`** and the **`resmgr_connect_funcs_t`** structures (see the *Library Reference*), you'll notice that there are actually *two* **`unblock`** message handlers: one in the I/O functions structure and one in the connect functions structure.

Why two? Because we may get an abort in one of two places. We can get the abort pulse right after the client has sent the _IO_OPEN message (but before we've replied to it), or we can get the abort during an I/O message.

Once we've performed the handling of the _IO_CONNECT message, the I/O functions' unblock member will be used to service an unblock pulse. Therefore, if you're supplying your own io_open handler, be sure to set up all relevant fields in the OCB *before* you call *resmgr_open_bind()*; otherwise, your I/O functions' version of the unblock handler may get called with invalid data in the OCB. (Note that this issue of abort pulses "during" message processing arises only if there are multiple threads running in your resource manager. If there's only one thread, then the messages will be serialized by the library's *MsgReceive()* function.)

The effect of this is that if the client is SEND-blocked, the server doesn't need to know that the client is aborting the request, because the server hasn't yet received it.

Only in the case where the server has received the request and is performing processing on that request does the server need to know that the client now wishes to abort.

For more information on these states and their interactions, see the *MsgSend()*, *MsgReceive()*, *MsgReply()*, and *ChannelCreate()* functions in the *Library Reference*; see also the chapter on Interprocess Communication in the *System Architecture* book.

If you're overriding the default unblock handler, you should always call the default handler to process any generic unblocking cases first. For example:

```
if((status = iofunc_unblock_default(...)) != _RESMGR_DEFAULT) {
return status;
}

/* Do your own thing to look for a client to unblock */
```

This ensures that any client waiting on a resource manager lists (such as an advisory lock list) will be unblocked if possible.

Handling interrupts

Resource managers that manage an actual hardware resource will likely need to handle interrupts generated by the hardware. For a detailed discussion on strategies for interrupt handlers, see the chapter on Writing an Interrupt Handler in this book.

How do interrupt handlers relate to resource managers? When a significant event happens within the interrupt handler, the handler needs to inform a thread in the resource manager. This is usually done via a pulse (discussed in the "Handling private messages and pulses" section), but it can also be done with the SIGEV_INTR event notification type. Let's look at this in more detail.

When the resource manager starts up, it transfers control to *thread_pool_start()*. This function may or may not return, depending on the flags passed to *thread_pool_create()* (if you don't pass any flags, the function returns after the thread pool is created). This means that if you're going to set up an interrupt handler, you should do so *before* starting the thread pool, or use one of the strategies we discussed above (such as starting a thread for your entire resource manager).

However, if you're going to use the SIGEV_INTR event notification type, there's a catch — the thread that *attaches* the interrupt (via *InterruptAttach()* or *InterruptAttachEvent()*) must be the same thread that calls *InterruptWait()*.

Sample code for handling interrupts

Here's an example that includes relevant portions of the interrupt service routine and the handling thread:

```
#define INTNUM 0
#include <stdio.h>
#include <stddef.h>
#include <stdlib.h>
#include <sys/iofunc.h>
#include <sys/dispatch.h>
#include <sys/neutrino.h>

static resmgr_connect_funcs_t   connect_funcs;
```

```
static resmgr_io_funcs_t        io_funcs;
static iofunc_attr_t            attr;

void *
interrupt_thread (void * data)
{
    struct sigevent event;
    int             id;

    /* fill in "event" structure */
    memset(&event, 0, sizeof(event));
    event.sigev_notify = SIGEV_INTR;

    /* Obtain I/O privileges */
    ThreadCtl( _NTO_TCTL_IO, 0 );

    /* intNum is the desired interrupt level */
    id = InterruptAttachEvent (INTNUM, &event, 0);

    /*... insert your code here ... */

    while (1) {
        InterruptWait (NULL, NULL);
        /*  do something about the interrupt,
         *  perhaps updating some shared
         *  structures in the resource manager
         *
         *  unmask the interrupt when done
         */
        InterruptUnmask(INTNUM, id);
    }
}

int
main(int argc, char **argv) {
    thread_pool_attr_t    pool_attr;
    resmgr_attr_t         resmgr_attr;
    dispatch_t            *dpp;
    thread_pool_t         *tpp;
    int                   id;


    if((dpp = dispatch_create()) == NULL) {
        fprintf(stderr,
                "%s: Unable to allocate dispatch handle.\n",
                argv[0]);
        return EXIT_FAILURE;
    }

    memset(&pool_attr, 0, sizeof pool_attr);
```

```
    pool_attr.handle = dpp;
    pool_attr.context_alloc = dispatch_context_alloc;
    pool_attr.block_func = dispatch_block;
    pool_attr.unblock_func = dispatch_unblock;
    pool_attr.handler_func = dispatch_handler;
    pool_attr.context_free = dispatch_context_free;
    pool_attr.lo_water = 2;
    pool_attr.hi_water = 4;
    pool_attr.increment = 1;
    pool_attr.maximum = 50;

    if((tpp = thread_pool_create(&pool_attr,
                                 POOL_FLAG_EXIT_SELF)) == NULL) {
        fprintf(stderr, "%s: Unable to initialize thread pool.\n",
                argv[0]);
        return EXIT_FAILURE;
    }

    iofunc_func_init(_RESMGR_CONNECT_NFUNCS, &connect_funcs,
                     _RESMGR_IO_NFUNCS, &io_funcs);
    iofunc_attr_init(&attr, S_IFNAM | 0666, 0, 0);

    memset(&resmgr_attr, 0, sizeof resmgr_attr);
    resmgr_attr.nparts_max = 1;
    resmgr_attr.msg_max_size = 2048;

    if((id = resmgr_attach(dpp, &resmgr_attr, "/dev/sample",
                           _FTYPE_ANY, 0,
                &connect_funcs, &io_funcs, &attr)) == -1) {
        fprintf(stderr, "%s: Unable to attach name.\n", argv[0]);
        return EXIT_FAILURE;
    }

    /* Start the thread that will handle interrupt events. */
    pthread_create (NULL, NULL, interrupt_thread, NULL);

    /* Never returns */
    thread_pool_start(tpp);
}
```

Here the *interrupt_thread()* function uses *InterruptAttachEvent()* to bind the interrupt source (*intNum*) to the event (passed in *event*), and then waits for the event to occur.

This approach has a major advantage over using a pulse. A pulse is delivered as a message to the resource manager, which means that if the resource manager's message-handling threads are busy processing requests, the pulse will be queued until a thread does a *MsgReceive()*.

With the *InterruptWait()* approach, if the thread that's executing the *InterruptWait()* is of sufficient priority, it unblocks and runs *immediately* after the SIGEV_INTR is generated.

Multi-threaded resource managers

In this section:

- Multi-threaded Resource Manager example
- Thread pool attributes
- Thread pool functions

Multi-threaded resource manager example

Let's look at our multi-threaded resource manager example in more detail:

```
#include <errno.h>
#include <stdio.h>
#include <stddef.h>
#include <stdlib.h>
#include <unistd.h>

/*
 *  define THREAD_POOL_PARAM_T such that we can avoid a compiler
 *  warning when we use the dispatch_*() functions below
 */
#define THREAD_POOL_PARAM_T dispatch_context_t

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

static resmgr_connect_funcs_t    connect_funcs;
static resmgr_io_funcs_t         io_funcs;
static iofunc_attr_t             attr;

main(int argc, char **argv)
{
    /* declare variables we'll be using */
    thread_pool_attr_t   pool_attr;
    resmgr_attr_t        resmgr_attr;
    dispatch_t           *dpp;
    thread_pool_t        *tpp;
    dispatch_context_t   *ctp;
```

```
int                 id;

/* initialize dispatch interface */
if((dpp = dispatch_create()) == NULL) {
    fprintf(stderr,
            "%s: Unable to allocate dispatch handle.\n",
            argv[0]);
    return EXIT_FAILURE;
}

/* initialize resource manager attributes */
memset(&resmgr_attr, 0, sizeof resmgr_attr);
resmgr_attr.nparts_max = 1;
resmgr_attr.msg_max_size = 2048;

/* initialize functions for handling messages */
iofunc_func_init(_RESMGR_CONNECT_NFUNCS, &connect_funcs,
                 _RESMGR_IO_NFUNCS, &io_funcs);

/* initialize attribute structure used by the device */
iofunc_attr_init(&attr, S_IFNAM | 0666, 0, 0);

/* attach our device name */
id = resmgr_attach(
        dpp,            /* dispatch handle        */
        &resmgr_attr,   /* resource manager attrs */
        "/dev/sample",  /* device name            */
        _FTYPE_ANY,     /* open type              */
        0,              /* flags                  */
        &connect_funcs, /* connect routines       */
        &io_funcs,      /* I/O routines           */
        &attr);         /* handle                 */
if(id == -1) {
    fprintf(stderr, "%s: Unable to attach name.\n", argv[0]);
    return EXIT_FAILURE;
}

/* initialize thread pool attributes */
memset(&pool_attr, 0, sizeof pool_attr);
pool_attr.handle = dpp;
pool_attr.context_alloc = dispatch_context_alloc;
pool_attr.block_func = dispatch_block;
pool_attr.unblock_func = dispatch_unblock;
pool_attr.handler_func = dispatch_handler;
pool_attr.context_free = dispatch_context_free;
pool_attr.lo_water = 2;
pool_attr.hi_water = 4;
pool_attr.increment = 1;
pool_attr.maximum = 50;
```

```
    /* allocate a thread pool handle */
    if((tpp = thread_pool_create(&pool_attr,
                                 POOL_FLAG_EXIT_SELF)) == NULL) {
        fprintf(stderr, "%s: Unable to initialize thread pool.\n",
                argv[0]);
        return EXIT_FAILURE;
    }

    /* start the threads, will not return */
    thread_pool_start(tpp);
}
```

The thread pool attribute (*pool_attr*) controls various aspects of the thread pool, such as which functions get called when a new thread is started or dies, the total number of worker threads, the minimum number, and so on.

Thread pool attributes

Here's the **_thread_pool_attr** structure:

```
typedef struct _thread_pool_attr {
  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);
  pthread_attr_t        *attr;
  unsigned short        lo_water;
  unsigned short        increment;
  unsigned short        hi_water;
  unsigned short        maximum;
  unsigned              reserved[8];
} thread_pool_attr_t;
```

The functions that you fill into the above structure can be taken from the dispatch layer (*dispatch_block()*, ...), the resmgr layer (*resmgr_block()*, ...) or they can be of your own making. If you're not using the resmgr layer functions, then you'll have to define THREAD_POOL_PARAM_T to some sort of context structure for the library to pass between the various functions. By default, it's defined as a **resmgr_context_t** but since this sample is using the dispatch

layer, we needed it to be a**`dispatch_context_t`**. We defined it prior to doing the includes above since the header files refer to it.
THREAD_POOL_PARAM_T

Part of the above structure contains information telling the resource manager library how you want it to handle multiple threads (if at all). During development, you should design your resource manager with multiple threads in mind. But during testing, you'll most likely have only one thread running (to simplify debugging). Later, after you've ensured that the base functionality of your resource manager is stable, you may wish to "turn on" multiple threads and revisit the debug cycle.

The following members control the number of threads that are running:

lo_water	Minimum number of blocked threads.
increment	Number of thread to create at a time to achieve *lo_water*.
hi_water	Maximum number of blocked threads.
maximum	Total number of threads created at any time.

The important parameters specify the maximum thread count and the increment. The value for *maximum* should ensure that there's always a thread in a RECEIVE-blocked state. If you're at the number of maximum threads, then your clients will block until a free thread is ready to receive data. The value you specify for *increment* will cut down on the number of times your driver needs to create threads. It's probably wise to err on the side of creating more threads and leaving them around rather than have them being created/destroyed all the time.

You determine the number of threads you want to be RECEIVE-blocked on the *MsgReceive()* at any time by filling in the *lo_water* parameter.

If you ever have fewer than *lo_water* threads RECEIVE-blocked, the *increment* parameter specifies how many threads should be created at

once, so that at least *lo_water* number of threads are once again RECEIVE-blocked.

Once the threads are done their processing, they will return to the block function. The *hi_water* variable specifies an upper limit to the number of threads that are RECEIVE-blocked. Once this limit is reached, the threads will destroy themselves to ensure that no more than *hi_water* number of threads are RECEIVE-blocked.

To prevent the number of threads from increasing without bounds, the *maximum* parameter limits the absolute maximum number of threads that will ever run simultaneously.

When threads are created by the resource manager library, they'll have a stack size as specified by the *thread_stack_size* parameter. If you want to specify stack size or priority, fill in *pool_attr.attr* with a proper *pthread_attr_t* pointer.

The **`thread_pool_attr_t`** structure contains pointers to several functions:

block_func()	Called by the worker thread when it needs to block waiting for some message.
handler_func()	Called by the thread when it has unblocked because it received a message. This function processes the message.
context_alloc()	Called when a new thread is created. Returns a context that this thread uses to do its work.
context_free()	Free the context when the worker thread exits.
unblock_func()	Called by the library to shutdown the thread pool or change the number of running threads.

Thread pool functions

The library provides the following thread pool functions:

thread_pool_create()

Initializes the pool context. Returns a thread pool handle (*tpp*) that's used to start the thread pool.

thread_pool_start()

Start the thread pool. This function may or may not return, depending on the flags passed to *thread_pool_create()*.

thread_pool_destroy()

Destroy a thread pool.

thread_pool_control()

Control the number of threads.

In the example provided in the multi-threaded resource managers section, **`thread_pool_start(tpp)`** never returns because we set the POOL_FLAG_EXIT_SELF bit. Also, the POOL_FLAG_USE_SELF flag itself never returns, but the current thread becomes part of the thread pool.

If no flags are passed (i.e. **`0`** instead of any flags), the function returns after the thread pool is created.

Filesystem resource managers

In this section:

- Considerations for Filesystem Resource Managers
- Taking over more than one device
- Handling directories

Considerations for filesystem resource managers

Since a filesystem resource manager may potentially receive long pathnames, it must be able to parse and handle each component of the path properly.

Let's say that a resource manager registers the mountpoint **/mount/**, and a user types:

```
ls -l /mount/home
```

where **/mount/home** is a directory on the device.

ls does the following:

```
d = opendir("/mount/home");
while (...) {
    dirent = readdir(d);
    ...
}
```

Taking over more than one device

If we wanted our resource manager to handle multiple devices, the change is really quite simple. We would call *resmgr_attach()* for each device name we wanted to register. We would also pass in an attributes structure that was unique to each registered device, so that functions like *chmod()* would be able to modify the attributes associated with the correct resource.

Here are the modifications necessary to handle both **/dev/sample1** and **/dev/sample2**:

```
/*
 *  MOD [1]:  allocate multiple attribute structures,
 *            and fill in a names array (convenience)
 */

#define NumDevices  2
iofunc_attr_t     sample_attrs [NumDevices];
char              *names [NumDevices] =
{
    "/dev/sample1",
    "/dev/sample2"
};

main ()
{
```

```
    ...
    /*
     *  MOD [2]:  fill in the attribute structure for each device
     *            and call resmgr_attach for each device
     */
    for (i = 0; i < NumDevices; i++) {
        iofunc_attr_init (&sample_attrs [i],
                          S_IFCHR | 0666, NULL, NULL);
        pathID = resmgr_attach (dpp, &resmgr_attr, name[i],
                                _FTYPE_ANY, 0,
                                &my_connect_funcs,
                                &my_io_funcs,
                                &sample_attrs [i]);
    }
    ...
}
```

The first modification simply declares an array of attributes, so that each device has its own attributes structure. As a convenience, we've also declared an array of names to simplify passing the name of the device in the *for* loop. Some resource managers (such as **`devc-ser8250`**) construct the device names on the fly or fetch them from the command line.

The second modification initializes the array of attribute structures and then calls *resmgr_attach()* multiple times, once for each device, passing in a unique name and a unique attribute structure.

Those are all the changes required. Nothing in our *io_read()* or *io_write()* functions has to change — the iofunc-layer default functions will gracefully handle the multiple devices.

Handling directories

Up until this point, our discussion has focused on resource managers that associate each device name via discrete calls to *resmgr_attach()*. We've shown how to "take over" a single pathname. (Our examples have used pathnames under **`/dev`**, but there's no reason you couldn't take over any other pathnames, e.g. **`/MyDevice`**.)

A typical resource manager can take over any number of pathnames. A practical limit, however, is on the order of a hundred — the real

limit is a function of memory size and lookup speed in the process manager.

What if you wanted to take over thousands or even millions of pathnames?

The most straightforward method of doing this is to take over a *pathname prefix* and manage a directory structure below that prefix (or *mountpoint*).

Here are some examples of resource managers that may wish to do this:

- A CD-ROM filesystem might take over the pathname prefix **`/cdrom`**, and then handle any requests for files below that pathname by going out to the CD-ROM device.
- A filesystem for managing compressed files might take over a pathname prefix of **`/uncompressed`**, and then uncompress disk files on the fly as read requests arrive.
- A network filesystem could present the directory structure of a remote machine called "flipper" under the pathname prefix of **`/mount/flipper`** and allow the user to access flipper's files as if they were local to the current machine.

And those are just the most obvious ones. The reasons (and possibilities) are almost endless.

The common characteristic of these resource managers is that they all implement *filesystems*. A filesystem resource manager differs from the "device" resource managers (that we have shown so far) in the following key areas:

1 The _RESMGR_FLAG_DIR flag in *resmgr_attach()* informs the library that the resource manager will accept matches *at or below* the defined mountpoint.

2 The _IO_CONNECT logic has to check the individual pathname components against permissions and access authorizations. It must also ensure that the proper attribute is bound when a particular filename is accessed.

3 The _IO_READ logic has to return the data for either the "file" or "directory" specified by the pathname.

Let's look at these points in turn.

Matching at or below a mountpoint

When we specified the *flags* argument to *resmgr_attach()* for our sample resource manager, we specified a 0, implying that the library should "use the defaults."

If we specified the value _RESMGR_FLAG_DIR instead of 0, the library would allow the resolution of pathnames at or below the specified mountpoint.

The _IO_OPEN message for filesystems

Once we've specified a mountpoint, it would then be up to the resource manager to determine a suitable response to an open request. Let's assume that we've defined a mountpoint of **`/sample_fsys`** for our resource manager:

```
pathID = resmgr_attach
             (dpp,
             &resmgr_attr,
             "/sample_fsys",    /* mountpoint */
            _FTYPE_ANY,
             _RESMGR_FLAG_DIR,   /* it's a directory */
             &connect_funcs,
             &io_funcs,
             &attr);
```

Now when the client performs a call like this:

```
fopen ("/sample_fsys/spud", "r");
```

we receive an _IO_CONNECT message, and our io_open handler will be called. Since we haven't yet looked at the _IO_CONNECT message in depth, let's take a look now:

```
struct _io_connect {
    unsigned short  type;
    unsigned short  subtype;     /* _IO_CONNECT_*             */
```

```
    unsigned long   file_type;   /* _FTYPE_* in sys/ftype.h    */
    unsigned short  reply_max;
    unsigned short  entry_max;
    unsigned long   key;
    unsigned long   handle;
    unsigned long   ioflag;      /* O_* in fcntl.h, _IO_FLAG_* */
    unsigned long   mode;        /* S_IF* in sys/stat.h        */
    unsigned short  sflag;       /* SH_* in share.h            */
    unsigned short  access;      /* S_I in sys/stat.h          */
    unsigned short  zero;
    unsigned short  path_len;
    unsigned char   eflag;       /* _IO_CONNECT_EFLAG_*        */
    unsigned char   extra_type;  /* _IO_EXTRA_*                */
    unsigned short  extra_len;
    unsigned char   path[1];     /* path_len, null, extra_len  */
};
```

Looking at the relevant fields, we see *ioflag*, *mode*, *sflag*, and *access*, which tell us how the resource was opened.

The *path_len* parameter tells us how many bytes the pathname takes; the actual pathname appears in the *path* parameter. Note that the pathname that appears is *not* **/sample_fsys/spud**, as you might expect, but instead is just **spud** — the message contains only the pathname relative to the resource manager's mountpoint. This simplifies coding because you don't have to skip past the mountpoint name each time, the code doesn't have to know what the mountpoint is, and the messages will be a little bit shorter.

Note also that the pathname will *never* have relative (`.` and `..`) path components, nor redundant slashes (e.g. **spud//stuff**) in it — these are all resolved and removed by the time the message is sent to the resource manager.

When writing filesystem resource managers, we encounter additional complexity when dealing with the pathnames. For verification of access, we need to break apart the passed pathname and check each component. You can use *strtok()* and friends to break apart the string, and then there's *iofunc_check_access()*, a convenient iofunc-layer call that performs the access verification of pathname components leading up to the target. (See the *Library Reference* page for the *iofunc_open()* for information detailing the steps needed for this level of checking.)

The binding that takes place after the name is validated requires that every path that's handled has its own attribute structure passed to *iofunc_open_default()*. Unexpected behavior will result if the wrong attribute is bound to the pathname that's provided.

Returning directory entries from _IO_READ

When the _IO_READ handler is called, it may need to return data for either a file (if **`S_ISDIR (ocb->attr->mode)`** is false) or a directory (if **`S_ISDIR (ocb->attr->mode)`** is true). We've seen the algorithm for returning data, especially the method for matching the returned data's size to the smaller of the data available or the client's buffer size.

A similar constraint is in effect for returning directory data to a client, except we have the added issue of returning *block-integral* data. What this means is that instead of returning a stream of bytes, where we can arbitrarily package the data, we're actually returning a number of **`struct dirent`** structures. (In other words, we can't return 1.5 of those structures; we always have to return an integral number.)

A **`struct dirent`** looks like this:

```
struct dirent {
    ino_t           d_ino;
    off_t           d_offset;
    unsigned short  d_reclen;
    unsigned short  d_namelen;
    char            d_name [NAME_MAX + 1];
};
```

The *d_ino* member contains a mountpoint-unique file serial number. This serial number is often used in various disk-checking utilities for such operations as determining infinite-loop directory links. (Note that the inode value cannot be zero, which would indicate that the inode represents an *unused* entry.)

The *d_offset* member is typically used to identify the directory entry itself. For a disk-based filesystem, this value might be the actual offset into the on-disk directory structure.

Other implementations may assign a directory entry index number (0 for the first directory entry in that directory, 1 for the next, and so on). The only constraint is that the numbering scheme used must be consistent between the _IO_LSEEK message handler and the _IO_READ message handler.

For example, if you've chosen to have *d_offset* represent a directory entry index number, this means that if an _IO_LSEEK message causes the current offset to be changed to 7, and then an _IO_READ request arrives, you must return directory information starting at directory entry number 7.

The *d_reclen* member contains the size of this directory entry *and any other associated information* (such as an optional **`struct stat`** structure appended to the **`struct dirent`** entry; see below).

The *d_namelen* parameter indicates the size of the *d_name* parameter, which holds the actual name of that directory entry. (Since the size is calculated using *strlen()*, the **`\0`** string terminator, which must be present, is *not* counted.)

So in our io_read handler, we need to generate a number of **`struct dirent`** entries and return them to the client.

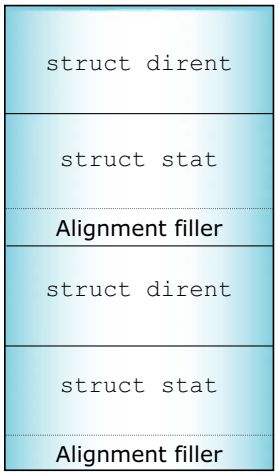
If we have a cache of directory entries that we maintain in our resource manager, it's a simple matter to construct a set of IOVs to point to those entries. If we don't have a cache, then we must manually assemble the directory entries into a buffer and then return an IOV that points to that.

Returning information associated with a directory structure

Instead of returning just the **`struct dirent`** in the _IO_READ message, you can also return a **`struct stat`**. Although this will improve efficiency, returning the **`struct stat`** is entirely optional. If you don't return one, the users of your device will then have to call the *stat()* function to get that information. (This is basically a usage question. If your device is typically used in such a way that *readdir()* is called, and then *stat()* is called, it will be more efficient to return

both. See the documentation for *readdir()* in the *Library Reference* for more information.)

The extra **`struct stat`** information is returned after each directory entry:



Returning the optional **`struct stat`** *along with the* **`struct dirent`** *entry can improve efficiency.*

The **`struct stat`** must be aligned on an 8-byte boundary. The *d_reclen* member of the **`struct dirent`** must contain the size of *both* structures, including any filler necessary for alignment.

Message types

Generally, a resource manager receives these types of messages:

- *connect messages*
- *I/O messages*

Connect messages

A connect message is issued by the client to perform an operation based on a pathname. This may be a message that establishes a longer term relationship between the client and the resource manager (e.g. *open()*), or it may be a message that is a "one-shot" event (e.g. *rename()*).

The library looks at the *connect_funcs* parameter (of type **`resmgr_connect_funcs_t`** — see the *Library Reference*) and calls out to the appropriate function.

If the message is the _IO_CONNECT message (and variants) corresponding with the *open()* outcall, then a *context* needs to be established for further I/O messages that will be processed later. This context is referred to as an *OCB* (Open Control Block) — it holds any information required between the connect message and subsequent I/O messages.

Basically, the OCB is a good place to keep information that needs to be stored on a per-open basis. An example of this would be the current position within a file. Each open file descriptor would have its own file position. The OCB is allocated on a per-open basis. During the open handling, you'd initialize the file position; during read and write handling, you'd advance the file position. For more information, see the section "The open control block (OCB) structure."

I/O messages

An I/O message is one that relies on an existing binding (e.g. OCB) between the client and the resource manager.

An an example, an _IO_READ (from the client's *read()* function) message depends on the client's having previously established an association (or *context*) with the resource manager by issuing an *open()* and getting back a file descriptor. This context, created by the *open()* call, is then used to process the subsequent I/O messages, like the _IO_READ.

There are good reasons for this design. It would be inefficient to pass the full pathname for each and every *read()* request, for example. The

open() handler can also perform tasks that we want done only once (e.g. permission checks), rather than with each I/O message. Also, when the *read()* has read 4096 bytes from a disk file, there may be another 20 megabytes still waiting to be read. Therefore, the *read()* function would need to have some context information telling it the position within the file it's reading from, how much has been read, and so on.

The **`resmgr_io_funcs_t`** structure is filled in a manner similar to the connect functions structure **`resmgr_connect_funcs_t`**.

Notice that the I/O functions all have a common parameter list. The first entry is a resource manager context structure, the second is a message (the type of which matches the message being handled and contains parameters sent from the client), and the last is an OCB (containing what we bound when we handled the client's *open()* function).

Resource manager data structures

`_resmgr_attr_t` control structure

The **`_resmgr_attr_t`** control structure contains at least the following:

```
typedef struct _resmgr_attr {
    unsigned            flags;
    unsigned            nparts_max;
    unsigned            msg_max_size;
    int                 (*other_func)(resmgr_context_t *,
                                      void *msg);
    unsigned            reserved[4];
} resmgr_attr_t;
```

nparts_max — The number of components that should be allocated to the IOV array.

msg_max_size — The size of the message buffer.

These members will be important when you start writing your own handler functions.

If you specify a value of zero for *nparts_max*, the resource manager library will bump the values to the minimum usable by the library itself. Why would you want to set the size of the IOV array? As we've seen in the Getting the resource manager library to do the reply section, you can tell the resource manager library to do our replying for us. We may want to give it an IOV array that points to *N* buffers containing the reply data. But, since we'll ask the library to do the reply for us, we need to use its IOV array, which of course would need to be big enough to point to our *N* buffers.

flags — Lets you change the behavior of the resource manager interface.

other_func — Lets you specify a routine to call in cases where the resource manager gets an I/O message that it doesn't understand. (In general, we don't recommend that you use this member. For more information, see the following section.) To attach an *other_func*, you must set the RESMGR_FLAG_ATTACH_OTHERFUNC flag.

If the resource manager library gets an I/O message that it doesn't know how to handle, it'll call the routine specified by the *other_func* member, if non-NULL. (If it's NULL, the resource manager library will return an ENOSYS to the client, effectively stating that it doesn't know what this message means.)

You might specify a non-NULL value for *other_func* in the case where you've specified some form of custom messaging between clients and your resource manager, although the recommended approach for this is the *devctl()* function call (client) and the _IO_DEVCTL message handler

(server) or a *MsgSend*()* function call (client) and the _IO_MSG message handler (server).

For non-I/O message types, you should use the *message_attach()* function, which attaches a message range for the dispatch handle. When a message with a type in that range is received, the *dispatch_block()* function calls a user-supplied function that's responsible for doing any specific work, such as replying to the client.

Chapter 5

Transparent Distributed Processing Using Qnet

In this chapter...

QNX Momentics Transparent Distributed Processing (TDP) allows you to leverage the processing power of your entire network by sharing resources and services transparently over the network. TDP uses Neutrino native network protocol Qnet to link the devices in your network.

What is Qnet?

Qnet is Neutrino's protocol for distributed networking. Using Qnet, you can build a transparent distributed-processing platform that is fast and scalable. This is accomplished by extending the Neutrino message passing architecture over a network. This creates a group of tightly integrated Neutrino nodes (systems) or CPUs — a Neutrino native network.

A program running on a Neutrino node in this Qnet network can transparently access any resource, whether it's a file, device, or another process. These resources reside on any other node (a computer, a workstation or a CPU in a system) in the Qnet network. The Qnet protocol builds an optimized network that provides a fast and seamless interface between Neutrino nodes.

For a high-level description, see Native Networking (Qnet) in the *System Architecture* guide; for information about what the *user* needs to know about networking, see Using Qnet for Transparent Distributed Processing in the Neutrino *User's Guide*.

For more advanced topics and programming hints on Qnet, see Advanced Qnet Topics appendix.

Benefits of Qnet

The Qnet protocol extends interprocess communication (IPC) transparently over a network of microkernels. This is done by taking advantage of the Neutrino's message-passing paradigm. Message passing is the central theme of Neutrino that manages a group of cooperating processes by routing messages. This enhances the

efficiency of all transactions among all processes throughout the system.

For more information about message passing and Qnet, see Advanced Qnet Topics appendix.

What works best

The Qnet protocol is deployed as a network of trusted machines. It lets these machines share all their resources efficiently with minimum overhead. This is accomplished by allowing a client process to send a message to a remote manager in the same way that it sends a message to a local one. See the "How does it work?" section of this chapter. For example, using Qnet, you can use the Neutrino utilities (**`cp`**, **`mv`** and so on) to manipulate files anywhere on the Qnet Network as if they were on your machine — by communicating with the filesystem manager on the remote nodes. In addition, the Qnet protocol doesn't do any authentication of remote requests. Files are protected by the normal permissions that apply to users and groups (see "File ownership and permissions" in Working with Files in the *User's Guide*).

Qnet, through its distributed processing platform, lets you do the following tasks efficiently:

- access your remote filesystem
- scale your application with unprecedented ease
- write applications using a collection of cooperating processes that communicate transparently with each other using Neutrino message passing
- extend your application easily beyond a single processor or symmetric multi-processor to several single processor machines and distribute your processes among these processors
- divide your large application into several processes that coordinate their work using messages

- debug your application easily for processes that communicate at a very low level, and that use Neutrino's memory protection feature
- use builtin remote procedure call functionality

Since Qnet extends Neutrino message passing over the network, other forms of interprocess communication (e.g. signals, message queues, and named semaphores) also work over the network.

What type of application is well-suited for Qnet?

Any application that inherently needs more than one computer, due to its processing or physical layout requirements, could likely benefit from Qnet.

For example, you can apply Qnet networking successfully in many industrial-automation applications (e.g. a fabrication plant, with computers scattered around). From an application standpoint, Qnet provides an efficient form of distributed computing where all computers look like one big computer because Qnet extends the fundamental Neutrino message passing across all the computers.

Another useful application is in the telecom space, where you need to implement large routers that have several processors. From an architectural standpoint, these routers generally have some interface cards and a central processor that runs a set of server processes. Each interface card, in turn, has a processor that runs another set of interface (e.g. client) processes. These client processes communicate via Qnet using Neutrino message passing with the server processes on the central processor, as if they were all running on the same processor. The scalability of Qnet allows more and more interface cards to be plugged into the router, without any code changes required to the application.

Qnet drivers

In order to support different hardware, you may need to write a driver for Qnet. The driver essentially performs three functions: transmits a packet, receives a packet, and resolves the remote node's interface.

In most cases, you don't need a specific driver for your hardware, for example, for implementing a local area network using Ethernet hardware or for implementing TCP/IP networking that require IP encapsulation. In these cases, the underlying **`io-net`** and **`tcpip`** layer is sufficient to interface with the Qnet layer for transmitting and receiving packets. You use standard Neutrino drivers to implement Qnet over a local area network or to encapsulate Qnet messages in IP (TCP/IP) to allow Qnet to be routed to remote networks.

But suppose you want to set up a very tightly coupled network between two CPUs over a super-fast interconnect (e.g. PCI or RapidIO). You can easily take advantage of the performance of such a high-speed link, because Qnet can talk directly to your hardware driver. There's no **`io-net`** layer in this case. All you need is a little code at the very bottom of Qnet layer that understands how to transmit and receive packets. This is simple as there is a standard internal API between the rest of Qnet and this very bottom portion, the driver interface. Qnet already supports different packet transmit/receive interfaces, so adding another is reasonably straightforward. The transport mechanism of Qnet (called the *L4*) is quite generic and can be configured for different size MTUs, whether or not ACK packets or CRC checks are required, to take the full advantage of your link's advanced features (e.g. guaranteed reliability).

For details about how to write a driver, see the section on "Writing a driver for Qnet" later in this chapter.

The QNX Momentics Transparent Distributed Processing Source Kit (TDP SK) is available to help you develop custom drivers and/or modify Qnet components to suit your particular application. For more information, contact your sales representative.

How does it work?

As explained in the *System Architecture* guide, Neutrino client and server applications communicate by Neutrino message passing. Function calls that need to communicate with a manager application, such as the POSIX functions *open()*, *write()*, *read()*, *ioctl()*, or other functions such as *devctl()* are all built on Neutrino message passing.

Qnet allows these messages to be sent over a network. If these messages are being sent over a network, how is a message sent to a remote manager vs a local manager?

When you access local devices or manager processes (such as a serial device, TCP/IP socket, or **mqueue**), you access these devices by opening a pathname under **/dev**. This may be apparent in the application source code:

```
/*Open a serial device*/
fd = open("/dev/ser1",O_RDWR....);
```

or it may not. For example, when you open a socket:

```
/*Create a UDP socket*/
sock = socket(AF_INET, SOCK_DGRAM, 0);
```

The *socket()* function opens a pathname under **/dev** called **/dev/socket/2** (in the case of AF_INET, which is address family two). The *socket()* function call uses this pathname to establish a connection with the socket manager (**npm-tcpip.so**), just as the *open()* call above established a connection to the serial device manager (**devc-ser8250**).

The magic of this is that you access all managers by the name that they added to the pathname space. For more information, see the Writing a Resource Manager chapter.

When you enable the Qnet native network protocol, the pathname spaces of all the nodes in your Qnet network are added to yours. The pathname space of remote nodes appears (by default) under the prefix **/net**.

Under QNX 4, you use a double slash followed by a node number to refer to another node.

The **/net** directory is created by the Qnet protocol manager (**npm-qnet.so**). If, for example, the other node is called **node1**, its pathname space appears as follows:

```
/net/node1/dev/socket
/net/node1/dev/ser1
/net/node1/home
/net/node1/bin
....
```

So with Qnet, you can now open pathnames (files or managers) on other remote Qnet nodes, in the same way that you open files locally. This means that you can access regular files or manager processes on other Qnet nodes as if they were executing on your local node.

First, let's see some basic examples of Qnet use:

- To display the contents of a file on another machine (**node1**), you can use **less**, specifying the path through **/net**:
  ```
  less /net/node1/etc/TIMEZONE
  ```

- To get system information about all of the remote nodes that are listed in **/net**, use **pidin** with the **net** argument:
  ```
  $ pidin net
  ```

- You can use **pidin** with the **-n** option to get information about the processes on another machine:
  ```
  pidin -n node1 | less
  ```

- You can even run a process on another machine, using the **-f** option to the **on** command:
  ```
  on -f node date
  ```

In all of these uses, the application source or the libraries (for example **libc**) they depend on, simply open the pathnames under **/net**. For example, if you wish to make use of a serial device on another node **node1**, perform an *open()* function with the pathname **/net/node1/dev/ser1** i.e.

```
fd = open("/net/node1/dev/ser1",O_RDWR...);
```

As you can see, the code required for accessing remote resources and local resources is identical. The only change is the pathname used.

In the TCP/IP *socket()* case, it's the same, but implemented differently. In the socket case, you don't directly open a filename. This is done inside the socket library. In this case, an environment variable is provided to set the pathname for the socket call (the **SOCK** environment variable — see **`npm-tcpip.so`**).

Some other applications are:

Remote filesystem access

In order to access **`/tmp/file1`** file on **`node1`** remotely from another node, use **`/net/node1/tmp/file1`** in *open()*.

Message queue

You can create or open a message queue by using *mq_open()*. The **`mqueue`** manager must be running. When a queue is created, it appears in the pathname space under **`/dev/mqueue`**. So, you can access **`/dev/mqueue`** on **`node1`** from another node by using **`/net/node1/dev/mqueue`**.

The alternate implementation of message queues that uses the **`mq`** server and asynchronous messages doesn't support access to a queue via Qnet.

Semaphores — Using Qnet, you can create or access named semaphores in another node. For example, use **`/net/node1/semaphore_location`** in the *sem_open()* function. This creates or accesses the named semaphore in **`node1`**.

This brings up an important issue for the client application or libraries that a client application uses. If you think that your application will be distributed over a network, you will want to include the capability to

specify another pathname for connecting to your services. This way, your application will have the flexibility of being able to connect to local or remote services via a user-configuration adjustment. This could be as simple as the ability to pass a node name. In your code, you would add the prefix **/net/***node_name* to any pathname that may be opened on the remote node. In the local case, or default case if appropriate, you could omit this prefix when accessing local managers.

In this example, you're using standard resource managers, such as would be developed using the resource manager framework (see the Writing a Resource Manager chapter). For further information, or for a more in-depth view of Qnet, see Advanced Qnet Topics appendix.

There is another design issue to contend with at this point: the above design is a static one. If you have services at known locations, or the user will be placing services at known locations, then this may be sufficient. It would be convenient, though, if your client application could locate these services automatically, without the need to know what nodes exist in the Qnet network, or what pathname they've added to the namespace. You can now use the Global Name Service (**gns**) manager to locate services with an arbitrary name representing that service. For example, you can locate a service with a name such as **printer** instead of opening a pathname of **/net/node/dev/par1** for a parallel port device. The **printer** name locates the parallel port manager process, whether it's running locally or remotely.

Locating services using GNS

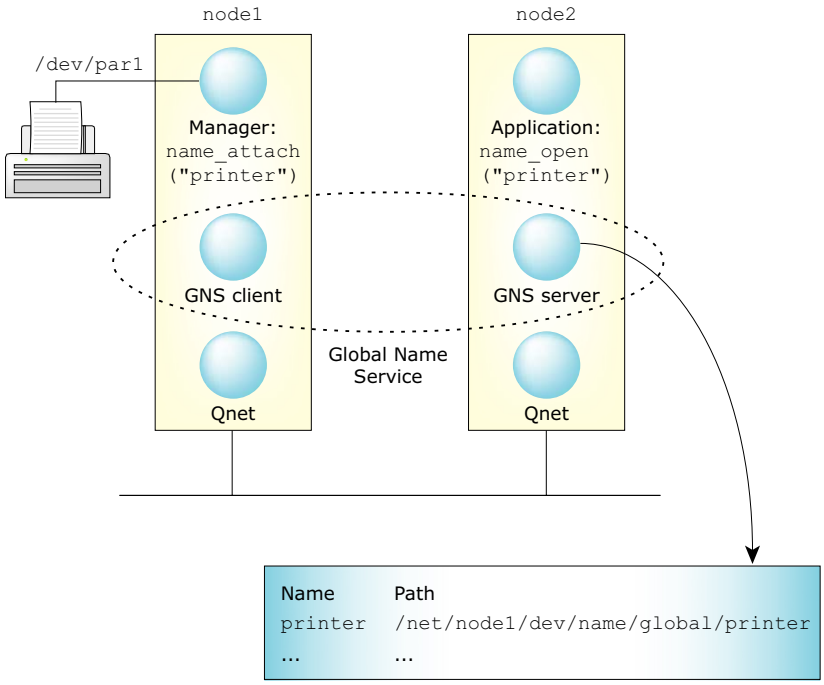
You use **gns**, the Global Name Service or GNS manager to locate services. GNS is a standalone resource manager. With the help of this utility, an application can advertise, look up, and use (connect to) a service across Qnet network, without knowing the details of where the service is, or who the provider is.

Different modes of gns

The **gns** utility runs in two different modes: server- and client-mode. A server-mode manager is a central database that stores advertised services, and handles lookup and connect requests. A client-mode manager relays advertisement, lookup, and connect requests between local application and the GNS server(s).

For more information on starting and configuring GNS, see the **gns** utility in the *Utilities Reference*.

Here's a simple layout for a GNS client and a GNS server distributed over a network:



A simple GNS setup.

In this example, there's one **gns** client and one **gns** server. As far as an application is concerned, the GNS service is one entity. The

client-server relationship is only between **gns** processes (we'll examine this later). The server GNS process keeps track of the globally registered services, while the client GNS process on the other node relays **gns** requests for that node to the **gns** server.

When a client and server application interacts with the GNS service, they use the following APIs:

Server

name_attach()

Register your service with the GNS server.

name_detach()

Deregister your service with the GNS server.

Client

name_open() Open a service via the GNS server.

name_close() Close the service opened with *name_open()*.

Registering a service

In order to use GNS, you need to first register the manager process with GNS, by calling *name_attach()*.

When you register a service, you need to decide whether to register this manager's service locally or globally. If you register your service locally, only the local node is able to see this service; another node is not able to see it. This allows you to have client applications that look for service *names* rather than pathnames on the node it is executing on. This document highlights registering services globally.

When you register GNS service globally, any node on the network running a client application can use this service, provided the node is running a **gns** client process and is connected to the **gns** server, along with client applications on the nodes running the **gns** server process. You can use a typical *name_attach()* call as follows:

```
if ((attach = name_attach(NULL, "printer", NAME_FLAG_ATTACH_GLOBAL)) == NULL) {
     return EXIT_FAILURE;
     }
```

First thing you do is to pass the flag NAME_FLAG_ATTACH_GLOBAL. This causes your service to be registered globally instead locally.

The last thing to note is the *name*. This is the name that clients search for. This name can have a single level, as above, or it can be nested, such as **`printer/ps`**. The call looks like this:

```
if ((attach = name_attach(NULL, "printer/ps", NAME_FLAG_ATTACH_GLOBAL)) == NULL) {
     return EXIT_FAILURE;
     }
```

Nested names have no impact on how the service works. The only difference is how the services are organized in the filesystem generated by **`gns`**. For example:

```
$ ls -l /dev/name/global/
total 2
dr-xr-xr-x  0 root      techies           1 Feb 06 16:20 net
dr-xr-xr-x  0 root      techies           1 Feb 06 16:21 printer

$ ls -l /dev/name/global/printer
total 1
dr-xr-xr-x  0 root      techies           1 Feb 06 16:21 ps
```

The first argument to the *name_attach()* function is the dispatch handle. You pass a dispatch handle to *name_attach()* once you've already created a dispatch structure. If this argument is NULL, a dispatch structure is created automatically.

What happens if more than one instance of the server application (or two or more applications that register the same service name) are started and registered with GNS? This is treated as a redundant service. If one application terminates or detaches its service, the other service takes over. However, it's not a round-robin configuration; all requests go to one application until it's no longer available. At that point, the requests resolve to another application that had registered the same service. There is no guaranteed ordering.

There's no credential restriction for applications that are attached as local services. An application can attach a service globally only if the application has **`root`** privilege.

When your application is to terminate, or you wish not to provide access to the service via GNS, you should call *name_detach()*. This removes the service from GNS.

For more information, see *name_attach()* and *name_detach()*.

Your client should call *name_open()* to locate the service. If you wish to locate a global service, you need to pass the flag NAME_FLAG_ATTACH_GLOBAL:

```
if ((fd = name_open("printer", NAME_FLAG_ATTACH_GLOBAL)) == -1) {
     return EXIT_FAILURE;
     }
```

or:

```
if ((fd = name_open("printer/ps", NAME_FLAG_ATTACH_GLOBAL)) == -1) {
     return EXIT_FAILURE;
     }
```

If you don't specify this flag, GNS looks only for a local service. The function returns an **fd** that you can then use to access the service manager by sending messages, just as if you it had opened the service directly as **/dev/par1**, or **/net/***node***/dev/par1**.

GNS path namespace

A service is represented by a path namespace (without a leading "/") and is registered under **/dev/name/global** or **/dev/name/local**, depending on how it attaches itself. Every machine running a **gns** client or server on the same network has the same view of the **/dev/name/global** namespace. Each machine has its own local namespace **/dev/name/local** that reflects its own local services.

Here's an example after a service called **printer** has attached itself globally:

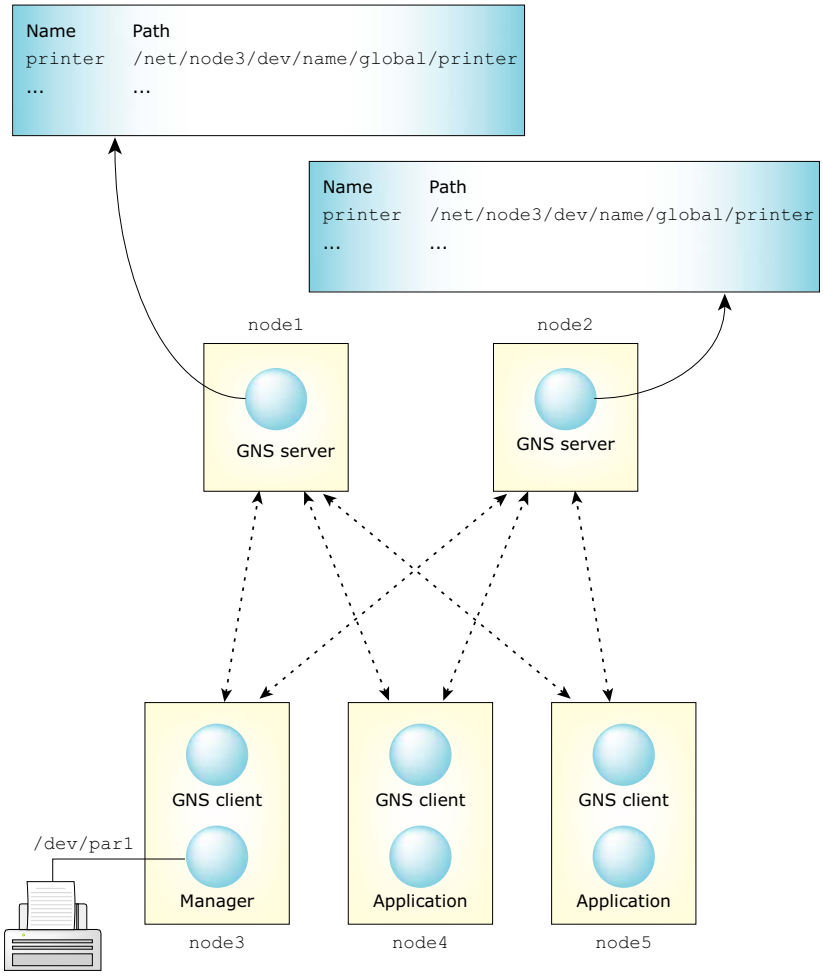
```
$ ls -l /dev/name/global/
total 2
dr-xr-xr-x  0 root      techies     1 Feb 06 16:20 net
dr-xr-xr-x  0 root      techies     1 Feb 06 16:21 printer
```

Deploying the gns processes

When you deploy the **gns** processes on your network, you start the **gns** process in two modes: server and client. You need at least one **gns** process running as a server on one node, and you can have one or more **gns** clients running on the remaining nodes. The role of the **gns** server process is to maintain the database that stores the advertised services. The role of a client **gns** process is to relay requests from its node to the **gns** server process on the other node. A **gns** process must be running on each node that wishes to access GNS.

It's possible to start multiple global name service managers (**gns** process) in server mode on different nodes. You can deploy server-mode **gns** processes in two ways: as redundant servers, or as servers that handle two or more different global domains.

In the first scenario, you have two or more servers with identical database information. The **gns** client processes are started with contact information for both servers. Operations are then sent to all **gns** server processes. The **gns** servers, however, don't communicate with each other. This means that if an application on one **gns** server node wants to register a global service, another **gns** server can't do it. This doesn't affect other applications on the network, because when they connect to that service, both GNS servers are contacted.

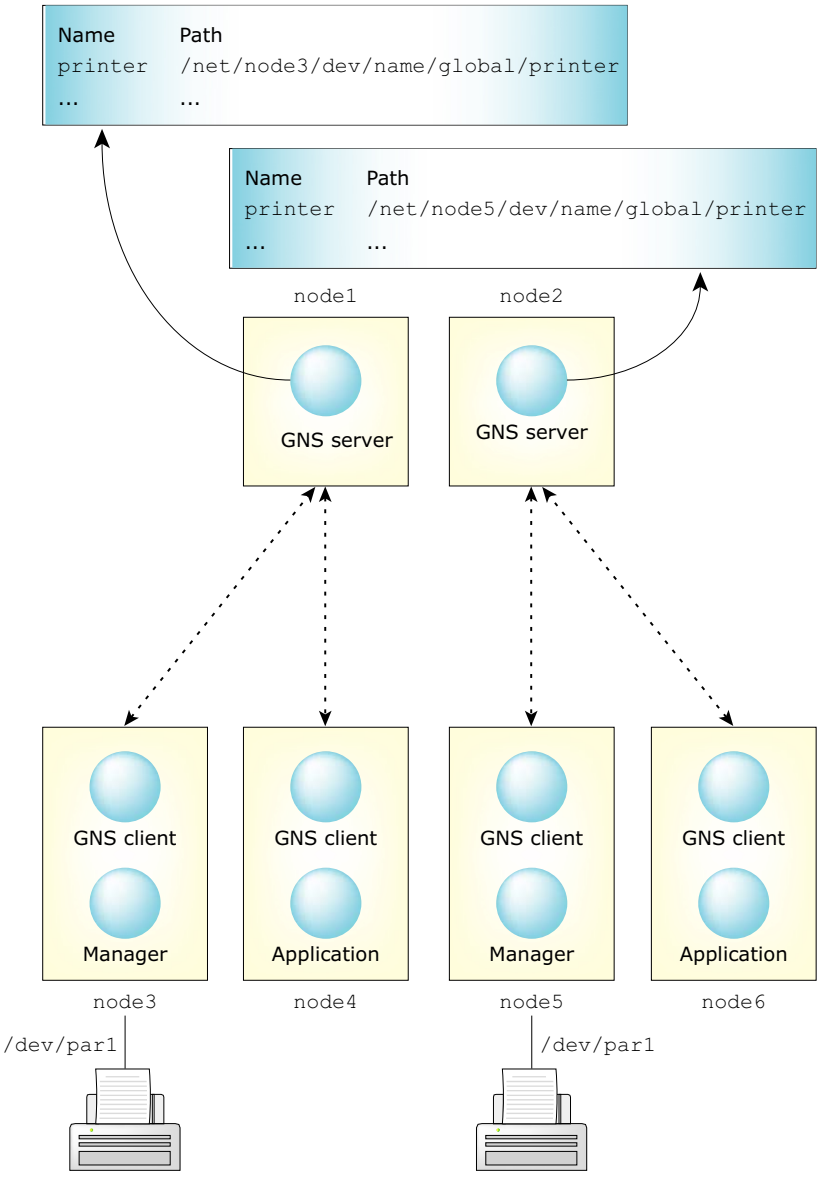


A redundant GNS setup.

You don't have to start all redundant **gns** servers at the same time. You can start one **gns** server process first, and then start a second **gns** server process at a later time. In this case, use the special option **-s** *backup_server* on the second **gns** server process to make it download the current service database from another node that's already running the **gns** server process. When you do this, the clients connected to the

first node (that's already running the **gns** server process) are notified of the existence of the other server.

In the second scenario, you maintain more than one global domain. For example, assume you have two nodes, each running a **gns** server process. You also have a client node that's running a **gns** client process and is connecting to one of the servers. A different client node connects to the other server. Each server node has unique services registered by each client. A client connected to server **node1** can't see the service registered on the server **node2**.



Separate global domains.

What is demonstrated in each scenario is that it's the client that determines whether a server is acting as a redundant server or not. If a client is configured to connect to two or more servers, then those servers are redundant servers for that client's services. The client can see the services that exist on those servers, and it registers its services with those servers.

There's no limit to the number of server mode **gns** processes that can be run on the network. Increasing the number of servers, however, in a redundant environment can increase network use and make **gns** function calls such as *name_attach()* more expensive as clients send requests to each server that exists in its configuration. It's recommended that you run only as many **gns** servers in a redundant configuration as your system design requires and no more than that.

For more information, see **gns** documentation in the *Utilities Reference*.

Quality of Service (QoS) and multiple paths

Quality of Service (QoS) is an issue that often arises in high-availability networks as well as realtime control systems. In the Qnet context, QoS really boils down to *transmission media selection* — in a system with two or more network interfaces, Qnet chooses which one to use, according to the policy you specify.

If you have only a single network interface, the QoS policies don't apply at all.

QoS policies

Qnet supports transmission over *multiple networks* and provides the following policies for specifying how Qnet should select a network interface for transmission:

`loadbalance` (the default)

Qnet is free to use all available network links, and shares transmission equally among them.

preferred Qnet uses one specified link, ignoring all other networks (unless the preferred one fails).

exclusive Qnet uses one — and only one — link, ignoring all others, even if the exclusive link fails.

loadbalance

Qnet decides which links to use for sending packets, depending on current load and link speeds as determined by **io-net**. A packet is queued on the link that can deliver the packet the soonest to the remote end. This effectively provides greater bandwidth between nodes when the links are up (the bandwidth is the sum of the bandwidths of all available links) and allows a graceful degradation of service when links fail.

If a link does fail, Qnet switches to the next available link. By default, this switch takes a few seconds *the first time*, because the network driver on the bad link will have timed out, retried, and finally died. But once Qnet "knows" that a link is down, it will *not* send user data over that link. (This is a significant improvement over the QNX 4 implementation.)

The time required to switch to another link can be set to whatever is appropriate for your application using command line options of Qnet. See **npm-qnet-l4_lite.so** documentation.

Using these options, you can create a redundant behavior by minimizing the latency that occurs when switching to another interface in case one of the interfaces fail.

While load-balancing among the live links, Qnet sends periodic maintenance packets on the failed link in order to detect recovery. When the link recovers, Qnet places it back into the pool of available links.

The **loadbalance** QoS policy is the default.

preferred

With this policy, you specify a preferred link to use for transmissions. Qnet uses only that one link until it fails. If your preferred link fails, Qnet then turns to the other available links and resumes transmission, using the **loadbalance** policy.

Once your preferred link is available again, Qnet again uses only that link, ignoring all others (unless the preferred link fails).

exclusive

You use this policy when you want to lock transmissions to only one link. Regardless of how many other links are available, Qnet will latch onto the one interface you specify. And if that exclusive link fails, Qnet will *not* use any other link.

Why would you want to use the **exclusive** policy? Suppose you have two networks, one much faster than the other, and you have an application that moves large amounts of data. You might want to restrict transmissions to only the fast network, in order to avoid swamping the slow network if the fast one fails.

Specifying QoS policies

You specify the QoS policy as part of the pathname. For example, to access **/net/node1/dev/ser1** with a QoS of **exclusive**, you could use the following pathname:

```
/net/node1~exclusive:en0/dev/ser1
```

The QoS parameter always begins with a tilde (**~**) character. Here we're telling Qnet to lock onto the **en**0 interface exclusively, even if it fails.

Symbolic links

You can set up symbolic links to the various "QoS-qualified" pathnames:

```
ln -sP /net/note1~preferred:en1 /remote/sql_server
```

This assigns an "abstracted" name of **/remote/sql_server** to the node **node1** with a preferred QoS (i.e. over the **en**1 link).

You can't create symbolic links inside **/net** because Qnet takes over that namespace.

Abstracting the pathnames by one level of indirection gives you multiple servers available in a network, all providing the same service. When one server fails, the abstract pathname can be "remapped" to point to the pathname of a different server. For example, if **node1** fails, then a monitoring program could detect this and effectively issue:

```
rm /remote/sql_server
ln -sP /net/magenta /remote/sql_server
```

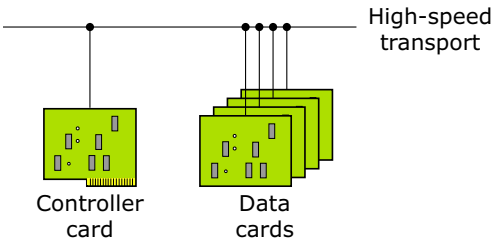
This removes **node1** and reassigns the service to **node2**. The real advantage here is that applications can be coded based on the abstract "service name" rather than be bound to a specific node name.

For a real world example of choosing appropriate QoS policy in an application, see the following section on designing a system using Qnet.

Designing a system using Qnet

The product

In order to explain the design of a system that takes advantage of the power of Qnet by performing distributed processing, consider a multiprocessor hardware configuration that is suitable for a typical telecom box. This configuration has a generic controller card and several data cards to start with. These cards are interconnected by a high-speed transport (HST) bus. The controller card configures the box by communicating with the data cards, and establishes/enables data transport in and out of the box (i.e. data cards) by routing packets.



The typical challenges to consider for this type of box include:

- Configuring the data cards
- Configuring the controller card
- Replacing a data card
- Enhancing reliability via multiple transport buses
- Enhancing reliability via multiple controller cards

Developing your distributed system

You need several pieces of software components (along with the hardware) to build your distributed system. Before going into further details, you may review the following sections from Using Qnet for Transparent Distributed Processing chapter in the Neutrino *User's Guide*:

- Software components for Qnet networking
- Starting Qnet
- Conventions for naming nodes

Configuring the data cards

Power up the data cards to start **`procnto`** and **`qnet`** in sequence. These data cards need a minimal amount of flash memory (e.g. typically 1 MB) to store the Neutrino image.

In the buildfile of the data cards, you should link the directories of the data cards to the controller cards as follows:

```
[type=link] /bin  = /net/cc0/bin
[type=link] /sbin = /net/cc0/sbin
[type=link] /usr  = /net/cc0/usr
```

where **cc0** is the name of the the controller card.

Assuming that the data card has a console and shell prompt, try the following commands:

```
$ ls /net
```

You get a list of boards running Neutrino and Qnet:

```
 cc0  dc0  dc1  dc2  dc3
```

Or, use the following command on a data card:

```
$ ls /net/cc0
```

You get the following output (i.e. the contents of the root of the filesystem for the controller card):

```
.               .inodes           mnt0        tmp
..              .longfilenames    mnt1        usr
.altboot        bin               net         var
.bad_blks       dev               proc        xfer
.bitmap         etc               sbin
.boot           home              scratch
```

Configuring the controller card

Configure the controller card in order to access different servers running on it — either by the data cards, or by the controller card itself. Make sure that the controller card has a larger amount of flash memory than the data cards do. This flash memory contains all the binaries, data and configuration files that the applications on the data cards access as if they were on a local storage device.

Call the following API to communicate with the **mqueue** server by any application:

```
mq_open("/net/cc0/dev/mqueue/app_q", ....)
```

A simple variation of the above command requires that you run the following command during initialization:

```
$ ln -s /net/cc0/dev/mqueue /mq
```

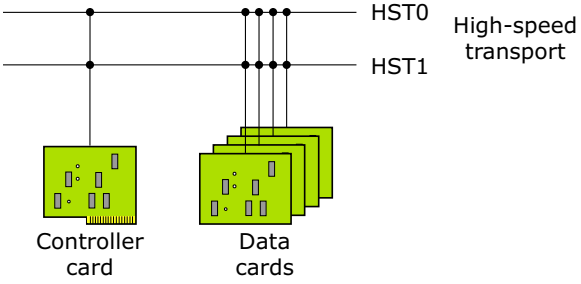
Then all applications, whether they're running on the data cards or on the controller card, can call:

```
mq_open("/mq/app_q", ....)
```

Similarly, applications can even utilize the TCP/IP stack running on the controller card.

Enhancing reliability via multiple transport buses

Qnet provides design choices to improve the reliability of a high-speed transport bus, most often a single-point of failure in such type of telecom box.



You can choose between different transport selections to achieve a different Quality of Service (or QoS), such as:

- load-balance — no interface specified
- preferred — specify an interface, but allow failover
- exclusive — specify an interface, no failover

These selections allow you to control how data will flow via different transports.

In order to do that, first, find out what interfaces are available. Use the following command at the prompt of any card:

```
ls /dev/io-net
```

You see the following:

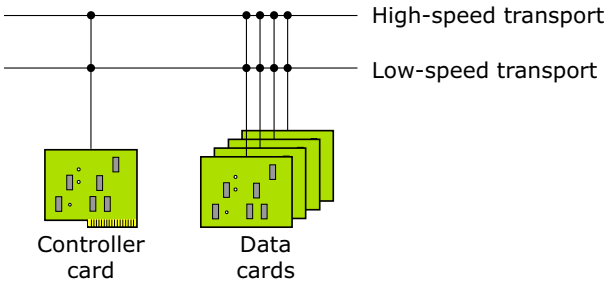
```
hs0 hs1
```

These are the interfaces available: HST 0 and HST 1.

Select your choice of transport as follows:

Use this command:	To select this transport:
`ls /net/cc0`	Loadbalance, the default choice
`ls /net/cc0~preferred:hs0`	Preferred. Try HST 0 first; if that fails, then transmit on HST 1.
`ls /net/cc0~exclusive:hs0`	Exclusive. Try HST 0 first. If that fails, terminate transmission.

You can have another economical variation of the above hardware configuration:



This configuration has asymmetric transport: a High-Speed Transport (HST) and a reliable and economical Low-Speed Transport (LST). You might use the HST for user data, and the LST exclusively for out-of-band control (which can be very helpful for diagnosis and during booting). For example, if you use generic Ethernet as the LST, you could use a **`bootp`** ROM on the data cards to economically boot — no flash would be required on the data cards.

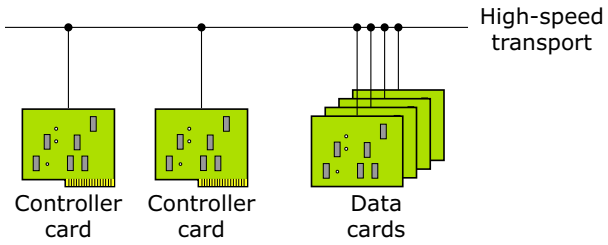
With asymmetric transport, use of the QoS policy as described above likely becomes even more useful. You might want some applications to use the HST link first, but use the LST if the HST fails. You might want applications that transfer large amounts of data to exclusively use the HST, to avoid swamping the LST.

Redundancy and scalability using multiple controller cards

Redundancy

The reliability of such a telecom box also hinges on the controller card, that's a critical component and certainly a potential SPOF (single point of failure). You can increase the reliability of this telecom box by using additional controller cards.

The additional controller card is for redundancy. Add another controller card as shown below:



Once the (second) controller card is installed, the challenge is in the determination of the primary controller card. This is done by the software running on the controller cards. By default, applications on the data cards access the primary controller card. Assuming **`cc0`** is

the primary controller card, Use the following command to access this card in **/cc** directory:

```
ln -s /net/cc0 /cc
```

The above indirection makes communication between data card and controller card transparent. In fact, the data cards remain unaware of the number of controller cards, or which card is the primary controller card.

Applications on the data cards access the primary controller card. In the event of failure of the primary controller card, the secondary controller card takes over. The applications on the data cards redirect their communications via Qnet to the secondary controller card.

Scalability

You can also scale your resources to run a particular server application using additional controller cards. For example, if your controller card (either a SMP or non-SMP board) doesn't have the necessary resources (e.g. CPU cycle, memory), you could increase the total processor and box resources by using additional controller cards. Qnet transparently distributes the (load of) application servers across two or more controller cards.

Autodiscovery vs static

When you're creating a network of Neutrino hosts via Qnet, one thing you must consider is how they locate and address each other. This falls into two categories: autodiscovery and static mappings.

The decision to use one or the other can depend on security and ease of use.

The discussion in this section applies only to **npm-qnet-l4_lite.so** (default). The other shared object **npm-qnet-compat.so** doesn't have the same functionality. You may also find the information on available Qnet resolvers in the description of **npm-qnet-l4_lite.so**.

The autodiscovery mechanism (i.e. **ndp** — Node Discovery Protocol; see **npm-qnet-l4_lite.so** for more information) allows Qnet nodes to discover each other automatically on a transport that supports broadcast. This is a very convenient and dynamic way to build your network, and doesn't require user intervention to access a new node.

One issue to consider is whether or not the physical link being used by your Qnet nodes is secure. Can another untrusted Qnet node be added to this physical network of Qnet nodes? If the answer is yes, you should consider another resolver (**file: filename**). If you use this resolver, only the nodes listed in the file can be accessed. This file consists of node names and a string representing the addressing scheme of your transport layer. In the Ethernet case, this is the unique MAC address of the Qnet node listed. If you're using the file resolver for this purpose, you also want to specify the option **auto_add**=0 in **npm-qnet-l4_lite.so**. This keeps your node from responding to node discovery protocol requests and adding a host that isn't listed in your resolver **file**.

Another available resolver, **dns** lets you access another Qnet node if you know its name (**IP**). This is used in combination with the IP transport (**npm-qnet-compat.so** option **bind=ip**). Since it doesn't have an **auto_add** feature as the **ndp** resolver does, you don't need to specify a similar Qnet option. Your Qnet node resolve the remote Qnet node's name only via the file used by the Qnet **file** resolver.

When should you use Qnet, TCP/IP, or NFS?

In your network design, when should you use Qnet, TCP/IP, or NFS? The decision depends on what your intended application is and what machines you need to connect.

The advantage of using Qnet is that it lets you build a truly distributed processing system with incredible scalability. For many applications, it could be a benefit to be able to share resources among your application systems (nodes). Qnet implements a native network protocol to build this distributed processing system.

The basic purpose of Qnet is to extend Neutrino message passing to work over a network link. It lets these machines share all their resources with little overhead. A Qnet network is a trusted environment where resources are tightly integrated, and remote manager processes can be accessed transparently. For example, with Qnet, you can use the Neutrino utilities (**cp**, **mv** and so on) to manipulate files anywhere on the Qnet network as if they were on your machine. Because it's meant for a group of trusted machines (such as you'd find in an embedded system), Qnet doesn't do any authentication of remote requests. Also, the application really doesn't know whether it's accessing a resource on a remote system; and most importantly, the application doesn't need any special code to handle this capability.

If you're developing a system that requires remote procedure calling (RPC), or remote file access, Qnet provides this capability transparently. In fact, you use a form of remote procedure call (a Neutrino message pass) every time you access a manager on your Neutrino system. Since Qnet creates an environment where there's no difference between accessing a manager locally or remotely, remote procedure calling (capability) is builtin. You don't need to write source code to distribute your services. Also, since you are sharing the filesystem between systems, there's no need for NFS to access files on other Neutrino hosts (of the same endian), because you can access remote filesystem managers the same way you access your local one. Files are protected by the normal permissions that apply to users and groups (see "File ownership and permissions" in the Working with Files chapter in the *User's Guide*).

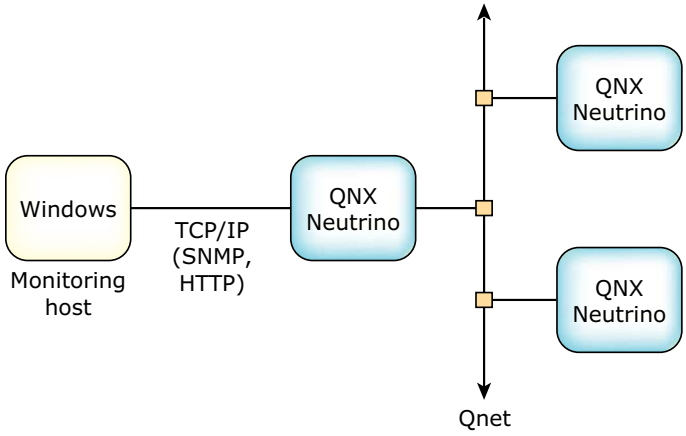
There are several ways to control access to a Qnet node, if required:

- Bind Qnet to a specific network interface; this ensures that the protocol functions only on that specific interface.

- Use **`maproot`** and **`mapany`** options to control — in a limited way — what other users can do on your system.
- Use a static list of your peer systems instead of dynamically discovering them.

You can also configure Qnet to be used on a local LAN, or routed over to a WAN if necessary (encapsulated in the IP protocol).

Depending on your system design, you may need to include TCP/IP protocols along with Qnet, or instead of Qnet. For example, you could use a TCP/IP-based protocol to connect your Qnet cluster to a host that's running another operating system, such as a monitoring station that controls your system, or another host providing remote access to your system. You'll probably want to deploy standard protocols (e.g SNMP, HTTP, or a **`telnet`** console) for this purpose. If all the hosts in your system are running different operating systems, then your likely choice to connect them would be TCP/IP. The TCP/IP protocols typically do authentication to control access; it's useful for connecting machines that you don't necessarily trust.



You can also build a Neutrino-based TCP/IP network. A Neutrino TCP/IP network can access resources located on any other system that supports TCP/IP protocol. For a discussion of Neutrino TCP/IP specifics, see TCP/IP Networking in the *System Architecture* guide.

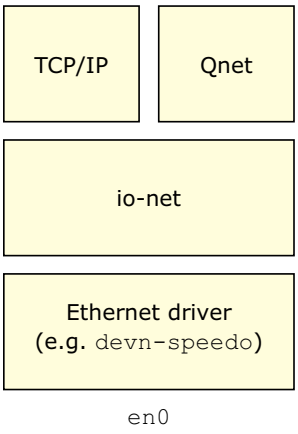
Another issue may be the required behavior. For example, NFS has been designed for filesystem operations between all hosts and all endians. It's widely supported and a connectionless protocol. In NFS, the server can be shut down and restarted, and the client resumes automatically. NFS also uses authentication and controls directory access. However, NFS retries forever to reach a remote host if it doesn't respond, whereas Qnet can return an error if connectivity is lost to a remote host. For more information, see "NFS filesystem" in Working with Filesystems in the *User's Guide*).

If you require broadcast or multicast services, you need to look at TCP/IP functionalities, because Qnet is based on Neutrino message passing, and has no concept of broadcasting or multicasting.

Writing a driver for Qnet

In order to support different hardware, you may need to write a driver for Neutrino's Qnet. The driver essentially performs three functions: transmitting a packet, receiving a packet, and resolving the remote node's interface (address). This section describes some of the issues you'll face when you need to write a driver.

First, let's define what exactly a driver is, from Qnet's perspective. When Qnet is run with its default binding of raw Ethernet (e.g. **`bind=en`**0), you'll find the following arrangement of layers that exists in the node:

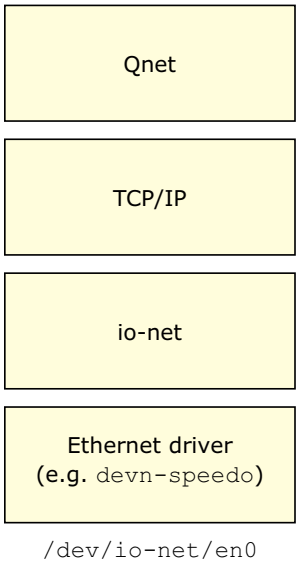


In the above case, **io-net** is actually the **driver** that transmits and receives packets, and thus acts as a hardware-abstraction layer. Qnet doesn't care about the details of the Ethernet hardware or driver.

So, if you simply want new Ethernet hardware supported, you don't need to write a Qnet-specific driver. What you need is just a normal Ethernet driver that knows how to interface to **io-net**.

There is a bit of code at the very bottom of Qnet that's specific to **io-net** and has knowledge of exactly how **io-net** likes to transmit and receive packets. This is the L4 driver API abstraction layer.

Let's take a look at the arrangement of layers that exist in the node when Qnet is run with the optional binding of IP encapsulation (e.g. **bind=ip**):

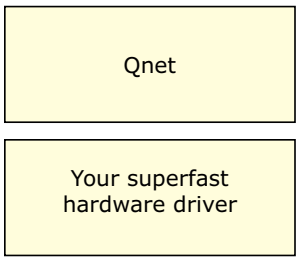


As far as Qnet is concerned, the TCP/IP stack is now its **`driver`**. This stack is responsible for transmitting and receiving packets.

Therefore, if IP encapsulation is acceptable for your application, you really don't need to write a Qnet **`driver`**, you can use any existing IP transport mechanism.

Again, it's worth mentioning that at the very bottom of Qnet there is a bit of code (L4 driver API) that's specific to TCP/IP and knows exactly how to transmit and receive packets using the TCP/IP stack.

If you have some superfast network hardware that you don't want to write an **`io-net`** driver for, you could get the ultimate in performance by writing a dedicated driver. A possible arrangement of layers is as follows:



Just as before, Qnet needs a little code at the very bottom that knows exactly how to transmit and receive packets to this new driver. There exists a standard internal API (L4 driver API) between the rest of Qnet and this very bottom portion, the driver interface. Qnet already supports different packet transmit/receive interfaces, so adding another is reasonably straightforward. The transport mechanism of Qnet (called the L4) is quite generic, and can be configured for different size MTUs, whether or not ACK packets or CRC checks are required, to take the full advantage of your link's advanced features (e.g. guaranteed reliability).

For more details, see the QNX Momentics Transparent Distributed Processing Source Kit (TDP SK) documentation.

Chapter 6

Writing an Interrupt Handler

In this chapter. . .

What's an interrupt?

The key to handling hardware events in a timely manner is for the hardware to generate an *interrupt*. An interrupt is simply a pause in, or interruption of, whatever the processor was doing, along with a request to do something else.

The hardware generates an interrupt whenever it has reached some state where software intervention is desired. Instead of having the software continually poll the hardware — which wastes CPU time — an interrupt is the preferred method of "finding out" that the hardware requires some kind of service. The software that handles the interrupt is therefore typically called an *Interrupt Service Routine* (ISR).

Although crucial in a realtime system, interrupt handling has unfortunately been a very difficult and awkward task in many traditional operating systems. Not so with Neutrino. As you'll see in this chapter, handling interrupts is almost trivial; given the fast context-switch times in Neutrino, most if not all of the "work" (usually done by the ISR) is actually done by a thread.

Let's take a look at the Neutrino interrupt functions and at some ways of dealing with interrupts.

Attaching and detaching interrupts

In order to install an ISR, the software must tell the OS that it wishes to associate the ISR with a particular source of interrupts. On x86 platforms, there are generally 16 hardware *Interrupt Request* lines (IRQs) and several sources of software interrupts. On other platforms (e.g. MIPS, PPC), the actual number of interrupts depends on the hardware configuration supplied by the manufacturer of the board. In any case, a thread specifies which interrupt source it wants to associate with which ISR, using the *InterruptAttach()* or *InterruptAttachEvent()* function calls.

When the software wishes to dissociate the ISR from the interrupt source, it can call *InterruptDetach()*:

```
#define IRQ3 3
```

```
/*  A forward reference for the handler */
extern const sigevent *serint (void *, int);
...

/*
 *  Associate the interrupt handler, serint,
 *  with IRQ 3, the 2nd PC serial port
 */
ThreadCtl( _NTO_TCTL_IO, 0 );
id = InterruptAttach (IRQ3, serint, NULL, 0, 0);
...

/*  Perform some processing. */
...

/*  Done; detach the interrupt source. */
InterruptDetach (id);
```

Because the interrupt handler can potentially gain control of the machine, we don't let just anybody associate an interrupt.

The thread must have *I/O privileges* — the privileges associated with being able to manipulate hardware I/O ports and affect the processor interrupt enable flag (the x86 processor instructions **`in`**, **`ins`**, **`out`**, **`outs`**, **`cli`**, and **`sti`**). Since currently only the **`root`** account can gain I/O privileges, this effectively limits the association of interrupt sources with ISR code.

Let's now take a look at the ISR itself.

Interrupt Service Routine (ISR)

In our example above, the function *serint()* is the ISR. In general, an ISR is responsible for:

- determining which hardware device requires servicing, if any
- performing some kind of servicing of that hardware (usually this is done by simply reading and/or writing the hardware's registers)
- updating some data structures shared between the ISR and some of the threads running in the application

- signalling the application that some kind of event has occurred

Depending on the complexity of the hardware device, the ISR, and the application, some of the above steps may be omitted.

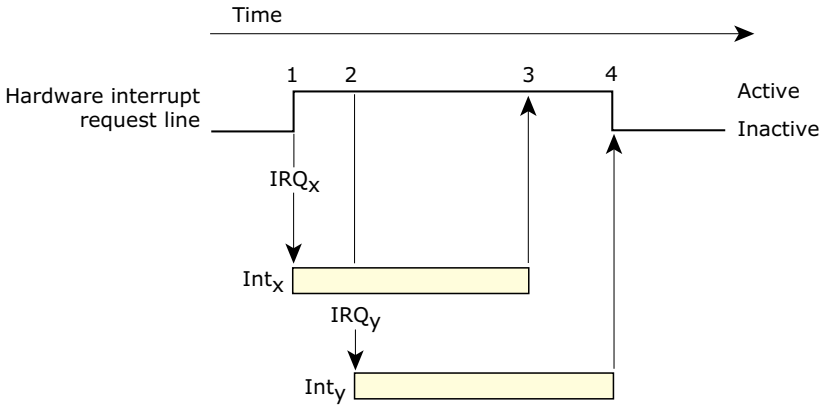
Let's take a look at these steps in turn.

Determining the source of the interrupt

Depending on your hardware configuration, there may actually be *multiple* hardware sources associated with an interrupt. This issue is a function of your specific hardware and bus type. This characteristic (plus good programming style) mandates that your ISR ensure that the hardware associated with it actually *caused* the interrupt.

Most *PIC* (Programmable Interrupt Controller) chips can be programmed to respond to interrupts in either an *edge-sensitive* or *level-sensitive* manner. Depending on this programming, interrupts may be sharable.

For example:



Interrupt request assertion with multiple interrupt sources.

In the above scenario, if the PIC is operating in a level-sensitive mode, the IRQ is considered active whenever it's high. In this configuration, while the second assertion (step 2) doesn't itself *cause*

a new interrupt, the interrupt is still considered active even when the original cause of the interrupt is removed (step 3). Not until the last assertion is cleared (step 4) will the interrupt be considered inactive.

In edge-triggered mode, the interrupt is "noticed" only once, at step 1. Only when the interrupt line is cleared, and then reasserted, does the PIC consider another interrupt to have occurred.

Neutrino allows ISR handlers to be *stacked*, meaning that multiple ISRs can be associated with one particular IRQ. The impact of this is that each handler in the chain must look at its associated hardware and determine if it caused the interrupt. This works reliably in a level-sensitive environment, but not an edge-triggered environment.

To illustrate this, consider the case where two hardware devices are sharing an interrupt. We'll call these devices "HW-A" and "HW-B." Two ISR routines are attached to one interrupt source (via the *InterruptAttach()* or *InterruptAttachEvent()* call), in sequence (i.e. ISR-A is attached first in the chain, ISR-B second).

Now, suppose HW-B asserts the interrupt line first. Neutrino detects the interrupt and dispatches the two handlers in order — ISR-A runs first and decides (correctly) that its hardware did *not* cause the interrupt. Then ISR-B runs and decides (correctly) that its hardware *did* cause the interrupt; it then starts servicing the interrupt. But before ISR-B clears the source of the interrupt, suppose HW-A asserts an interrupt; what happens depends on the type of IRQ.

Edge-triggered IRQ

If you have an edge-triggered bus, when ISR-B clears the source of the interrupt, the IRQ line is still held active (by HW-A). But because it's edge-triggered, the PIC is waiting for the next clear/assert transition before it decides that another interrupt has occurred. Since ISR-A already ran, it can't possibly run again to actually *clear* the source of the interrupt. The result is a "hung" system, because the interrupt will *never* transit between clear and asserted again, so no further interrupts on that IRQ line will ever be recognized.

Level-sensitive IRQ

On a level-sensitive bus, when ISR-B clears the source of the interrupt, the IRQ line is still held active (by HW-A). When ISR-B finishes running and Neutrino sends an *EOI* (End Of Interrupt) command to the PIC, the PIC immediately reinterrupts the kernel, causing ISR-A (and then ISR-B) to run.

Since ISR-A clears the source of the interrupt (and ISR-B doesn't do anything, because its associated hardware doesn't require servicing), everything functions as expected.

Servicing the hardware

The above discussion may lead you to the conclusion that "level-sensitive is *good*; edge-triggered is *bad*." However, another issue comes into play.

In a level-sensitive environment, your ISR *must* clear the source of the interrupt (or at least mask it via *InterruptMask()*) before it completes. (If it didn't, then when the kernel issued the EOI to the PIC, the PIC would then immediately reissue a processor interrupt and the kernel would loop forever, continually calling your ISR code.)

In an edge-triggered environment, there's no such requirement, because the interrupt won't be noticed again until it transits from clear to asserted.

In general, to actually service the interrupt, your ISR has to do very little; the minimum it can get away with is to clear the source of the interrupt and then schedule a thread to actually do the work of handling the interrupt. This is the recommended approach, for a number of reasons:

- Context-switch times between the ISR completing and a thread executing are very small — typically on the order of a few microseconds.
- The type of functions that the ISR itself can execute is very limited (those that don't call any kernel functions, except the ones listed below).

- The ISR runs at a priority *higher* than any software priority in the system — having the ISR consume a significant amount of processor has a negative impact on the realtime aspects of Neutrino.

Since the range of hardware attached to an interrupt source can be very diverse, the specific how-to's of servicing the interrupt are beyond the scope of this document — this really depends on what your hardware requires you to do.

Safe functions

When the ISR is servicing the interrupt, it can't make any kernel calls (except for the few that we'll talk about shortly). This means that you need to be careful about the library functions that you call in an ISR, because their underlying implementation may use kernel calls.

For a list of the functions that you can call from an ISR, see the Summary of Safety Information appendix in the *Library Reference*.

Here are the only kernel calls that the ISR can use:

- *InterruptMask()*
- *InterruptUnmask()*
- *TraceEvent()*

You'll also find these functions (which aren't kernel calls) useful in an ISR:

- *InterruptEnable()* (not recommended)
- *InterruptDisable()* (not recommended)
- *InterruptLock()*
- *InterruptUnlock()*

Let's look at these functions.

To prevent a thread and ISR from interfering with each other, you'll need to tell the kernel to disable interrupts. On a single-processor system, you can simply disable interrupts using the processor's "disable interrupts" opcode. But on an SMP system, disabling interrupts on one processor doesn't disable them on another processor.

The function *InterruptDisable()* (and the reverse, *InterruptEnable()*) performs this operation on a single-processor system. The function *InterruptLock()* (and the reverse, *InterruptUnlock()*) performs this operation on an SMP system.

We recommend that you *always* use the SMP versions of these functions — this makes your code portable to SMP systems, with a negligible amount of overhead.

The *InterruptMask()* and *InterruptUnmask()* functions disable and enable the PIC's recognition of a particular hardware IRQ line. These calls are useful if your interrupt handler ISR is provided by the kernel via *InterruptAttachEvent()* or if you can't clear the cause of the interrupt in a level-sensitive environment quickly. (This would typically be the case if clearing the source of the interrupt is time-consuming — you don't want to spend a lot of time in the interrupt handler. The classic example of this is a floppy-disk controller, where clearing the source of the interrupt may take many milliseconds.) In this case, the ISR would call *InterruptMask()* and schedule a thread to do the actual work. The thread would call *InterruptUnmask()* when it had cleared the source of the interrupt.

Note that these two functions are *counting* — *InterruptUnmask()* must be called the same number of times as *InterruptMask()* in order to have the interrupt source considered enabled again.

The *TraceEvent()* function traces kernel events; you can call it, with some restrictions, in an interrupt handler. For more information, see the System Analysis Toolkit *User's Guide*.

Updating common data structures

Another issue that arises when using interrupts is how to safely update data structures in use between the ISR and the threads in the application. Two important characteristics are worth repeating:

- The ISR runs at a higher priority than any software thread.
- The ISR can't issue kernel calls (except as noted).

This means that you *can't* use thread-level synchronization (such as mutexes, condvars, etc.) in an ISR.

Because the ISR runs at a higher priority than any software thread, it's up to the thread to protect itself against any preemption caused by the ISR. Therefore, the thread should issue *InterruptDisable()* and *InterruptEnable()* calls around any critical data-manipulation operations. Since these calls effectively turn off interrupts, the thread should keep the data-manipulation operations to a bare minimum.

With SMP, there's an additional consideration: one processor could be running the ISR, and another processor could be running a thread related to the ISR. Therefore, on an SMP system, you must use the *InterruptLock()* and *InterruptUnlock()* functions instead. Again, using these functions on a non-SMP system is safe; they'll work just like *InterruptDisable()* and *InterruptEnable()*, albeit with an insignificantly small performance penalty.

Another solution that can be used in some cases to at least guarantee atomic accesses to data elements is to use the *atomic_*()* function calls (below).

Signalling the application code

Since the environment the ISR operates in is very limited, generally you'll want to perform most (if not all) of your actual "servicing" operations at the thread level.

At this point, you have two choices:

- You may decide that some time-critical functionality needs to be done in the ISR, with a thread being scheduled later to do the "real" work.
- You may decide that *nothing* needs to be done in the ISR; you just want to schedule a thread.

This is effectively the difference between *InterruptAttach()* (where an ISR is attached to the IRQ) and *InterruptAttachEvent()* (where a **`struct sigevent`** is bound to the IRQ).

Let's take a look at the prototype for an ISR function and the *InterruptAttach()* and *InterruptAttachEvent()* functions:

```
int
InterruptAttach (int intr,
                 const struct sigevent * (*handler) (void *, int),
                 const void *area,
                 int size,
                 unsigned flags);

int
InterruptAttachEvent (int intr,
                      const struct sigevent *event,
                      unsigned flags);

const struct sigevent *
handler (void *area, int id);
```

Using *InterruptAttach()*

Looking at the prototype for *InterruptAttach()*, the function associates the IRQ vector (*intr*) with your ISR handler (*handler*), passing it a communications area (*area*). The *size* and *flags* arguments aren't germane to our discussion here (they're described in the *Library Reference* for the *InterruptAttach()* function).

For the ISR, the *handler()* function takes a **`void *`** pointer and an **`int`** identification parameter; it returns a **`const struct sigevent *`** pointer. The **`void *`** *area* parameter is the value given to the *InterruptAttach()* function — any value you put in the *area* parameter to *InterruptAttach()* is passed to your *handler()* function. (This is

simply a convenient way of coupling the interrupt handler ISR to some data structure. You're certainly free to pass in a **NULL** value if you wish.)

After it has read some registers from the hardware or done whatever processing is required for servicing, the ISR may or may not decide to schedule a thread to actually do the work. In order to schedule a thread, the ISR simply returns a pointer to a **const struct sigevent** structure — the kernel looks at the structure and delivers the event to the destination. (See the *Library Reference* under **sigevent** for a discussion of event types that can be returned.) If the ISR decides not to schedule a thread, it simply returns a **NULL** value.

As mentioned in the documentation for **sigevent**, the event returned can be a signal or a pulse. You may find that a signal or a pulse is satisfactory, especially if you already have a signal or pulse handler for some other reason.

Note, however, that for ISRs we can also return a SIGEV_INTR. This is a special event that really has meaning only for an ISR and its associated *controlling thread*.

A very simple, elegant, and fast way of servicing interrupts from the thread level is to have a thread dedicated to interrupt processing. The thread attaches the interrupt (via *InterruptAttach()*) and then the thread blocks, waiting for the ISR to tell it to do something. Blocking is achieved via the *InterruptWait()* call. This call blocks until the ISR returns a SIGEV_INTR event:

```
main ()
{
    // perform initializations, etc.
    ...
    // start up a thread that is dedicated to interrupt processing
    pthread_create (NULL, NULL, int_thread, NULL);
    ...
    // perform other processing, as appropriate
    ...
}

// this thread is dedicated to handling and managing interrupts
void *
int_thread (void *arg)
{
```

```
    // enable I/O privilege
    ThreadCtl (_NTO_TCTL_IO, NULL);
    ...
    // initialize the hardware, etc.
    ...
    // attach the ISR to IRQ 3
    InterruptAttach (IRQ3, isr_handler, NULL, 0, 0);
    ...
    // perhaps boost this thread's priority here
    ...
    // now service the hardware when the ISR says to
    while (1)
    {
        InterruptWait (NULL, NULL);
        // at this point, when InterruptWait unblocks,
        // the ISR has returned a SIGEV_INTR, indicating
        // that some form of work needs to be done.


        ...
        // do the work
        ...
        // if the isr_handler did an InterruptMask, then
        // this thread should do an InterruptUnmask to
        // allow interrupts from the hardware
    }
}

// this is the ISR
const struct sigevent *
isr_handler (void *arg, int id)
{
    // look at the hardware to see if it caused the interrupt
    // if not, simply return (NULL);
    ...
    // in a level-sensitive environment, clear the cause of
    // the interrupt, or at least issue InterruptMask to
    // disable the PIC from reinterrupting the kernel
    ...
    // return a pointer to an event structure (preinitialized
    // by main) that contains SIGEV_INTR as its notification type.
    // This causes the InterruptWait in "int_thread" to unblock.
    return (&event);
}
```

In the above code sample, we see a typical way of handling interrupts. The main thread creates a special interrupt-handling thread (*int_thread()*). The sole job of that thread is to service the interrupts at

the thread level. The interrupt-handling thread attaches an ISR to the interrupt (*isr_handler()*), and then waits for the ISR to tell it to do something. The ISR informs (unblocks) the thread by returning an event structure with the notification type set to SIGEV_INTR.

This approach has a number of advantages over using an event notification type of SIGEV_SIGNAL or SIGEV_PULSE:

- The application doesn't have to have a *MsgReceive()* call (which would be required to wait for a pulse).
- The application doesn't have to have a signal-handler function (which would be required to wait for a signal).
- If the interrupt servicing is critical, the application can create the *int_thread()* thread with a high priority; when the SIGEV_INTR is returned from the *isr_handler()* function, if the *int_thread()* function is of sufficient priority, it runs *immediately*. There's no delay as there might be, for example, between the time that the ISR sent a pulse and another thread eventually called a *MsgReceive()* to get it.

The only caveat to be noted when using *InterruptWait()* is that the thread that *attached* the interrupt is the one that must *wait* for the SIGEV_INTR.

Using *InterruptAttachEvent()*

Most of the discussion above for *InterruptAttach()* applies to the *InterruptAttachEvent()* function, with the obvious exception of the ISR. You don't provide an ISR in this case — the kernel notes that you called *InterruptAttachEvent()* and handles the interrupt itself. Since you also bound a **`struct sigevent`** to the IRQ, the kernel can now dispatch the event. The major advantage is that we avoid a context switch into the ISR and back.

An important point to note is that the kernel automatically performs an *InterruptMask()* in the interrupt handler. Therefore, it's up to you to perform an *InterruptUnmask()* when you actually clear the source of the interrupt in your interrupt-handling thread. This is why *InterruptMask()* and *InterruptUnmask()* are counting.

Running out of interrupt events

If you're working with interrupts, you might see an **`Out of Interrupt Events`** error. This happens when the system is no longer able to run user code and is stuck in the kernel, most frequently because:

- The interrupt load is too high for the CPU (it's spending all of the time handling the interrupt).

  Or:

- There's an interrupt handler — one connected with *InterruptAttach()*, not *InterruptAttachEvent()* — that doesn't properly clear the interrupt condition from the device (leading to the case above).

If you call *InterruptAttach()* in your code, look at the handler code first and make sure you're properly clearing the interrupt condition from the device before returning to the OS.

If you encounter this problem, even with all hardware interrupts disabled, it could be caused by misuse or excessive use of software timers.

Advanced topics

Now that we've seen the basics of handling interrupts, let's take a look at some more details and some advanced topics.

Interrupt environment

When your ISR is running, it runs in the context of the process that attached it, except with a different stack. Since the kernel uses an internal interrupt-handling stack for hardware interrupts, your ISR is impacted in that the internal stack is small. Generally, you can assume that you have about 200 bytes available.

The PIC doesn't get the EOI command until *after* all ISRs — whether supplied by your code via *InterruptAttach()* or by the kernel if you use *InterruptAttachEvent()* — for that particular interrupt have been

run. Then the kernel itself issues the EOI; your code should *not* issue the EOI command.

Normally, any interrupt sources that don't have an ISR associated with them are masked off by the kernel. The kernel automatically unmasks an interrupt source when at least one ISR is attached to it and masks the source when no more ISRs are attached.

Ordering of shared interrupts

If you're using interrupt sharing, then by default when you attach an ISR using *InterruptAttach()* or *InterruptAttachEvent()*, the new ISR goes to the beginning of the list of ISRs for that interrupt. You can specifically request that your ISR be placed at the end of the list by specifying a *flags* argument of **_NTO_INTR_FLAGS_END**.

Note that there's no way to specify any other order (e.g. middle, 5th, 2nd, etc.).

Interrupt latency

Another factor of concern for realtime systems is the amount of time taken between the generation of the hardware interrupt and the first line of code executed by the ISR. There are two factors to consider here:

- If any thread in the system calls *InterruptDisable()* or *InterruptLock()*, then no interrupts are processed until the *InterruptEnable()* or *InterruptUnlock()* function call is issued.
- In any event, if interrupts are enabled, the kernel begins executing the first line of the *first* ISR (in case multiple ISRs are associated with an interrupt) in short order (e.g. under 21 CPU instructions on an x86).

Atomic operations

Some convenience functions are defined in the include file **<atomic.h>** — these allow you to perform atomic operations (i.e. operations that are guaranteed to be indivisible or uninterruptible).

Using these functions alleviates the need to disable and enable interrupts around certain small, well-defined operations with variables, such as:

- adding a value
- subtracting a value
- clearing bits
- setting bits
- toggling bits

Variables used in an ISR must be marked as "**`volatile`**".

See the *Library Reference* under *atomic_*()* for more information.

Chapter 7

Heap Analysis: Making Memory Errors a Thing of the Past

In this chapter. . .

Introduction

If you develop a program that dynamically allocates memory, you're also responsible for tracking any memory that you allocate whenever a task is performed, and for releasing that memory when it's no longer required. If you fail to track the memory correctly you may introduce "memory leaks," or unintentionally write to an area outside of the memory space.

Conventional debugging techniques usually prove to be ineffective for locating the source of corruption or leak because memory-related errors typically manifest themselves in an unrelated part of the program. Tracking down an error in a multithreaded environment becomes even more complicated because the threads all share the same memory address space.

In this chapter, we'll introduce you to a special version of our memory management functions that'll help you to diagnose your memory management problems.

Dynamic memory management

In a program, you'll dynamically request memory buffers or blocks of a particular size from the runtime environment using *malloc()*, *realloc()*, or *calloc()*, and then you'll release them back to the runtime environment when they're no longer required using *free()*.

The *memory allocator* ensures that your requests are satisfied by managing a region of the program's memory area known as the *heap*. In this heap, it tracks all of the information — such as the size of the original block — about the blocks and heap buffers that it has allocated to your program, in order that it can make the memory available to you during subsequent allocation requests. When a block is released, it places it on a list of available blocks called a *free list*. It usually keeps the information about a block in the header that precedes the block itself in memory.

The runtime environment grows the size of the heap when it no longer has enough memory available to satisfy allocation requests, and it

returns memory from the heap to the system when the program releases memory.

Heap corruption

Heap corruption occurs when a program damages the allocator's view of the heap. The outcome can be relatively benign and cause a memory leak (where some memory isn't returned to the heap and is inaccessible to the program afterwards), or it may be fatal and cause a memory fault, usually within the allocator itself. A memory fault typically occurs within the allocator when it manipulates one or more of its free lists after the heap has been corrupted.

It's especially difficult to identify the source of corruption when the source of the fault is located in another part of the code base. This is likely to happen if the fault occurs when:

- a program attempts to free memory
- a program attempts to allocate memory after it's been freed
- the heap is corrupted long before the release of a block of memory
- the fault occurs on a subsequent block of memory
- contiguous memory blocks are used
- your program is multithreaded
- the memory allocation strategy changes

Contiguous memory blocks

When contiguous blocks are used, a program that writes outside of the bounds can corrupt the allocator's information about the block of memory it's using, as well as, the allocator's view of the heap. The view may include a block of memory that's before or after the block being used, and it may or may not be allocated. In this case, a fault in the allocator will likely occur during an unrelated allocation or release attempt.

Multithreaded programs

Multithreaded execution may cause a fault to occur in a different thread from the thread that actually corrupted the heap, because threads interleave requests to allocate or release memory.

When the source of corruption is located in another part of the code base, conventional debugging techniques usually prove to be ineffective. Conventional debugging typically applies breakpoints — such as stopping the program from executing — to narrow down the offending section of code. While this may be effective for single-threaded programs, it's often unyielding for multithreaded execution because the fault may occur at an unpredictable time and the act of debugging the program may influence the appearance of the fault by altering the way that thread execution occurs. Even when the source of the error has been narrowed down, there may be a substantial amount of manipulation performed on the block before it's released, particularly for long-lived heap buffers.

Allocation strategy

A program that works in a particular memory allocation strategy may abort when the allocation strategy is changed in a minor way. A good example of this would be a memory overrun condition (for more information see "Overrun and underrun errors," below) where the allocator is free to return blocks that are larger than requested in order to satisfy allocation requests. Under this circumstance, the program may behave normally in the presence of overrun conditions. But a simple change, such as changing the size of the block requested, may result in the allocation of a block of the exact size requested, resulting in a fatal error for the offending program.

Fatal errors may also occur if the allocator is configured slightly differently, or if the allocator policy is changed in a subsequent release of the runtime library. This makes it all the more important to detect errors early in the life cycle of an application, even if it doesn't exhibit fatal errors in the testing phase.

Common sources

Some of the most common sources of heap corruption include:

- a memory assignment that corrupts the header of an allocated block
- an incorrect argument that's passed to a memory allocation function
- an allocator that made certain assumptions in order to avoid keeping additional memory to validate information, or to avoid costly runtime checking
- invalid information that's passed in a request, such as to *free()*.
- overrun and underrun errors
- releasing memory
- using uninitialized or stale pointers

Even the most robust allocator can occasionally fall prey to the above problems.

Let's take a look at the last three bullets in more detail:

Overrun and underrun errors

Overrun and underrun errors occur when your program writes outside of the bounds of the allocated block. They're one of the most difficult type of heap corruption to track down, and usually the most fatal to program execution.

Overrun errors occur when the program writes *past* the end of the allocated block. Frequently this causes corruption in the next contiguous block in the heap, whether or not it's allocated. When this occurs, the behavior that's observed varies depending on whether that block is allocated or free, and whether it's associated with a part of the program related to the source of the error. When a neighboring block that's allocated becomes corrupted, the corruption is usually apparent when that block is released elsewhere in the program. When

an unallocated block becomes corrupted, a fatal error will usually result during a subsequent allocation request. Although this may well be the next allocation request, it's actually dependent on a complex set of conditions that could result in a fault at a much later point in time, in a completely unrelated section of the program, especially when small blocks of memory are involved.

Underrun errors occur when the program writes *before* the start of the allocated block. Often they corrupt the header of the block itself, and sometimes, the preceding block in memory. Underrun errors usually result in a fault that occurs when the program attempts to release a corrupted block.

Releasing memory

Requests to release memory requires your program to track the pointer for the allocated block and pass it to the *free()* function. If the pointer is stale, or if it doesn't point to the exact start of the allocated block, it may result in heap corruption.

A pointer is *stale* when it refers to a block of memory that's already been released. A duplicate request to *free()* involves passing *free()* a stale pointer — there's no way to know whether this pointer refers to unallocated memory, or to memory that's been used to satisfy an allocation request in another part of the program.

Passing a stale pointer to *free()* may result in a fault in the allocator, or worse, it may release a block that's been used to satisfy another allocation request. If this happens, the code making the allocation request may compete with another section of code that subsequently allocated the same region of heap, resulting in corrupted data for one or both. The most effective way to avoid this error is to NULL out pointers when the block is released, but this is uncommon, and difficult to do when pointers are aliased in any way.

A second common source of errors is to attempt to release an interior pointer (i.e. one that's somewhere inside the allocated block rather than at the beginning). This isn't a legal operation, but it may occur when the pointer has been used in conjunction with pointer arithmetic. The result of providing an interior pointer is highly

dependent on the allocator and is largely unpredictable, but it frequently results in a fault in the *free()* call.

A more rare source of errors is to pass an uninitialized pointer to *free()*. If the uninitialized pointer is an automatic (stack) variable, it may point to a heap buffer, causing the types of coherency problems described for duplicate *free()* requests above. If the pointer contains some other nonNULL value, it may cause a fault in the allocator.

Using uninitialized or stale pointers

If you use uninitialized or stale pointers, you might corrupt the data in a heap buffer that's allocated to another part of the program, or see memory overrun or underrun errors.

Detecting and reporting errors

The primary goal for detecting heap corruption problems is to correctly identify the source of the error, rather than getting a fault in the allocator at some later point in time.

A first step to achieving this goal is to create an allocator that's able to determine whether the heap was corrupted on every entry into the allocator, whether it's for an allocation request or for a release request. For example, on a release request, the allocator should be capable of determining whether:

- the pointer given to it is valid
- the associated block's header is corrupt
- either of the neighboring blocks are corrupt

To achieve this goal, we'll use a replacement library for the allocator that can keep additional block information in the header of every heap buffer. This library may be used during the testing of the application to help isolate any heap corruption problems. When a source of heap corruption is detected by this allocator, it can print an error message indicating:

- the point at which the error was detected

- the program location that made the request
- information about the heap buffer that contained the problem

The library technique can be refined to also detect some of the sources of errors that may still elude detection, such as memory overrun or underrun errors, that occur before the corruption is detected by the allocator. This may be done when the standard libraries are the vehicle for the heap corruption, such as an errant call to *memcpy()*, for example. In this case, the standard memory manipulation functions and string functions can be replaced with versions that make use of the information in the debugging allocator library to determine if their arguments reside in the heap, and whether they would cause the bounds of the heap buffer to be exceeded. Under these conditions, the function can then call the error reporting functions to provide information about the source of the error.

Using the `malloc` debug library

The **`malloc`** debug library provides the capabilities described in the above section. It's available when you link to either the normal memory allocator library, or to the debug library:

To access:	Link using this option:
Nondebug library	**`-lmalloc`**
Debug library	**`-lmalloc_g`**

If you use the debug library, you must also include:

`/usr/lib/malloc_g`

as the first entry of your **$LD_LIBRARY_PATH** environment variable before running your application.

Another way to use the debug **`malloc`** library is to use the **LD_PRELOAD** capability to the dynamic loader. The **LD_PRELOAD** environment variable lets you specify libraries to load prior to any other library in the system. In this case, set the

LD_PRELOAD variable to point to the location of the debug **malloc** library (or the nondebug one as the case may be), by saying:

```
LD_PRELOAD=/usr/lib/malloc_g/libmalloc.so.2
```

or:

```
LD_PRELOAD=/usr/lib/libmalloc.so.2
```

In this chapter, all references to the **malloc** library refer to the debug version, unless otherwise specified.

Both versions of the library share the same internal shared object name, so it's actually possible to link against the nondebug library and test using the debug library when you run your application. To do this, you must change the **$LD_LIBRARY_PATH** as indicated above.

The nondebug library doesn't perform heap checking; it provides the same memory allocator as the system library.

By default, the **malloc** library provides a minimal level of checking. When an allocation or release request is performed, the library checks only the immediate block under consideration and its neighbors, looking for sources of heap corruption.

Additional checking and more informative error reporting can be done by using additional calls provided by the **malloc** library. The *mallopt()* function provides control over the types of checking performed by the library. There are also debug versions of each of the allocation and release routines that you can use to provide both file and line information during error-reporting. In addition to reporting the file and line information about the caller when an error is detected, the error-reporting mechanism prints out the file and line information that was associated with the allocation of the offending heap buffer.

To control the use of the **malloc** library and obtain the correct prototypes for all the entry points into it, it's necessary to include a different header file for the library. This header file is included in **<malloc_g/malloc.h>**. If you want to use any of the functions

defined in this header file, other than *mallopt()*, make sure that you link your application with the debug library. If you forget, you'll get undefined references during the link.

The recommended practice for using the library is to always use the library for debug variants in builds. In this case, the macro used to identify the debug variant in C code should trigger the inclusion of the **<malloc_g/malloc.h>** header file, and the **malloc** debug library option should always be added to the link command. In addition, you may want to follow the practice of always adding an exit handler that provides a dump of leaked memory, and initialization code that turns on a reasonable level of checking for the debug variant of the program.

The **malloc** library achieves what it needs to do by keeping additional information in the header of each heap buffer. The header information includes additional storage for keeping doubly-linked lists of all allocated blocks, file, line and other debug information, flags and a CRC of the header. The allocation policies and configuration are identical to the normal system memory allocation routines except for the additional internal overhead imposed by the **malloc** library. This allows the **malloc** library to perform checks without altering the size of blocks requested by the program. Such manipulation could result in an alteration of the behavior of the program with respect to the allocator, yielding different results when linked against the **malloc** library.

All allocated blocks are integrated into a number of allocation chains associated with allocated regions of memory kept by the allocator in *arenas* or *blocks*. The **malloc** library has intimate knowledge about the internal structures of the allocator, allowing it to use short cuts to find the correct heap buffer associated with any pointer, resorting to a lookup on the appropriate allocation chain only when necessary. This minimizes the performance penalty associated with validating pointers, but it's still significant.

The time and space overheads imposed by the **malloc** library are too great to make it suitable for use as a production library, but are

manageable enough to allow them to be used during the test phase of development and during program maintenance.

What's checked?

As indicated above, the **`malloc`** library provides a minimal level of checking by default. This includes a check of the integrity of the allocation chain at the point of the local heap buffer on every allocation request. In addition, the flags and CRC of the header are checked for integrity. When the library can locate the neighboring heap buffers, it also checks their integrity. There are also checks specific to each type of allocation request that are done. Call-specific checks are described according to the type of call below.

You can enable additional checks by using the *mallopt()* call. For more information on the types of checking, and the sources of heap corruption that can be detected, see of "Controlling the level of checking," below.

Allocating memory

When a heap buffer is allocated using any of the heap-allocation routines, the heap buffer is added to the allocation chain for the *arena* or *block* within the heap that the heap buffer was allocated from. At this time, any problems detected in the allocation chain for the arena or block are reported. After successfully inserting the allocated buffer in the allocation chain, the previous and next buffers in the chain are also checked for consistency.

Reallocating memory

When an attempt is made to resize a buffer through a call to the *realloc()* function, the pointer is checked for validity if it's a non-NULL value. If it's valid, the header of the heap buffer is checked for consistency. If the buffer is large enough to satisfy the request, the buffer header is modified, and the call returns. If a new buffer is required to satisfy the request, memory allocation is performed to obtain a new buffer large enough to satisfy the request with the same consistency checks being applied as in the case of memory allocation described above. The original buffer is then released.

If fill-area boundary checking is enabled (described in the "Manual Checking" section) the guard code checks are also performed on the allocated buffer before it's actually resized. If a new buffer is used, the guard code checks are done just before releasing the old buffer.

Releasing memory

This includes, but isn't limited to, checking to ensure that the pointer provided to a *free()* request is correct and points to an allocated heap buffer. Guard code checks may also be performed on release operations to allow fill-area boundary checking.

Controlling the level of checking

The *mallopt()* function call allows extra checks to be enabled within the library. The call to *mallopt()* requires that the application is aware that the additional checks are programmatically enabled. The other way to enable the various levels of checking is to use environment variables for each of the *mallopt()* options. Using environment variables lets the user specify options that will be enabled from the time the program runs, as opposed to only when the code that triggers these options to be enabled (i.e. the *mallopt()* call) is reached. For certain programs that perform a lot of allocations before *main()*, setting options using *mallopt()* calls from *main()* or after that may be too late. In such cases it is better to use environment variables.

The prototype of *mallopt()* is:

```
int mallopt ( int cmd,
              int value );
```

The arguments are:

cmd Options used to enable additional checks in the library.

- MALLOC_CKACCESS
- MALLOC_FILLAREA
- MALLOC_CKCHAIN

value A value corresponding to the command used.

See the Description section for *mallopt()* for more details.

Description of optional checks

MALLOC_CKACCESS

Turn on (or off) boundary checking for memory and string operations. Environment variable: **MALLOC_CKACCESS**.

The *value* argument can be:

- zero to disable the checking
- nonzero to enable it.

This helps to detect buffer overruns and underruns that are a result of memory or string operations. When on, each pointer operand to a memory or string operation is checked to see if it's a heap buffer. If it is, the size of the heap buffer is checked, and the information is used to ensure that no assignments are made beyond the bounds of the heap buffer. If an attempt is made that would assign past the buffer boundary, a diagnostic warning message is printed.

Here's how you can use this option to find an overrun error:

```
...
char *p;
int opt;
opt = 1;
mallopt(MALLOC_CKACCESS, opt);
p = malloc(strlen("hello"));
strcpy(p, "hello, there!");  /* a warning is generated
                                here */
...
```

The following illustrates how access checking can trap a reference through a stale pointer:

```
...

char *p;
int opt;
opt = 1;
mallopt(MALLOC_CKACCESS, opt);
p = malloc(30);
free(p);
strcpy(p, "hello, there!");
```

MALLOC_FILLAREA

Turn on (or off) fill-area boundary checking that validates that the program hasn't overrun the user-requested size of a heap buffer. Environment variable: **MALLOC_FILLAREA**.

The *value* argument can be:

- zero to disable the checking
- nonzero to enable it.

It does this by applying a guard code check when the buffer is released or when it's resized. The guard code check works by filling any excess space available at the end of the heap buffer with a pattern of bytes. When the buffer is released or resized, the trailing portion is checked to see if the pattern is still present. If not, a diagnostic warning message is printed.

The effect of turning on fill-area boundary checking is a little different than enabling other checks. The checking is performed only on memory buffers allocated after the point in time at which the check was enabled. Memory buffers allocated before the change won't have the checking performed.

Here's how you can catch an overrun with the fill-area boundary checking option:

```
...
...
int *foo, *p, i, opt;
opt = 1;
mallopt(MALLOC_FILLAREA, opt);
foo = (int *)malloc(10*4);
for (p = foo, i = 12; i > 0; p++, i--)
    *p = 89;
free(foo);  /* a warning is generated here */
```

MALLOC_CKCHAIN

Enable (or disable) full-chain checking. This option is expensive and should be considered as a last resort when some

code is badly corrupting the heap and otherwise escapes the detection of boundary checking or fill-area boundary checking. Environment variable: **MALLOC_CKCHAIN**.

The *value* argument can be:

- zero to disable the checking
- nonzero to enable it.

This can occur under a number of circumstances, particularly when they're related to direct pointer assignments. In this case, the fault may occur before a check such as fill-area boundary checking can be applied. There are also circumstances in which both fill-area boundary checking and the normal attempts to check the headers of neighboring buffer fail to detect the source of the problem. This may happen if the buffer that's overrun is the first or last buffer associated with a block or arena. It may also happen when the allocator chooses to satisfy some requests, particularly those for large buffers, with a buffer that exactly fits the program's requested size.

Full-chain checking traverses the entire set of allocation chains for all arenas and blocks in the heap every time a memory operation (including allocation requests) is performed. This lets the developer narrow down the search for a source of corruption to the nearest memory operation.

Forcing verification

You can force a full allocation chain check at certain points while your program is executing, without turning on chain checking. Specify the following option for *cmd*:

MALLOC_VERIFY

Perform a chain check immediately. If an error is found, perform error handling. The *value* argument is ignored.

Specifying an error handler

Typically, when the library detects an error, a diagnostic message is printed and the program continues executing. In cases where the allocation chains or another crucial part of the allocator's view is hopelessly corrupted, an error message is printed and the program is aborted (via *abort()*).

You can override this default behavior by specifying a handler that determines what is done when a warning or a fatal condition is detected.

cmd Specify the error handler to use.

MALLOC_FATAL

Specify the malloc fatal handler. Environment variable: **MALLOC_FATAL**.

MALLOC_WARN

Specify the malloc warning handler handler. Environment variable: **MALLOC_WARN**.

value An integer value that indicates which one of the standard handlers provided by the library.

M_HANDLE_ABORT

Terminate execution with a call to *abort()*.

M_HANDLE_EXIT

Exit immediately.

M_HANDLE_IGNORE

Ignore the error and continue.

M_HANDLE_CORE

Cause the program to dump a core file.

M_HANDLE_SIGNAL

Stop the program when this error occurs, by sending itself a stop signal. This lets you one attach to this

process using a debugger. The program is stopped inside the error handler function, and a backtrace from there should show you the exact location of the error.

If you use environment variables to specify options to the **malloc** library for either **MALLOC_FATAL** or **MALLOC_WARN**, you must pass the value that indicates the handler, not its symbolic name.

Handler	Value
M_HANDLE_IGNORE	0
M_HANDLE_ABORT	1
M_HANDLE_EXIT	2
M_HANDLE_CORE	3
M_HANDLE_SIGNAL	4

These values are also defined in **/usr/include/malloc_g/malloc-lib.h**

You can OR any of these handlers with the value, **MALLOC_DUMP**, to cause a complete dump of the heap before the handler takes action.

Here's how you can cause a memory overrun error to abort your program:

```
...
int *foo, *p, i;
int opt;
opt = 1;
mallopt(MALLOC_FILLAREA,  opt);
foo = (int *)malloc(10*4);
for (p = foo, i = 12; i > 0; p++, i--)
    *p = 89;
opt = M_HANDLE_ABORT;
mallopt(MALLOC_WARN, opt);
free(foo); /* a fatal error is generated here */
```

Other environment variables

MALLOC_INITVERBOSE

Enable some initial verbose output regarding other variables that are enabled.

MALLOC_BTDEPTH

Set the depth of the backtrace on CPUs that support deeper backtrace levels. Currently the builtin-return-address feature of **`gcc`** is used to implement deeper backtraces for the debug malloc library. This environment variable controls the depth of the backtrace for allocations (i.e. where the allocation occurred). The default value is 0.

MALLOC_TRACEBT

Set the depth of the backtrace, on CPUs that support deeper backtrace levels. Currently the builtin-return-address feature of **`gcc`** is used to implement deeper backtraces for the debug malloc library. This environment variable controls the depth of the backtrace for errors and warning. The default value is 0.

MALLOC_DUMP_LEAKS

Trigger leak detection on exit of the program. The output of the leak detection is sent to the file named by this variable.

MALLOC_TRACE

Enable tracing of all calls to *malloc(), free(), calloc(), realloc()* etc. A trace of the various calls is made available in the file named by this variable.

MALLOC_CKACCESS_LEVEL

Specify the level of checking performed by the **`MALLOC_CKACCESS`** option. By default, a basic level of checking is performed. By increasing the LEVEL of checking, additional things that could be errors are also flagged. For

example, a call to *memset()* with a length of zero is normally safe, since no data is actually moved. If the arguments, however, point to illegal locations (memory references that are invalid), this normally suggests a case where there is a problem potentially lurking inside the code. By increasing the level of checking, these kinds of errors are also flagged.

Caveats

The debug **`malloc`** library, when enabled with various checking, uses more stack space (i.e. calls more functions, uses more local variables etc.) than the regular **`libc`** allocator. This implies that programs that explicitly set the stack size to something smaller than the default may encounter problems such as running out of stack space. This may cause the program to crash. You can prevent this by increasing the stack space allocated to the threads in question.

MALLOC_FILLAREA is used to do fill-area checking. If fill-area checking isn't enabled, the program can't detected certain types of errors. For example, errors that occur where an application accesses beyond the end of a block, and the real block allocated by the allocator is larger than what was requested, the allocator won't flag an error unless **MALLOC_FILLAREA** is enabled. By default, this environment variable isn't enabled.

MALLOC_CKACCESS is used to validate accesses to the **`str*`** and **`mem*`** family of functions. If this variable isn't enabled, such accesses won't be checked, and errors aren't reported. By default, this environment variable isn't enabled.

MALLOC_CKCHAIN performs extensive heap checking on every allocation. When you enable this environment variable, allocations can be much slower. Also since full heap checking is performed on every allocation, an error anywhere in the heap could be reported upon entry into the allocator for any operation. For example, a call to **`free(x)`** will check block *x*, and also the complete heap for errors before completing the operation (to free block *x*). So any error in the heap will be reported in the context of freeing block *x*, even if the error itself isn't specifically related to this operation.

When the debug library reports errors, it doesn't always exit immediately; instead it continues to perform the operation that causes the error, and corrupts the heap (since that operation that raises the warning is actually an illegal operation). You can control this behavior by using the MALLOC_WARN and MALLOC_FATAL handler described earlier. If specific handlers are not provided, the heap will be corrupted and other errors could result and be reported later because of the first error. The best solution is to focus on the first error and fix it before moving onto other errors. Look at description of **MALLOC_CKCHAIN** for more information on how these errors may end up getting reported.

Although the debug **`malloc`** library allocates blocks to the user using the same algorithms as the standard allocator, the library itself requires additional storage to maintain block information, as well as to perform sanity checks. This means that the layout of blocks in memory using the debug allocator is slightly different than with the standard allocator.

The use of certain optimization options such as **`-O1`**, **`-O2`** or **`-O3`** don't allow the debug **`malloc`** library to work correctly. The problem occurs due to the fact that, during compilation and linking, the **`gcc`** command call the builtin functions instead of the intended functions, e.g. *strcpy()* or *strcmp()*. You should use **`-fno-builtin`** option to circumvent this problem.

Manual checking (bounds checking)

There are times when it may be desirable to obtain information about a particular heap buffer or print a diagnostic or warning message related to that heap buffer. This is particularly true when the program has its own routines providing memory manipulation and the developer wishes to provide bounds checking. This can also be useful for adding additional bounds checking to a program to isolate a problem such as a buffer overrun or underrun that isn't associated with a call to a memory or string function.

In the latter case, rather than keeping a pointer and performing direct manipulations on the pointer, the program may define a pointer type

that contains all relevant information about the pointer, including the current value, the base pointer and the extent of the buffer. Access to the pointer can then be controlled through macros or access functions. The accessors can perform the necessary bounds checks and print a warning message in response to attempts to exceed the bounds.

Any attempt to dereference the current pointer value can be checked against the boundaries obtained when the pointer was initialized. If the boundary is exceeded the *malloc_warning()* function should be called to print a diagnostic message and perform error handling. The arguments are: *file*, *line*, *message*.

Getting pointer information

To obtain information about the pointer, two functions are provided:

find_malloc_ptr()

```
void* find_malloc_ptr ( const void* ptr,
                        arena_range_t* range );
```

This function finds information about the heap buffer containing the given C pointer, including the type of allocation structure it's contained in and the pointer to the header structure for the buffer. The function returns a pointer to the **Dhead** structure associated with this particular heap buffer. The pointer returned can be used in conjunction with the *DH_()* macros to obtain more information about the heap buffer. If the pointer doesn't point into the range of a valid heap buffer, the function returns NULL.

For example, the result from *find_malloc_ptr()* can be used as an argument to *DH_ULEN()* to find out the size that the program requested for the heap buffer in the call to *malloc()*, *calloc()* or a subsequent call to *realloc()*.

_mptr()

```
char* _mptr ( const char* ptr );
```

Return a pointer to the beginning of the heap buffer containing the given C pointer. Information about the size

of the heap buffer can be obtained with a call to *_msize()* or *_musize()* with the value returned from this call.

Getting the heap buffer size

Three interfaces are provided so that you can obtain information about the size of a heap buffer:

_msize()

```
ssize_t _msize( const char* ptr );
```

Return the actual size of the heap buffer given the pointer to the beginning of the heap buffer. The value returned by this function is the actual size of the buffer as opposed to the program-requested size for the buffer. The pointer must point to the beginning of the buffer — as in the case of the value returned by *_mptr()* — in order for this function to work.

_musize()

```
ssize_t _musize( const char* ptr );
```

Return the program-requested size of the heap buffer given the pointer to the beginning of the heap buffer. The value returned by this function is the size argument that was given to the routine that allocated the block, or to a subsequent invocation of *realloc()* that caused the block to grow.

DH_ULEN()

```
DH_ULEN( ptr )
```

Return the program-requested size of the heap buffer given a pointer to the **Dhead** structure, as returned by a call to *find_malloc_ptr()*. This is a macro that performs the appropriate cast on the pointer argument.

Memory leaks

The ability of the malloc library to keep full allocation chains of all the heap memory allocated by the program — as opposed to just accounting for some heap buffers — allows heap memory leaks to be detected by the library in response to requests by the program. Leaks can be detected in the program by performing tracing on the entire heap. This is described in the sections that follow.

Tracing

Tracing is an operation that attempts to determine whether a heap object is reachable by the program. In order to be reachable, a heap buffer must be available either directly or indirectly from a pointer in a global variable or on the stack of one of the threads. If this isn't the case, then the heap buffer is no longer visible to the program and can't be accessed without constructing a pointer that refers to the heap buffer — presumably by obtaining it from a persistent store such as a file or a shared memory object. The set of global variables and stack for all threads is called the root set. Because the root set must be stable for tracing to yield valid results, tracing requires that all threads other than the one performing the trace be suspended while the trace is performed.

Tracing operates by constructing a reachability graph of the entire heap. It begins with a *root set scan* that determines the root set comprising the initial state of the reachability graph. The roots that can be found by tracing are:

- data of the program
- uninitialized data of the program
- initialized and uninitialized data of any shared objects dynamically linked into the program
- used portion of the stacks of all active threads in the program

Once the root set scan is complete, tracing initiates a *mark* operation for each element of the root set. The mark operation looks at a node

of the reachability graph, scanning the memory space represented by the node, looking for pointers into the heap. Since the program may not actually have a pointer directly to the start of the buffer — but to some interior location — and it isn't possible to know which part of the root set or a heap object actually contains a pointer, tracing utilizes specialized techniques for coping with *ambiguous roots*. The approach taken is described as a conservative pointer estimation since it assumes that any word-sized object on a word-aligned memory cell that *could* point to a heap buffer or the interior of that heap buffer actually points to the heap buffer itself.

Using conservative pointer estimation for dealing with ambiguous roots, the mark operation finds all children of a node of the reachability graph. For each child in the heap that's found, it checks to see whether the heap buffer has been marked as *referenced*. If the buffer has been marked, the operation moves on to the next child. Otherwise, the trace marks the buffer, and recursively initiates a mark operation on that heap buffer.

The tracing operation is complete when the reachability graph has been fully traversed. At this time every heap buffer that's reachable will have been marked, as could some buffers that aren't actually reachable, due to the conservative pointer estimation. Any heap buffer that hasn't been marked is definitely unreachable, constituting a memory leak. At the end of the tracing operation, all unmarked nodes can be reported as leaks.

Causing a trace and giving results

A program can cause a trace to be performed and memory leaks to be reported by calling the *malloc_dump_unreferenced()* function provided by the library:

```
int malloc_dump_unreferenced ( int fd,
                               int detail );
```

Suspend all threads, clear the mark information for all heap buffers, perform the trace operation, and print a report of all memory leaks detected. All items are reported in memory order.

fd The file descriptor on which the report should be produced.

detail Indicate how the trace operation should deal with any heap corruption problems it encounters. For a value of:

1 Any problems encountered can be treated as fatal errors. After the error encountered is printed abort the program. No report is produced.

0 Print case errors, and a report based on whatever heap information is recoverable.

Analyzing dumps

The dump of unreferenced buffers prints out one line of information for each unreferenced buffer. The information provided for a buffer includes:

- address of the buffer
- function that was used to allocate it (*malloc(), calloc(), realloc()*)
- file that contained the allocation request, if available
- line number or return address of the call to the allocation function
- size of the allocated buffer

File and line information is available if the call to allocate the buffer was made using one of the library's debug interfaces. Otherwise, the return address of the call is reported in place of the line number. In some circumstances, no return address information is available. This usually indicates that the call was made from a function with no frame information, such as the system libraries. In such cases, the entry can usually be ignored and probably isn't a leak.

From the way tracing is performed we can see that some leaks may escape detection and may not be reported in the output. This happens if the root set or a reachable buffer in the heap has something that looks like a pointer to the buffer.

Likewise, each reported leak should be checked against the suspected code identified by the line or call return address information. If the code in question keeps interior pointers — pointers to a location inside the buffer, rather than the start of the buffer — the trace operation will likely fail to find a reference to the buffer. In this case, the buffer may well not be a leak. In other cases, there is almost certainly a memory leak.

Compiler support

Manual bounds checking can be avoided in circumstances where the compiler is capable of supporting bounds checking under control of a compile-time option. For C compilers this requires explicit support in the compiler. Patches are available for the Gnu C Compiler that allow it to perform bounds checking on pointers in this manner. This will be dealt with later. For C++ compilers extensive bounds checking can be performed through the use of operator overloading and the information functions described earlier.

C++ issues

In place of a raw pointer, C++ programs can make use of a **`CheckedPtr`** template that acts as a smart pointer. The smart pointer has initializers that obtain complete information about the heap buffer on an assignment operation and initialize the current pointer position. Any attempt to dereference the pointer causes bounds checking to be performed and prints a diagnostic error in response an attempt to dereference a value beyond the bounds of the buffer. The **`CheckedPtr`** template is provided in the **`<malloc_g/malloc>`** header for C++ programs.

The checked pointer template provided for C++ programs can be modified to suit the needs of the program. The bounds checking performed by the checked pointer is restricted to checking the actual bounds of the heap buffer, rather than the program requested size.

For C programs it’s possible to compile individual modules that obey certain rules with the C++ compiler to get the behavior of the

CheckedPtr template. C modules obeying these rules are written to a dialect of ANSI C that can be referred to as Clean C.

Clean C

The Clean C dialect is that subset of ANSI C that is compatible with the C++ language. Writing Clean C requires imposing coding conventions to the C code that restrict use to features that are acceptable to a C++ compiler. This section provides a summary of some of the more pertinent points to be considered. It is a mostly complete but by no means exhaustive list of the rules that must be applied.

To use the C++ checked pointers, the module including all header files it includes must be compatible with the Clean C subset. All the system headers for Neutrino as well as the **<malloc_g/malloc.h>** header satisfy this requirement.

The most obvious aspect to Clean C is that it must be strict ANSI C with respect to function prototypes and declarations. The use of K&R prototypes or definitions isn't allowable in Clean C. Similarly, default types for variable and function declarations can't be used.

Another important consideration for declarations is that forward declarations must be provided when referencing an incomplete structure or union. This frequently occurs for linked data structures such as trees or lists. In this case the forward declaration must occur before any declaration of a pointer to the object in the same or another structure or union. For example, a list node may be declared as follows:

```
struct ListNode;
struct ListNode {
   struct ListNode *next;
   void *data;
};
```

Operations on void pointers are more restrictive in C++. In particular, implicit coercions from void pointers to other types aren't allowed including both integer types and other pointer types. Void pointers should be explicitly cast to other types.

The use of **const** should be consistent with C++ usage. In particular, pointers that are declared as **const** must always be used in a compatible fashion. Const pointers can't be passed as non-**const** arguments to functions unless **const** is cast away.

C++ example

Here's how the overrun example from earlier could have the exact source of the error pinpointed with checked pointers:

```
typedef CheckedPtr<int> intp_t;
...
intp_t foo, p;
int i;
int opt;
opt = 1;
mallopt(MALLOC_FILLAREA, opt);
foo = (int *)malloc(10*4);
opt = M_HANDLE_ABORT;
mallopt(MALLOC_WARN, opt);
for (p = foo, i = 12; i > 0; p++, i--)
    *p = 89; /* a fatal error is generated here */
opt = M_HANDLE_IGNORE;
mallopt(MALLOC_WARN, opt);
free(foo);
```

Bounds checking GCC

Bounds checking GCC is a variant of GCC that allows individual modules to be compiled with bounds checking enabled. When a heap buffer is allocated within a checked module, information about the buffer is added to the runtime information about the memory space kept on behalf of the compiler. Attempts to dereference or update the pointer in checked modules invokes intrinsic functions that obtain information about the bounds of the object — it may be stack, heap or an object in the data segment — and checks to see that the reference is in bounds. When an access is out of bounds, the runtime environment generates an error.

The bounds checking variant of GCC hasn't been ported to the Neutrino environment. In order to check objects that are kept within the data segment of the application, the compiler runtime environment

requires some Unix functions that aren't provided by Neutrino. The intrinsics would have to be modified to work in the Neutrino environment.

The model for obtaining information about heap buffers with this compiler is also slightly different than the model employed by the malloc library. Instead of this, the compiler includes an alternative malloc implementation that registers checked heap buffers with a tree data structure outside of the program's control. This tree is used for searches made by the intrinsics to obtain information about checked objects. This technique may take more time than the malloc mechanism for some programs, and is incompatible with the checking and memory leak detection provided by the malloc library. Rather than performing multiple test runs, a port which reimplemented the compiler intrinsics to obtain heap buffer information from the malloc library would be desirable.

Summary

When you develop an application, we recommend that you test it against a debug version that incorporates the malloc library to detect possible sources of memory errors, such as overruns and memory leaks.

The malloc library and the different levels of compiler support can be very useful in detecting the source of overrun errors (which may escape detection during integration testing) during unit testing and program maintenance. However, in this case, more stringent checking for low-level bounds checking of individual pointers may prove useful. The use of the Clean C subset may also help by facilitating the use of C++ templates for low-level checking. Otherwise, you might consider porting the bounds checking variant of GCC to meet your individual project requirements.

Appendix A

Freedom from Hardware and Platform Dependencies

In this appendix. . .

Common problems

With the advent of multiplatform support, which involves non-x86 platforms as well as peripheral chipsets across these multiple platforms, we don't want to have to write different versions of device drivers for each and every platform.

While some platform dependencies are unavoidable, let's talk about some of the things that you as a developer can do to minimize the impact. At QNX Software Systems, we've had to deal with these same issues — for example, we support the 8250 serial chip on several different types of processors. Ethernet controllers, SCSI controllers, and others are no exception.

Let's look at these problems:

- I/O space vs memory-mapped
- Big-endian vs little-endian
- alignment and structure packing
- atomic operations

I/O space vs memory-mapped

The x86 architecture has two distinct address spaces:

- 16-address-line I/O space
- 32-address-line instruction and data space

The processor asserts a hardware line to the external bus to indicate which address space is being referenced. The x86 has special instructions to deal with I/O space (e.g. **`IN AL, DX`** vs **`MOV AL,`** *address*). Common hardware design on an x86 indicates that the control ports for peripherals live in the I/O address space. On non-x86 platforms, this requirement doesn't exist — all peripheral devices are mapped into various locations within the same address space as the instruction and code memory.

Big-endian vs little-endian

Big-endian vs little-endian is another compatibility issue with various processor architectures. The issue stems from the byte ordering of multibyte constants. The x86 architecture is little-endian. For example, the hexadecimal number 0x12345678 is stored in memory as:

```
address contents
      0 0x78
      1 0x56
      2 0x34
      3 0x12
```

A big-endian processor would store the data in the following order:

```
address contents
      0 0x12
      1 0x34
      2 0x56
      3 0x78
```

This issue is worrisome on a number of fronts:

- typecast mangling
- hardware access
- network transparency

The first and second points are closely related.

Typecast mangling

Consider the following code:

```
func ()
{
    long a = 0x12345678;
    char *p;

    p = (char *) &a;
    printf ("%02X\n", *p);
}
```

On a little-endian machine, this prints the value "**0x78**"; on a big-endian machine, it prints "**0x12**". This is one of the big (pardon the pun) reasons that structured programmers generally frown on typecasts.

Hardware access

Sometimes the hardware can present you with a conflicting choice of the "correct" size for a chunk of data. Consider a piece of hardware that has a 4 KB memory window. If the hardware brings various data structures into view with that window, it's impossible to determine *a priori* what the data size should be for a particular element of the window. Is it a 32-bit long integer? An 8-bit character? Blindly performing operations as in the above code sample will land you in trouble, because the CPU will determine what it believes to be the correct endianness, regardless of what the hardware manifests.

Network transparency

These issues are naturally compounded when heterogeneous CPUs are used in a network with messages being passed among them. If the implementor of the message-passing scheme doesn't decide up front what byte order will be used, then some form of identification needs to be done so that a machine with a different byte ordering can receive and correctly decode a message from another machine. This problem has been solved with protocols like TCP/IP, where a defined *network byte order* is always adhered to, even between homogeneous machines whose byte order differs from the network byte order.

Alignment and structure packing

On the x86 CPU, you can access any sized data object at any address (albeit some accesses are more efficient than others). On non-x86 CPUs, you can't — as a general rule, you can access only N-byte objects on an N-byte boundary. For example, to access a 4-byte **long** integer, it must be aligned on a 4-byte address (e.g. 0x7FBBE008). An address like 0x7FBBE009 will cause the CPU to generate a fault. (An x86 processor happily generates multiple bus cycles and gets the data anyway.)

Generally, this will not be a problem with structures defined in the header files for Neutrino, as we've taken care to ensure that the members are aligned properly. The major place that this occurs is with hardware devices that can map a window into the address space (for configuration registers, etc.), and protocols where the protocol itself presents data in an unaligned manner (e.g. CIFS/SMB protocol).

Atomic operations

One final problem that can occur with different families of processors, and SMP configurations in general, is that of atomic access to variables. Since this is so prevalent with interrupt service routines and their handler threads, we've already talked about this in the chapter on Writing an Interrupt Handler.

Solutions

Now that we've seen the problems, let's take a look at some of the solutions you can use. The following header files are shipped standard with Neutrino:

`<gulliver.h>`

isolates big-endian vs little-endian issues

`<hw/inout.h>`

provides input and output functions for I/O or memory address spaces

Determining endianness

The file **`<gulliver.h>`** contains macros to help resolve endian issues. The first thing you may need to know is the target system's endianness, which you can find out via the following macros:

__LITTLEENDIAN__

defined if little-endian

__BIGENDIAN__

defined if big-endian

A common coding style in the header files (e.g. **<gulliver.h>**) is to check which macro is defined and to report an error if none is defined:

```
#if defined(__LITTLEENDIAN__)
// do whatever for little-endian
#elif defined(__BIGENDIAN__)
// do whatever for big-endian
#else
#error ENDIAN Not defined for system
#endif
```

The **#error** statement will cause the compiler to generate an error and abort the compilation.

Swapping data if required

Suppose you need to ensure that data obtained in the host order (i.e. whatever is "native" on this machine) is returned in a particular order, either big- or little-endian. Or vice versa: you want to convert data from host order to big- or little-endian. You can use the following macros (described here as if they're functions for syntactic convenience):

ENDIAN_LE16()

uint16_t ENDIAN_LE16 (uint16_t *var***)**

If the host is little-endian, this macro does nothing (expands simply to *var*); else, it performs a byte swap.

ENDIAN_LE32()

uint32_t ENDIAN_LE32 (uint32_t *var***)**

If the host is little-endian, this macro does nothing (expands simply to *var*); else, it performs a quadruple byte swap.

ENDIAN_LE64()

uint64_t ENDIAN_LE64 (uint64_t *var***)**

If the host is little-endian, this macro does nothing (expands simply to *var*); else, it swaps octets of bytes.

ENDIAN_BE16()

uint16_t ENDIAN_BE16 (uint16_t *var***)**

If the host is big-endian, this macro does nothing (expands simply to *var*); else, it performs a byte swap.

ENDIAN_BE32()

uint32_t ENDIAN_BE32 (uint32_t *var***)**

If the host is big-endian, this macro does nothing (expands simply to *var*); else, it performs a quadruple byte swap.

ENDIAN_BE64()

uint64_t ENDIAN_BE64 (uint64_t *var***)**

If the host is big-endian, this macro does nothing (expands simply to *var*); else, it swaps octets of bytes.

Accessing unaligned data

To access data on nonaligned boundaries, you have to access the data one byte at a time (the correct endian order is preserved during byte access). The following macros (documented as functions for convenience) accomplish this:

UNALIGNED_RET16()

uint16_t UNALIGNED_RET16 (uint16_t ***_addr16_)**

Returns a 16-bit quantity from the address specified by *addr16*.

UNALIGNED_RET32()

uint32_t UNALIGNED_RET32 (uint32_t ****addr32*)**

Returns a 32-bit quantity from the address specified by *addr32*.

UNALIGNED_RET64()

uint64_t UNALIGNED_RET64 (uint64_t ****addr64*)**

Returns a 64-bit quantity from the address specified by *addr64*.

UNALIGNED_PUT16()

void UNALIGNED_PUT16 (uint16_t ****addr16*, uint16_t** *val16***)**

Stores the 16-bit value *val16* into the address specified by *addr16*.

UNALIGNED_PUT32()

void UNALIGNED_PUT32 (uint32_t ****addr32*, uint32_t** *val32***)**

Stores the 32-bit value *val32* into the address specified by *addr32*.

UNALIGNED_PUT64()

void UNALIGNED_PUT64 (uint64_t ****addr64*, uint64_t** *val64***)**

Stores the 64-bit value *val64* into the address specified by *addr64*.

Examples

Here are some examples showing how to access different pieces of data using the macros introduced so far.

Mixed-endian accesses

This code is written to be portable. It accesses *little_data* (i.e. data that's known to be stored in little-endian format, perhaps as a result of some on-media storage scheme), and then manipulates it, writing the data back. This illustrates that the *ENDIAN_*()* macros are bidirectional.

```
uint16_t    native_data;
uint16_t    little_data;

native_data = ENDIAN_LE16 (little_data);// used as "from little-endian"
native_data++;                          // do something with native form
little_data = ENDIAN_LE16 (native_data);// used as "to little-endian"
```

Accessing hardware with dual-ported memory

Hardware devices with dual-ported memory may "pack" their respective fields on nonaligned boundaries. For example, if we had a piece of hardware with the following layout, we'd have a problem:

Address	Size	Name
0x18000000	1	PKTTYPE
0x18000001	4	PKTCRC
0x18000005	2	PKTLEN

Let's see why.

The first field, PKTTYPE, is fine — it's a 1-byte field, which according to the rules could be located anywhere. But the second and third fields aren't fine. The second field, PKTCRC, is a 4-byte object, but it's *not* located on a 4-byte boundary (the address is not evenly divisible by 4). The third field, PKTLEN, suffers from a similar problem — it's a 2-byte field that's not on a 2-byte boundary.

The *ideal* solution would be for the hardware manufacturer to obey the same alignment rules that are present on the target processor, but this isn't always possible. For example, if the hardware presented a raw data buffer at certain memory locations, the hardware would have no idea how you wish to interpret the bytes present — it would simply manifest them in memory.

To access these fields, you'd make a set of manifest constants for their offsets:

```
#define PKTTYPE_OFF     0x0000
```

```
#define PKTCRC_OFF      0x0001
#define PKTLEN_OFF      0x0005
```

Then, you'd map the memory region via *mmap_device_memory()*. Let's say it gave you a **`char *`** pointer called *ptr*. Using this pointer, you'd be tempted to:

```
cr1 = *(ptr + PKTTYPE_OFF);
// wrong!
sr1 = * (uint32_t *) (ptr + PKTCRC_OFF);
er1 = * (uint16_t *) (ptr + PKTLEN_OFF);
```

However, this would give you an alignment fault on non-x86 processors for the *sr1* and *er1* lines.

One solution would be to manually assemble the data from the hardware, byte by byte. And that's exactly what the *UNALIGNED_*()* macros do. Here's the rewritten example:

```
cr1 = *(ptr + PKTTYPE_OFF);
// correct!
sr1 = UNALIGNED_RET32 (ptr + PKTCRC_OFF);
er1 = UNALIGNED_RET16 (ptr + PKTLEN_OFF);
```

The access for *cr1* didn't change, because it was already an 8-bit variable — these are *always* "aligned." However, the access for the 16- and 32-bit variables now uses the macros.

An implementation trick used here is to make the pointer that serves as the base for the mapped area by a **`char *`** — this lets us do pointer math on it.

To write to the hardware, you'd again use macros, but this time the *UNALIGNED_PUT*()* versions:

```
*(ptr + PKTTYPE_OFF) = cr1;
UNALIGNED_PUT32 (ptr + PKTCRC_OFF, sr1);
UNALIGNED_PUT16 (ptr + PKTLEN_OFF, er1);
```

Of course, if you're writing code that should be portable to different-endian processors, you'll want to combine the above tricks with the previous endian macros. Let's define the hardware as

big-endian. In this example, we've decided that we're going to store everything that the program uses in host order and do translations whenever we touch the hardware:

```
cr1 = *(ptr + PKTTYPE_OFF);  // endian neutral
sr1 = ENDIAN_BE32 (UNALIGNED_RET32 (ptr + PKTCRC_OFF));
er1 = ENDIAN_BE16 (UNALIGNED_RET16 (ptr + PKTLEN_OFF));
```

And:

```
*(ptr + PKTTYPE_OFF) = cr1;  // endian neutral
UNALIGNED_PUT32 (ptr + PKTCRC_OFF, ENDIAN_BE32 (sr1));
UNALIGNED_PUT16 (ptr + PKTLEN_OFF, ENDIAN_BE16 (er1));
```

Here's a simple way to remember which *ENDIAN_*()* macro to use. Recall that the *ENDIAN_*()* macros won't change the data on their respective platforms (i.e. the **LE** macro will return the data unchanged on a little-endian platform, and the **BE** macro will return the data unchanged on a big-endian platform). Therefore, to access the data (which we know has a *defined* endianness), we effectively want to select the *same macro as the type of data*. This way, if the platform is the same as the type of data present, no changes will occur (which is what we expect).

Accessing I/O ports

When porting code that accesses hardware, the x86 architecture has a set of instructions that manipulate a separate address space called the *I/O address space*. This address space is completely separate from the memory address space. On non-x86 platforms (MIPS, PPC, etc.), such an address space doesn't exist — all devices are mapped into memory.

In order to keep code portable, we've defined a number of functions that isolate this behavior. By including the file **<hw/inout.h>**, you get the following functions:

in8() Reads an 8-bit value.

in16(), inbe16(), inle16()

Reads a 16-bit value.

in32(), inbe32(), inle32()
: Reads a 32-bit value.

in8s()
: Reads a number of 8-bit values.

in16s()
: Reads a number of 16-bit values.

in32s()
: Reads a number of 32-bit values.

out8()
: Writes a 8-bit value.

out16(), outbe16(), outle16()
: Writes a 16-bit value.

out32(), outbe32(), outle32()
: Writes a 32-bit value.

out8s()
: Writes a number of 8-bit values.

out16s()
: Writes a number of 16-bit values.

out32s()
: Writes a number of 32-bit values.

On the x86 architecture, these functions perform the machine instructions **`in`**, **`out`**, **`rep ins*`**, and **`rep outs*`**. On non-x86 architectures, they dereference the supplied address (the *addr* parameter) and perform memory accesses.

The bottom line is that code written for the x86 will be portable to MIPS and PPC. Consider the following fragment:

```
iir = in8 (baseport);
if (iir & 0x01) {
    return;
}
```

On an x86 platform, this will perform **`IN AL, DX`**, whereas on a MIPS or PPC, it will dereference the 8-bit value stored at location *baseport*.

Note that the calling process must use *mmap_device_io()* to access the device's I/O registers.

Appendix B

Conventions for Makefiles and Directories

In this appendix. . .

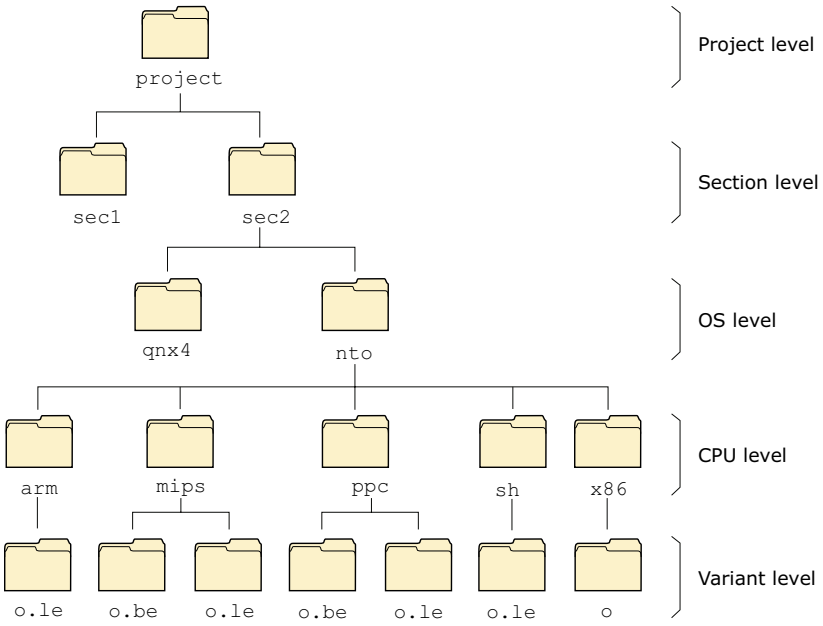
In this appendix, we'll take a look at the supplementary files used in the Neutrino development environment. Although we use the standard **`make`** command to create libraries and executables, you'll notice we use some of our own conventions in the **`Makefile`** syntax.

We'll start with a general description of a full, multiplatform source tree. Then we'll look at how you can build a tree for your products. Finally, we'll wrap up with a discussion of some advanced topics, including collapsing unnecessary levels and performing partial builds.

Although you're certainly not obliged to use our format for the directory structure and related tools, you may choose to use it because it's convenient for developing multiplatform code.

Structure

Here's a sample directory tree for a product that can be built for two different operating systems (QNX 4 and Neutrino), on five CPU platforms (x86, MIPS, PowerPC, ARM, and SH4), with both endian combinations on the MIPS and PowerPC:



Source tree for a multiplatform project.

We'll talk about the names of the directory levels shortly. At each directory level is a **`Makefile`** file used by the **`make`** utility to determine what to do in order to make the final executable.

However, if you examine the makefiles, you can see that most of them simply contain:

```
include recurse.mk
```

Why do we have makefiles at every level? Because **`make`** can recurse into the bottommost directory level (the Variant level in the diagram). That's where the actual work of building the product occurs. This means that you could type **`make`** at the topmost directory, and it would go into all the subdirectories and compile everything. Or you could type **`make`** from a particular point in the tree, and it would compile only what's needed from that point down.

We'll discuss how to cause **make** to compile only certain parts of the source tree, even if invoked from the top of the tree, in the "Advanced topics" section.

When deciding where to place source files, as a rule of thumb you should place them as high up in the directory tree as possible. This not only reduces the number of directory levels to traverse when looking for source, but also encourages you to develop source that's as generic (i.e. non-OS, non-CPU, and non-board-specific) as possible. Lower directory levels are reserved for more and more specific pieces of source code.

If you look at the source tree that we ship, you'll notice that we follow the directory structure defined above, but with a few shortcuts. We'll cover those shortcuts in the "Advanced Topics" section.

Makefile structure

As mentioned earlier, the makefile structure is almost identical, regardless of the level that the makefile is found in. All makefiles (except the bottommost level) include the **recurse.mk** file and may set one or more macros.

Here's an example of one of our standard (nonbottommost) **Makefile**s:

```
LATE_DIRS=boards
include recurse.mk
```

The recurse.mk file

The **recurse.mk** file resides under **/usr/include/mk**. This directory contains other files that are included within makefiles. Note that while the **make** utility automatically searches **/usr/include**, we've created symbolic links from there to **/usr/include/mk**.

The **recurse.mk** include file is typically used by higher-level makefiles to recurse into lower-level makefiles. All subdirectories

present are scanned for files called **makefile** or **Makefile**. Any subdirectories that contain such files are recursed into, then **make** is invoked from within those directories, and so on, down the directory tree.

The special filename **Makefile.dnm** ("dnm" stands for "Do Not Make") can be placed next to a real **Makefile** to cause **recurse.mk** *not* to descend into that directory. The contents of **Makefile.dnm** aren't examined in any way — you can use **touch** to create an empty file for it.

Macros

The example given above uses the LATE_DIRS macro. Here are the macros that can be placed within a makefile:

- EARLY_DIRS
- LATE_DIRS
- LIST
- MAKEFILE
- CHECKFORCE

The EARLY_DIRS and LATE_DIRS macros

To give you some control over the ordering of the directories, the macros EARLY_DIRS and LATE_DIRS specify directories to be recursed into *before* or *after* all others. You'd use this facility with directory trees that contain one directory that depends on another directory at the same level — you want the independent directory to be done first, followed by the dependent directory.

In our example above, we've specified a LATE_DIRS value of **boards**, because the **boards** directory depends on the library directory (**lib**).

Note that the EARLY_DIRS and LATE_DIRS macros accept a list of directories. The list is treated as a group, with no defined ordering *within* that group.

The LIST macro

The LIST macro serves as a tag for the particular directory level that the makefile is found in.

The LIST macro can contain a list of names that are separated by spaces. This is used when we squash directory levels together; see "Advanced Topics," later in this appendix.

Here are the common values corresponding to the directory levels:

- VARIANT
- CPU
- OS

Note that you're free to define whatever values you wish — these are simply conventions that we've adopted for the three directory levels specified. See the section on "More uses for LIST," below.

Once the directory has been identified via a tag in the makefile, you can specifically exclude or include the directory and its descendents in a **`make`** invocation. See "Performing partial builds" below.

The MAKEFILE macro

The MAKEFILE macro identifies the name of the makefile that **`recurse.mk`** should search for in the child directories. Normally this is **`[Mm]akefile`**, but you can set it to anything you wish by changing the MAKEFILE macro. For example, in a GNU **`configure`**-style makefile, you'd set it to **`GNUmakefile`** (see "GNU **`configure`**," later in this appendix.

The CHECKFORCE macro

The CHECKFORCE macro is a trigger. Its actual value is unimportant, but if you set it, the **`recurse.mk`** file looks for **`Makefile.force`** files in the subdirectories. If it finds one, that directory is recursed into, even if the LIST macro settings would normally prevent this from happening.

Directory structure

Let's look at the directory levels themselves in some detail. Note that you can add as many levels as you want *above* the levels described here — these levels would reflect your product. For example, in a factory automation system, the product would consist of the *entire* system — you would then have several subdirectories under that directory level to describe various projects within that product (e.g. **`gui`**, **`pidloop`**, **`robot_plc`**, etc.).

The project level

The project level directory is used mainly to store the bulk of the source code and other directories. These directories would be structured logically around the project being developed. For our factory-automation example, a particular project level might be the **`gui`** directory, which would contain the source code for the graphical user interface as well as further subdirectories.

The section level (optional)

The section level directory is used to contain the source base relevant to a part of the project. It may be omitted if not required; see "Collapsing unnecessary directory levels," below.

The OS level

If you were building products to run on multiple operating systems, you'd include an OS level directory structure. This would serve as a branchpoint for OS-specific subdirectories. In our factory-floor example, the **`gui`** section might be built for both QNX 4 and Neutrino, whereas the other sections might be built just for Neutrino.

If no OS level is detected, Neutrino is assumed.

The CPU level

Since we're building executables and libraries for multiple platforms, we need a place to serve as a branchpoint for the different CPUs.

Generally, the CPU level would contain nothing but subdirectories for the various CPUs, but it may also contain CPU-specific source files.

The variant level

Finally, the variant level contains object, library, or executable files specific to a particular variant of the processor. For example, a MIPS processor could operate in big-endian or little-endian mode. In that case, we'd have to generate two different sets of output modules. On the other hand, an x86 processor is a little-endian machine only, so we need to build only one set of output modules.

Specifying options

At the project level, there's a file called **`common.mk`**.

This file contains any special flags and settings that need to be in effect in order to compile and link.

At the bottommost level (the variant level), the format of the makefile is different — it *doesn't* include **`recurse.mk`**, but instead includes **`common.mk`** (from the project level).

The `common.mk` file

The **`common.mk`** include file is where you put the traditional makefile options, such as compiler options.

In order for the **`common.mk`** makefile to be able to determine which system to build the particular objects, libraries, or executables for, we analyze the pathname components in the bottommost level *in reverse order* as follows:

- the last component is assigned to the VARIANT1 macro
- the next previous component is assigned to the CPU macro
- the next previous component is assigned to the OS macro
- the next previous component is assigned to the SECTION macro
- the next previous component is assigned to the PROJECT macro

For example, if we have a pathname of **/source/factory/robot_plc/driver/nto/mips/o.be**, then the macros are set as follows:

Macro	Value
VARIANT1	**o.be**
CPU	**mips**
OS	**nto**
SECTION	**driver**
PROJECT	**robot_plc**

The variant-level makefile

The variant-level makefile (i.e. the bottommost makefile in the tree) contains the single line:

```
include ../../common.mk
```

The number of **../** components must be correct to get at the **common.mk** include file, which resides in the project level of the tree. The reason that the number of **../** components isn't necessarily the same in all cases has to do with whether directory levels are being collapsed.

Recognized variant names

Variant names can be combined into a *compound variant*; use a period (**.**), dash (**-**) or slash (**/**) between the variants.

The common makefiles are triggered by a number of distinguished variant names:

a The image being built is an object library.

so The image being built is a shared object.

dll The image being built is a DLL; it's linked with the **-Bsymbolic** option (see **ld** in the *Utilities Reference*).

If the compound variant doesn't include **a**, **so**, or **dll**, an executable is being built.

shared Compile the object files for **.so** use, but don't create an actual shared object. You typically use this name in an **a.shared** variant to create a static link archive that can be linked into a shared object.

g Compile and link the source with the debugging flag set.

be, **le** Compile and link the source to generate big (if **be**) or little (if **le**) endian code. If a CPU supports bi-endian operation, one of these variants should always be present in the compound variant name. Conversely, if the CPU is mono-endian, neither **be** nor **le** should be specified in the compound variant.

gcc Use the GCC (**gcc**) compiler to compile the source. If you don't specify a compiler, the makefiles provide a default.

o This is the NULL variant name. It's used when building an image that doesn't really have any variant components to it (e.g an executable for an x86 CPU, which doesn't support bi-endian operation).

Variant names can be placed in any order in the compound variant, but to avoid confusing a source configuration management tool (e.g. CVS), make sure that the last variant in the list never looks like a generated file suffix. In other words, don't use variant names ending in **.a**, **.so**, or **.o**.

The following table lists some examples:

Variant	Purpose
g.le	A debugging version of a little-endian executable.
so.be	A big-endian version of a shared object.
403.be	A user-defined “403” variant for a big-endian system.

The only valid characters for variant names are letters, digits, and underscores (_).

In order for the source code to tell what variant(s) it’s being compiled for, the common makefiles arrange for each variant name to be postfixed to the string VARIANT_ and have that defined as a C or assembler macro on the command line. For example, if the compound variant is **so.403.be**, the following C macros are defined: VARIANT_so, VARIANT_403, and VARIANT_be. Note that neither VARIANT_be nor VARIANT_le is defined on a CPU that doesn’t support bi-endian operation, so any endian-specific code should always test for the C macros __LITTLEENDIAN__ or __BIGENDIAN__ (instead of VARIANT_le or VARIANT_be) to determine what endianness it’s running under.

Using the standard macros and include files

We’ve described the pieces you’ll provide when building your system, including the **common.mk** include file. There are two other include files to discuss:

- **qconfig.mk**
- **qmacros.mk**

We’ll also look at some of the macros that are set or used by those include files.

The `qconfig.mk` include file

Since the common makefiles have a lot of defaults based on the names of various directories, you can simplify your life enormously in the **`common.mk`** include file if you choose your directory names to match what the common makefiles want. For example, if the name of the project directory is the same as the name of the image, you don't have to set the NAME macro in **`common.mk`**.

The prototypical **`common.mk`** file looks like this:

```
ifndef QCONFIG
QCONFIG=qconfig.mk
endif
include $(QCONFIG)

# Preset make macros go here

include $(MKFILES_ROOT)/qtargets.mk

# Post-set make macros go here
```

The **`qconfig.mk`** include file provides the root paths to various install, and usage trees on the system, along with macros that define the compilers and some utility commands that the makefiles use. The purpose of the **`qconfig.mk`** include file is to let you tailor the root directories, compilers, and commands used at your site, if they differ from the standard ones that we use and ship. Therefore, nothing in a project's makefiles should refer to a compiler name, absolute path, or command name directly. Always use the **`qconfig.mk`** macros.

The **`qconfig.mk`** file resides in **`/usr/include/mk`** as **`qconf-`***os*`.mk`** (where *os* is the host OS, e.g. nto, qnx4, solaris, NT), which is a symbolic link from the place where **`make`** wants to find it (namely **`/usr/include/qconfig.mk`**). You can override the location of the include file by specifying a value for the QCONFIG macro.

If you wish to override the values of some of the macros defined in **`qconfig.mk`** without modifying the contents of the file, set the **QCONF_OVERRIDE** environment variable (or **`make`** macro) to be the name of a file to include at the end of the main **`qconfig.mk`** file.

Preset macros

Before including **qtargets.mk**, some macros need to be set to determine things like what additional libraries need to be searched in the link, the name of the image (if it doesn't match the project directory name), and so on. This would be done in the area tagged as "**Preset make macros go here**" in the sample above.

Postset macros

Following the include of **qtargets.mk**, you can override or (more likely) add to the macros set by **qtargets.mk**. This would be done in the area tagged as "**Post-set make macros go here**" in the sample above.

qconfig.mk macros

Here's a summary of the macros available from **qconfig.mk**:

CP_HOST	Copy files from one spot to another.
LN_HOST	Create a symbolic link from one file to another.
RM_HOST	Remove files from the filesystem.
TOUCH_HOST	Update a file's access and modification times.
PWD_HOST	Print the full path of the current working directory.
CL_*which*	Compile and link.
CC_*which*	Compile C/C++ source to an object file.
AS_*which*	Assemble something to an object file.
AR_*which*	Generate an object file library (archive).
LR_*which*	Link a list of objects/libraries to a relocatable object file.
LD_*which*	Link a list of objects/libraries to a executable/shared object.

UM_*which* Add a usage message to an executable.

The *which* parameter can be either the string HOST for compiling something for the host system or a triplet of the form *os_cpu_compiler* to specify a combination of target OS and CPU, as well as the compiler to be used.

The *os* would usually be the string **nto** to indicate Neutrino. The *cpu* would be one of **x86**, **mips**, **ppc**, **arm** or **sh**. Finally, the compiler would be one of **gcc**.

For example, the macro CC_nto_x86_gcc would be used to specify:

- the compilation tool
- a Neutrino target system
- an x86 platform
- the GNU GCC compiler

The following macro would contain the command-line sequence required to invoke the GCC compiler:

```
CC_nto_x86_gcc = qcc -Vgcc_ntox86 -c
```

The macros CP_HOST, LN_HOST, RM_HOST, TOUCH_HOST, and PWD_HOST are used by the various makefiles to decouple the OS commands from the commands used to perform the given actions. For example, under most POSIX systems, the CP_HOST macro expands to the **cp** utility. Under other operating systems, it may expand to something else (e.g. **copy**).

In addition to the macros mentioned above, you can use the following macros to specify options to be placed at the end of the corresponding command lines:

- CLPOST_*which*
- CCPOST_*which*
- ASPOST_*which*

- ARPOST_*which*
- LRPOST_*which*
- LDPOST_*which*
- UMPOST_*which*

The parameter "*which*" is the same as defined above: either the string "HOST" or the ordered triplet defining the OS, CPU, and compiler.

For example, specifying the following:

```
CCPOST_nto_x86_gcc = -ansi
```

would cause the command line specified by **CC_nto_x86_gcc** to have the additional string "**-ansi**" appended after it.

The `qrules.mk` include file

The **qrules.mk** include file has the definitions for compiling.

The following macros can be set and/or inspected when **qrules.mk** is used. Since the **qtargets.mk** file includes **qrules.mk**, these are available there as well. Don't modify those that are marked "(read-only)."

VARIANT_LIST (read-only)
: A space-separated list of the variant names macro. Useful with the **$(filter ...) make** function for picking out individual variant names.

CPU
: The name of the target CPU. Defaults to the name of the next directory up with all parent directories stripped off.

CPU_ROOT (read-only)
: The full pathname of the directory tree up to and including the OS level.

OS
: The name of the target OS. Defaults to the name of the directory two levels up with all parent directories stripped off.

OS_ROOT (read-only)
: The full pathname of the directory tree up to and including the OS level.

SECTION
: The name of the section. Set only if there's a section level in the tree.

SECTION_ROOT (read-only)
: The full pathname of the directory tree up to and including the section level.

PROJECT (read-only)
: The *basename()* of the directory containing the **`common.mk`** file.

PROJECT_ROOT (read-only)
: The full pathname of the directory tree up to and including the project level.

PRODUCT (read-only)
: The *basename()* of the directory above the project level.

PRODUCT_ROOT (read-only)
: The full pathname of the directory tree up to and including the product level.

NAME
: The *basename()* of the executable or library being built. Defaults to $(PROJECT).

SRCVPATH
: A space-separated list of directories to search for source files. Defaults to all the directories from the current working directory up to and including the project root directory. You'd almost never want to set this; use EXTRA_SRCVPATH to add paths instead.

EXTRA_SRCVPATH

Added to the end of SRCVPATH. Defaults to none.

INCVPATH — A space-separated list of directories to search for include files. Defaults to $(SRCVPATH) plus $(USE_ROOT_INCLUDE). You'd almost never want to set this; use EXTRA_INCVPATH to add paths instead.

EXTRA_INCVPATH

Added to INCVPATH just before the $(USE_ROOT_INCLUDE). Default is none.

LIBVPATH — A space-separated list of directories to search for library files. Defaults to:

```
. $(INSTALL_ROOT_support)/$(OS)/$(CPUDIR)/lib $(USE_ROOT_LIB).
```

You'll almost never want to use this; use EXTRA_LIBVPATH to add paths instead.

EXTRA_LIBVPATH

Added to LIBVPATH just before $(INSTALL_ROOT_support)**/**$(OS)**/**$(CPUDIR)**/lib**. Default is none.

DEFFILE — The name of an assembler define file created by **mkasmoff**. Default is none.

SRCS — A space-separated list of source files to be compiled. Defaults to all ***.s**, ***.S**, ***.c**, and ***.cc** files in SRCVPATH.

EXCLUDE_OBJS

A space-separated list of object files *not* to be included in the link/archive step. Defaults to none.

EXTRA_OBJS — A space-separated list of object files to be added to the link/archive step even though they don't have

corresponding source files (or have been excluded by EXCLUDE_OBJS). Default is none.

OBJPREF_*object*, OBJPOST_*object*

Options to add before or after the specified object:

```
OBJPREF_object = options
OBJPOST_object = options
```

The *options* string is inserted verbatim. Here's an example:

```
OBJPREF_libc_cut.a = -Wl,--whole-archive
OBJPOST_libc_cut.a = -Wl,--no-whole-archive
```

LIBS

A space-separated list of library stems to be included in the link. Default is none.

LIBPREF_*library*, LIBPOST_*library*

Options to add before or after the specified library:

```
LIBPREF_library = options
LIBPOST_library = options
```

The *options* string is inserted verbatim.

You can use these macros to link some libraries statically and others dynamically. For example, here's how to bind **libmystat.a** and **libmydyn.so** to the same program:

```
LIBS += mystat mydyn

LIBPREF_mystat = -Bstatic
LIBPOST_mystat = -Bdynamic
```

This places the **`-Bstatic`** option just before **`-lmystat`**, and **`-Bdynamic`** right after it, so that only that library is linked statically.

CCFLAGS — Flags to add to the C compiler command line.

ASFLAGS — Flags to add to the assembler command line.

LDFLAGS — Flags to add to the linker command line.

VFLAG_*which* — Flags to add to the command line for C compiles, assemblies, and links; see below.

CCVFLAG_*which*

Flags to add to C compiles; see below.

ASVFLAG_*which*

Flags to add to assemblies; see below.

LDVFLAG_*which*

Flags to add to links; see below.

OPTIMIZE_TYPE

The optimization type; one of:

- OPTIMIZE_TYPE=TIME — optimize for execution speed
- OPTIMIZE_TYPE=SIZE — optimize for executable size (the default)
- OPTIMIZE_TYPE=NONE — turn off optimization

Note that for the VFLAG_*which*, CCVFLAG_*which*, ASVFLAG_*which*, and LDVFLAG_*which* macros, the *which* part is the name of a variant. This combined macro is passed to the appropriate command line. For example, if there were a variant called "403," then the macro VFLAG_403 would be passed to the C compiler, assembler, and linker.

Don't use this mechanism to define a C macro constant that you can test in the source code to see if you're in a particular variant. The makefiles do that automatically for you. Don't set the *VFLAG_* macros for any of the distinguished variant names (listed in the "Recognized variant names" section, above). The common makefiles will get confused if you do.

The `qtargets.mk` include file

The **`qtargets.mk`** include file has the linking and installation rules.

The following macros can be set and/or inspected when **`qtargets.mk`** is used:

INSTALLDIR — Subdirectory where the executable or library is to be installed. Defaults to **`bin`** for executables and **`lib/dll`** for DLLs. If set to **`/dev/null`**, then no installation is done.

USEFILE — The file containing the usage message for the application. Defaults to none for archives and shared objects and to $(PROJECT_ROOT)**`/`**$(NAME)**`.use`** for executables. The application-specific makefile can set the macro to a null string, in which case nothing is added to the executable.

LINKS — A space-separated list of symbolic link names that are aliases for the image being installed. They're placed in the same directory as the image. Default is none.

PRE_TARGET, POST_TARGET — Extra steps to do before/after the main target.

PRE_CLEAN, POST_CLEAN — Extra steps to do before/after **`clean`** target.

PRE_ICLEAN, POST_ICLEAN

Extra steps to do before/after **`iclean`** target.

PRE_HINSTALL, POST_HINSTALL

Extra steps to do before/after **`hinstall`** target.

PRE_CINSTALL, POST_CINSTALL

Extra steps to do before/after **`cinstall`** target.

PRE_INSTALL, POST_INSTALL

Extra steps to do before/after **`install`** target.

PRE_BUILD, POST_BUILD

Extra steps to do before/after building the image.

SO_VERSION — Set the SONAME version number when building a shared object (the default is 1).

PINFO — Define information to go into the **`*.pinfo`** file.

For example, you can use the PINFO NAME option to to keep a permanent record of the original filename of a binary. If you use this option, the name that you specify appears in the information from the **`use -i`** *filename* command. Otherwise, the information from **`use -i`** contains the NAME entry specified outside of the PINFO define.

For more information about PINFO, see the *hook_pinfo()* function described below for the GNU **`configure`** command.

Advanced topics

In this section, we'll discuss how to:

- collapse unnecessary directory levels
- perform partial builds
- use GNU **`configure`**

Collapsing unnecessary directory levels

The directory structure shown above (in "Structure") defines the complete tree — every possible directory level is shown. In the real world, however, some of these directory levels aren't required. For example, you may wish to build a particular module for a PowerPC in little-endian mode and *never* need to build it for anything else (perhaps due to hardware constraints). Therefore, it seems a waste to have a variant level that has only the directory **`o.le`** and a CPU level that has only the directory **`ppc`**.

In this situation, you can *collapse* unnecessary directory components out of the tree. You do this by simply separating the name of the components with dashes (**`-`**) rather than slashes (**`/`**).

For example, in our source tree (**`/usr/src/hardware`**), let's look at the **`startup/boards/800fads/ppc-be`** makefile:

```
include ../common.mk
```

In this case, we've specified both the variant (as "be" for big-endian) and the CPU (as "ppc" for PowerPC) with a single directory.

Why did we do this? Because the **`800fads`** directory refers to a very specific board — it's not going to be useful for anything other than a PowerPC running in big-endian mode.

In this case, the makefile macros would have the following values:

Macro	Value
VARIANT1	ppc-be
CPU	ppc
OS	nto (default)
SECTION	800fads
PROJECT	boards

The **addvariant** command knows how to create both the squashed and unsquashed versions of the directory tree. You should always use it when creating the OS, CPU, and variant levels of the tree.

Performing partial builds

By using the LIST tag in the makefile, you can cause the **make** command to perform a partial build, even if you're at the top of the source tree.

If you were to simply type **make** without having used the LIST tag, all directories would be recursed into and everything would be built.

However, by defining a macro on **make**'s command line, you can:

- recurse into only the specified tagged directories

  Or:

- recurse into all of the directories except for the specified tagged ones

Let's consider an example. The following (issued from the top of the source tree):

```
make CPULIST=x86
```

causes only the directories that are at the CPU level and below (and tagged as LIST=CPU), *and that are called x86*, to be recursed into.

You can specify a space-separated list of directories (note the use of quoting in the shell to capture the space character):

```
make "CPULIST=x86 mips"
```

This causes the x86 *and* MIPS versions to be built.

There's also the inverse form, which causes the specific lists *not* to be built:

```
make EXCLUDE_CPULIST=ppc
```

This causes everything *except* the PowerPC versions to be built.

As you can see from the above examples, the following are all related to each other via the CPU portion:

- LIST=CPU
- CPULIST
- EXCLUDE_CPULIST

More uses for LIST

Besides using the standard LIST values that we use, you can also define your own. Therefore, in certain makefiles, you'd put the following definition:

```
LIST=CONTROL
```

Then you can decide to build (or prevent from building) various subcomponents marked with CONTROL. This might be useful in a very big project, where compilation times are long and you need to test only a particular subsection, even though other subsections may be affected and would ordinarily be made.

For example, if you had marked two directories, **`robot_plc`** and **`pidloop`**, with the LIST=CONTROL macro within the makefile, you could then make just the **`robot_plc`** module:

```
make CONTROLLIST=robot_plc
```

Or make both (note the use of quoting in the shell to capture the space character):

```
make "CONTROLLIST=robot_plc pidloop"
```

Or make everything *except* the **`robot_plc`** module:

```
make EXCLUDE_CONTROLLIST=robot_plc
```

Or make only the **`robot_plc`** module for MIPS big-endian:

```
make CONTROLLIST=robot_plc CPULIST=mips VARIANTLIST=be
```

GNU `configure`

The way things are being done now can be used with any future third-party code that uses a GNU **`./configure`** script for configuration.

The steps given below shouldn't overwrite any existing files in the project; they just add new ones.

Here's how to set up a project:

1. Go to the root directory of your project.
2. Use **`addvariant`** to create a **`Makefile`** in the project root directory that looks like this:

```
LIST=OS CPU VARIANT
MAKEFILE=GNUmakefile
include recurse.mk
```

3. Now, create a directory (or directories) of the form *os*`-`*cpu*`-`*variant*, e.g. **`nto-x86-o`** or **`nto-mips-le`**. This the same as our common makefiles, except that rather than being in different directories, all the levels are squashed together (which **`recurse.mk`** knows because it has multiple recursion control variables specified).

   You can add further variants following the first ones, if there are additional different variations that you need to build.

   For example, the GCC directories look like:
   `nto-x86-o-ntoarm` for the Neutrino/X86 hosted, Neutrino/ARM targeted compiler, or
   `solaris-sparc-o-ntox86` for the Solaris/Sparc hosted, Neutrino/X86 targeted compiler.

4. In each of the new directories, use **`addvariant`** to create a file called a **`GNUmakefile`** (note the name!) that looks like this:

```
ifndef QCONFIG
QCONFIG=qconfig.mk
endif
include $(QCONFIG)
```

```
include $(MKFILES_ROOT)/qmake-cfg.mk
```

5. In the root of the project, create a **build-hooks** file. It's a shell script, so it needs be marked as executable. It needs to define one or more of the following shell functions (described in more detail below):

   - *hook_preconfigure()*
   - *hook_postconfigure()*
   - *hook_premake()*
   - *hook_postmake()*
   - *hook_pinfo()*

Every time that you type **make** in one of the newly created directories, the **GNUmakefile** is read (a small trick that works only with GNU **make**). **GNUmakefile** in turn invokes the **/usr/include/mk/build-cfg** script, which notices whether or not **configure** has been run in the directory:

- If it hasn't, **build-cfg** invokes the *hook_preconfigure()* function, then the project's **configure**, and then the *hook_postconfigure()* function.
- If the configure has already been done, or we just did it successfully, **build-cfg** invokes the *hook_premake()*, then does a **make -fMakefile**, then *hook_postmake()*, then *hook_pinfo()*.

If a function isn't defined in **build-hooks**, **build-cfg** doesn't bother trying to invoke it.

Within the **build-hooks** script, the following variables are available:

SYSNAME	This is the host OS (e.g. **nto**, **solaris**) that we're running on. This is automatically set by **build-cfg** based on the results of **uname**.

TARGET_SYSNAME

This is the target OS (e.g. **nto**, **win32**) that we're going to be generating executables for. It's set automatically by **build-cfg**, based on the directory that you're in.

make_CC — This variable is used to set the CC **make** variable when we invoke **make**. This typically sets the compiler that **make** uses. It's set automatically by **build-cfg**, based on the directory that you're in.

make_opts — Any additional options that you want to pass to **make** (the default is **""**).

make_cmds — The command goals passed to **make** (e.g. **all**). It's set automatically by **build-cfg** what you passed on the original **make** command line.

configure_opts — The list of options that should be passed to **configure**. The default is **""**, but **--srcdir=..** is automatically added just before **configure** is called.

hook_preconfigure()

This function is invoked just before we run the project's **configure** script. Its main job is to set the configure_opts variable properly. Here's a fairly complicated example (this is from GCC):

```
# The "target" variable is the compilation target: "ntoarm", "ntox86", etc.
function hook_preconfigure {
    case ${SYSNAME} in
    nto)
        case "${target}" in
        nto*)   basedir=/usr ;;
        *)      basedir=/opt/QNXsdk/host/qnx6/x86/usr ;;
        esac
        ;;
    solaris)
        host_cpu=$(uname -p)
        case ${host_cpu} in
        i[34567]86) host_cpu=x86 ;;
        esac
        basedir=/opt/QNXsdk/host/solaris/${host_cpu}/usr
        ;;
```

```
    *)
        echo "Don't have config for ${SYSNAME}"
        exit 1
        ;;
    esac
    configure_opts="${configure_opts} --target=${target}"
    configure_opts="${configure_opts} --prefix=${basedir}"
    configure_opts="${configure_opts} --exec-prefix=${basedir}"
    configure_opts="${configure_opts} --with-local-prefix=${basedir}"
    configure_opts="${configure_opts} --enable-haifa"
    configure_opts="${configure_opts} --enable-languages=c++"
    configure_opts="${configure_opts} --enable-threads=posix"
    configure_opts="${configure_opts} --with-gnu-as"
    configure_opts="${configure_opts} --with-gnu-ld"
    configure_opts="${configure_opts} --with-as=${basedir}/bin/${target}-as"
    configure_opts="${configure_opts} --with-ld=${basedir}/bin/${target}-ld"
    if [ ${SYSNAME} == nto ]; then
        configure_opts="${configure_opts} --enable-multilib"
        configure_opts="${configure_opts} --enable-shared"
    else
        configure_opts="${configure_opts} --disable-multilib"
    fi
}
```

hook_postconfigure()

This is invoked after **`configure`** has been successfully run. Usually you don't need to define this function, but sometimes you just can't quite convince **`configure`** to do the right thing, so you can put some hacks in here to munge things appropriately. For example, again from GCC:

```
function hook_postconfigure {
    echo "s/^GCC_CFLAGS *=/&-I\$\(QNX_TARGET\)\/usr\/include /"  >/tmp/fix.$$
    if [ ${SYSNAME} == nto ]; then
        echo "s/OLDCC = cc/OLDCC = .\/xgcc -B.\/ -I \$\(QNX_TARGET\)\/usr\/include/" >>/tmp/fix.$$
        echo "/^INCLUDES = /s/\$/ -I\$\(QNX_TARGET\)\/usr\/include/" >>/tmp/fix.$$
        if [ ${target} == ntosh ]; then
            # We've set up GCC to support both big and little endian, but
            # we only actually support little endian right now. This will
            # cause the configures for the target libraries to fail, since
            # it will test the compiler by attempting a big endian compile
            # which won't link due to a missing libc & crt?.o files.
            # Hack things by forcing compiles/links to always be little endian
            sed -e "s/^CFLAGS_FOR_TARGET *=/&-ml /"  <Makefile >1.$$
            mv 1.$$ Makefile
        fi
    else
        # Only need to build libstdc++ & friends on one host
        rm -Rf ${target}

        echo "s/OLDCC = cc/OLDCC = .\/xgcc -B.\//" >>/tmp/fix.$$
    fi
    cd gcc
    sed -f/tmp/fix.$$ <Makefile >1.$$
    mv 1.$$ Makefile
    cd ..
    rm /tmp/fix.$$
}
```

hook_premake()

This function is invoked just before the **`make`**. You don't usually need it.

hook_postmake()

This function is invoked just after the **`make`**. We haven't found a use for this one yet, but included it for completeness.

hook_pinfo()

This function is invoked after *hook_postmake()*. Theoretically, we don't need this hook at all and we could do all its work in *hook_postmake()*, but we're keeping it separate in case we get fancier in the future.

This function is responsible for generating all the **`*.pinfo`** files in the project. It does this by invoking the *gen_pinfo()* function that's defined in **`build-cfg`**, which generates one **`.pinfo`**. The command line for *gen_pinfo()* is:

gen_pinfo [-n*src_name* **]** *install_name install_dir pinfo_line***...**

The arguments are:

src_name — The name of the pinfo file (minus the **.pinfo** suffix). If it's not specified, *gen_pinfo()* uses *install_name*.

install_name — The basename of the executable when it's installed.

install_dir — The directory the executable should be installed in. If it doesn't begin with a **/**, the target CPU directory is prepended to it. For example, if *install_dir* is **usr/bin** and you're generating an X86 executable, the true installation directory is **/x86/usr/bin**.

pinfo_line — Any additional pinfo lines that you want to add. You can repeat this argument as many times as required. Favorites include:

- **DESCRIPTION="This executable performs no useful purpose"**
- **SYMLINK=foobar.so**

Here's an example from the **nasm** project:

```
function hook_pinfo {
    gen_pinfo nasm    usr/bin LIC=NASM DESCRIPTION="Netwide X86 Assembler"
    gen_pinfo ndisasm usr/bin LIC=NASM DESCRIPTION="Netwide X86 Disassembler"
}
```

Appendix C

Developing SMP Systems

In this appendix. . .

Introduction

As described in the *System Architecture* guide, there's an *SMP* (Symmetrical MultiProcessor) version of Neutrino that runs on:

- Pentium-based multiprocessor systems that conform to the Intel MultiProcessor Specification (MP Spec)
- MIPS-based systems
- PowerPC-based systems

If you have one of these systems, then you're probably itching to try it out, but are wondering what you have to do to get Neutrino running on it. Well, the answer is not much. The only part of Neutrino that's different for an SMP system is the microkernel — another example of the advantages of a microkernel architecture!

The SMP versions of **procnto** are available only in the Symmetric Multiprocessing Technology Development Kit (TDK).

Building an SMP image

Assuming you're already familiar with building a bootable image for a single-processor system (as described in the Making an OS Image chapter in *Building Embedded Systems*), let's look at what you have to change in the buildfile for an SMP system.

As we mentioned above, basically all you need to use is the SMP kernel (**procnto-smp**) when building the image.

Here's an example of a buildfile:

```
#   A simple SMP buildfile

[virtual=x86,bios] .bootstrap = {
    startup-bios
    PATH=/proc/boot procnto-smp
}
[+script] .script = {
    devc-con -e &
    reopen /dev/con1
```

```
    [+session] PATH=/proc/boot esh
}

libc.so
[type=link] /usr/lib/ldqnx.so.2=/proc/boot/libc.so

[data=copy]
devc-con
esh
ls
```

After building the image, you proceed in the same way as you would with a single-processor system.

The impact of SMP

Although the actual changes to the way you set up the processor to run SMP are fairly minor, the *fact* that you're running on an SMP system can have a major impact on your software!

The main thing to keep in mind is this: in a single processor environment, it may be a nice "design abstraction" to pretend that threads execute in parallel; under an SMP system, they *really do* execute in parallel!

In this section, we'll examine the impact of SMP on your system design.

To SMP or not to SMP

It's possible to use the non-SMP kernel on an SMP box. In this case, only processor 0 will be used; the other processors won't run your code. This is a waste of additional processors, of course, but it does mean that you *can* run images from single-processor boxes on an SMP box. (You can also run SMP-ready images on single-processor boxes.)

It's also possible to run the SMP kernel on a uniprocessor system, but it requires a 486 or higher on x86 architectures, and PPCs require an SMP-capable implementation.

Processor affinity

One issue that often arises in an SMP environment can be put like this: "Can I make it so that one processor handles the GUI, another handles the database, and the other two handle the realtime functions?"

The answer is: "Yes, absolutely."

This is done through the magic of *processor affinity* — the ability to associate certain programs (or even threads within programs) with a particular processor or processors.

Processor affinity works like this. When a thread starts up, its processor affinity mask is set to allow it to run on all processors. This implies that there's *no* inheritance of the processor affinity mask, so it's up to the thread to use *ThreadCtl()* with the _NTO_TCTL_RUNMASK control flag to set the processor affinity mask.

The processor affinity mask is simply a bitmap; each bit position indicates a particular processor. For example, the processor affinity mask **`0x05`** (binary **`00000101`**) allows the thread to run on processors **`0`** (the **`0x01`** bit) and **`2`** (the **`0x04`** bit).

SMP and synchronization primitives

Standard synchronization primitives (barriers, mutexes, condvars, semaphores, and all of their derivatives, e.g. sleepon locks) are safe to use on an SMP box. You don't have to do anything special here.

SMP and FIFO scheduling

A common single-processor "trick" for coordinated access to a shared memory region is to use FIFO scheduling between two threads running at the same priority. The idea is that one thread will access the region and then call *SchedYield()* to give up its use of the processor. Then, the second thread would run and access the region. When it was done, the second thread too would call *SchedYield()*, and the first thread would run again. Since there's only one processor, both threads would cooperatively share that processor.

This FIFO trick won't work on an SMP system, because *both* threads may run simultaneously on different processors. You'll have to use the more "proper" thread synchronization primitives (e.g. a mutex).

SMP and interrupts

The following method is closely related to the FIFO scheduling trick. On a single-processor system, a thread and an interrupt service routine were mutually exclusive, due to the fact that the ISR ran at a priority higher than that of any thread. Therefore, the ISR would be able to preempt the thread, but the thread would *never* be able to preempt the ISR. So the only "protection" required was for the thread to indicate that during a particular section of code (the *critical section*) interrupts should be disabled.

Obviously, this scheme breaks down in an SMP system, because again the thread and the ISR could be running on different processors.

The solution in this case is to use the *InterruptLock()* and *InterruptUnlock()* calls to ensure that the ISR won't preempt the thread at an unexpected point. But what if the thread preempts the ISR? The solution is the same — use *InterruptLock()* and *InterruptUnlock()* in the ISR as well.

We recommend that you *always* use the *InterruptLock()* and *InterruptUnlock()* function calls, both in the thread and in the ISR. The small amount of extra overhead on a single-processor box is negligible.

SMP and atomic operations

Note that if you wish to perform simple atomic operations, such as adding a value to a memory location, it isn't necessary to turn off interrupts to ensure that the operation won't be preempted. Instead, use the functions provided in the C include file **`<atomic.h>`**, which allow you to perform the following operations with memory locations in an atomic manner:

Function	Operation
atomic_add()	Add a number.
atomic_add_value()	Add a number and return the original value of **loc*.
atomic_clr()	Clear bits.
atomic_clr_value()	Clear bits and return the original value of **loc*.
atomic_set()	Set bits.
atomic_set_value()	set bits and return the original value of **loc*.
atomic_sub()	Subtract a number.
atomic_sub_value()	Subtract a number and return the original value of **loc*.
atomic_toggle()	Toggle (complement) bits
atomic_toggle_value()	Toggle (complement) bits and return the original value of **loc*.

The **_value()* functions may be slower on some systems (e.g. 386) — don't use them unless you really want the return value.

Designing with SMP in mind

You may not have an SMP system today, but wouldn't it be great if your software just ran faster on one when you or your customer upgrade the hardware?

While the general topic of how to design programs so that they can scale to N processors is still the topic of research, this section contains some general tips.

Use the SMP primitives

Don't assume that your program will run only on one processor. This means staying away from the FIFO synchronization trick mentioned above. Also, you should use the SMP-aware *InterruptLock()* and *InterruptUnlock()* functions.

By doing this, you'll be "SMP-ready" with little negative impact on a single-processor system.

Assume that threads *really do* run concurrently

As mentioned above, it's not merely a useful "programming abstraction" to pretend that threads run simultaneously; you should design as if they really do. That way, when you move to an SMP system, you won't have any nasty surprises.

Break the problem down

Most problems can be broken down into independent, parallel tasks. Some are easy to break down, some are hard, and some are impossible. Generally, you want to look at the data flow going through a particular problem. If the data flows are *independent* (i.e. one flow doesn't rely on the results of another), this can be a good candidate for parallelization within the process by starting multiple threads. Consider the following graphics program snippet:

```
do_graphics ()
{
    int     x;

    for (x = 0; x < XRESOLUTION; x++) {
        do_one_line (x);
    }
}
```

In the above example, we're doing ray-tracing. We've looked at the problem and decided that the function *do_one_line()* only generates output to the screen — it doesn't rely on the results from any other invocation of *do_one_line()*.

To make optimal use of an SMP system, you would start multiple threads, each running on one processor.

The question then becomes how many threads to start. Obviously, starting XRESOLUTION threads (where XRESOLUTION is far greater than the number of processors, perhaps 1024 to 4) is not a particularly good idea — you're creating a lot of threads, all of which will consume stack resources and kernel resources as they compete for the limited pool of CPUs.

A simple solution would be to find out the number of CPUs that you have available to you (via the system page pointer) and divide the work up that way:

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

int     num_x_per_cpu;

do_graphics ()
{
    int     num_cpus;
    int     i;
    pthread_t *tids;

    // figure out how many CPUs there are...
    num_cpus = _syspage_ptr -> num_cpu;

    // allocate storage for the thread IDs
    tids = malloc (num_cpus * sizeof (pthread_t));

    // figure out how many X lines each CPU can do
    num_x_per_cpu = XRESOLUTION / num_cpus;

    // start up one thread per CPU, passing it the ID
    for (i = 0; i < num_cpus; i++) {
        pthread_create (&tids[i], NULL, do_lines, (void *) i);
    }

    // now all the "do_lines" are off running on the processors

    // we need to wait for their termination
    for (i = 0; i < num_cpus; i++) {
        pthread_join (tids[i], NULL);
    }

    // now they are all done
}

void *
do_lines (void *arg)
{
```

```
    int    cpunum = (int) arg;  // convert void * to an integer
    int    x;

    for (x = cpunum * num_x_per_cpu; x < (cpunum + 1) *
          num_x_per_cpu; x++) { do_line (x);
    }
}
```

The above approach will allow the maximum number of threads to run simultaneously on the SMP system. There's no point creating more threads than there are CPUs, because they'll simply compete with each other for CPU time.

An alternative approach is to use a semaphore. You could preload the semaphore with the count of available CPUs. Then, you create threads whenever the semaphore indicates that a CPU is available. This is conceptually simpler, but involves thread creation/destruction overhead for each iteration.

Appendix D

Using GDB

In this appendix. . .

The Neutrino implementation of GDB includes some extensions:

`target qnx` Set the target; see "Setting the target."

`set qnxinheritenv`

Set where the remote process inherits its environment from; see "Your program's environment."

`set qnxremotecwd`

Set the working directory for the remote process; see "Starting your program."

`set qnxtimeout`

Set the timeout for remote reads; see "Setting the target."

`upload` *local_path remote_path*

Send a file to a remote target system.

`download` *remote_path local_path*

Retrieve a file from a remote target system.

`info pidlist` Display a list of processes and their process IDs on the remote system

`info meminfo` Display a list of memory-region mappings (shared objects) for the current process being debugged.

To debug an application on a remote target, do the following:

1. Start GDB, but don't specify the application as an argument:
   ```
   gdb
   ```

2. Load the symbol information for the application:
   ```
   sym my_application
   ```

3. Set the target:
   target qnx *com_port_specifier* **|** *host:port* **| pty**

4. Send the application to the target:
   upload my_application /tmp/my_application

5. Start the application:
   run /tmp/my_application

GDB commands

You can abbreviate a GDB command to the first few letters of the command name, if that abbreviation is unambiguous; and you can repeat certain GDB commands by typing just Enter. You can also use the Tab key to get GDB to fill out the rest of a word in a command (or to show you the alternatives available, if there's more than one possibility).

You may also place GDB commands in an initialization file and these commands will be run before any that have been entered via the command line. For more information, see:

- **gdb** in the *Utilities Reference*
- the GNU documentation for GDB

Command syntax

A GDB command is a single line of input. There's no limit on how long it can be. It starts with a command name, which is followed by arguments whose meaning depends on the command name. For example, the command **step** accepts an argument that is the number of times to step, as in **step 5**. You can also use the **step** command

with no arguments. Some command names don't allow any arguments.

GDB command names may always be truncated if that abbreviation is unambiguous. Other possible command abbreviations are listed in the documentation for individual commands. In some cases, even ambiguous abbreviations are allowed; for example, **s** is specifically defined as equivalent to **step** even though there are other commands whose names start with **s**. You can test abbreviations by using them as arguments to the **help** command.

A blank line as input to GDB (typing just Enter) means to repeat the previous command. Certain commands (for example, **run**) don't repeat this way; these are commands whose unintentional repetition might cause trouble and which you're unlikely to want to repeat.

When you repeat the **list** and **x** commands with Enter, they construct new arguments rather than repeat exactly as typed. This permits easy scanning of source or memory.

GDB can also use Enter in another way: to partition lengthy output, in a way similar to the common utility **more**. Since it's easy to press one Enter too many in this situation, GDB disables command repetition after any command that generates this sort of display.

Any text from a # to the end of the line is a comment. This is useful mainly in command files.

Command completion

GDB can fill in the rest of a word in a command for you if there's only one possibility; it can also show you what the valid possibilities are for the next word in a command, at any time. This works for GDB commands, GDB subcommands, and the names of symbols in your program.

Press the Tab key whenever you want GDB to fill out the rest of a word. If there's only one possibility, GDB fills in the word, and waits for you to finish the command (or press Enter to enter it). For example, if you type:

```
(gdb) info bre Tab
```

GDB fills in the rest of the word **breakpoints**, since that is the only **info** subcommand beginning with **bre**:

```
(gdb) info breakpoints
```

You can either press Enter at this point, to run the **info breakpoints** command, or backspace and enter something else, if **breakpoints** doesn't look like the command you expected. (If you were sure you wanted **info breakpoints** in the first place, you might as well just type Enter immediately after **info bre**, to exploit command abbreviations rather than command completion).

If there's more than one possibility for the next word when you press Tab, GDB sounds a bell. You can either supply more characters and try again, or just press Tab a second time; GDB displays all the possible completions for that word. For example, you might want to set a breakpoint on a subroutine whose name begins with **make_**, but when you type:

```
b make_Tab
```

GDB just sounds the bell. Typing Tab again displays all the function names in your program that begin with those characters, for example:

```
make_a_section_from_file     make_environ
make_abs_section             make_function_type
make_blockvector             make_pointer_type
make_cleanup                 make_reference_type
make_command                 make_symbol_completion_list
(gdb) b make_
```

After displaying the available possibilities, GDB copies your partial input (**b make_** in the example) so you can finish the command.

If you just want to see the list of alternatives in the first place, you can press Esc followed by ? (rather than press Tab twice).

Sometimes the string you need, while logically a "word", may contain parentheses or other characters that GDB normally excludes from its notion of a word. To permit word completion to work in this situation, you may enclose words in ' (single quote marks) in GDB commands.

The most likely situation where you might need this is in typing the name of a C++ function. This is because C++ allows function overloading (multiple definitions of the same function, distinguished by argument type). For example, when you want to set a breakpoint you may need to distinguish whether you mean the version of **name** that takes an **int** parameter, **name(int)**, or the version that takes a **float** parameter, **name(float)**. To use the word-completion facilities in this situation, type a single quote **'** at the beginning of the function name. This alerts GDB that it may need to consider more information than usual when you press Tab, or Esc followed by ?, to request word completion:

```
(gdb) b 'bubble(Esc?
bubble(double,double)    bubble(int,int)
(gdb) b 'bubble(
```

In some cases, GDB can tell that completing a name requires using quotes. When this happens, GDB inserts the quote for you (while completing as much as it can) if you don't type the quote in the first place:

```
(gdb) b bub Tab
```

GDB alters your input line to the following, and rings a bell:

```
(gdb) b 'bubble(
```

In general, GDB can tell that a quote is needed (and inserts it) if you haven't yet started typing the argument list when you ask for completion on an overloaded symbol.

Getting help

You can always ask GDB itself for information on its commands, using the command **help**.

help
h

You can use **help** (**h**) with no arguments to display a short list of named classes of commands:

```
(gdb) help
List of classes of commands:

running -- Running the program
stack -- Examining the stack
data -- Examining data
breakpoints -- Making program stop at certain
points
files -- Specifying and examining files
status -- Status inquiries
support -- Support facilities
user-defined -- User-defined commands
aliases -- Aliases of other commands
obscure -- Obscure features

Type "help" followed by a class name for a list
of commands in that class.
Type "help" followed by command name for full
documentation.
Command name abbreviations are allowed if
unambiguous.
(gdb)
```

`help` *class* Using one of the general help classes as an argument, you can get a list of the individual commands in that class. For example, here's the help display for the class **`status`**:

```
(gdb) help status
Status inquiries.

List of commands:

show -- Generic command for showing things set
with "set"
info -- Generic command for printing status

Type "help" followed by command name for full
documentation.
Command name abbreviations are allowed if
unambiguous.
(gdb)
```

help *command*

With a command name as **help** argument, GDB displays a short paragraph on how to use that command.

complete *args*

The **complete** *args* command lists all the possible completions for the beginning of a command. Use *args* to specify the beginning of the command you want completed. For example:

```
complete i
```

results in:

```
info
inspect
ignore
```

This is intended for use by GNU Emacs.

In addition to **help**, you can use the GDB commands **info** and **show** to inquire about the state of your program, or the state of GDB itself. Each command supports many topics of inquiry; this manual introduces each of them in the appropriate context. The listings under **info** and **show** in the index point to all the sub-commands.

info This command (abbreviated **i**) is for describing the state of your program. For example, you can list the arguments given to your program with **info args**, list the registers currently in use with **info registers**, or list the breakpoints you've set with **info breakpoints**. You can get a complete list of the **info** sub-commands with **help info**.

set You can assign the result of an expression to an environment variable with **set**. For example, you can set the GDB prompt to a $-sign with **set prompt $**.

show In contrast to **info**, **show** is for describing the state of GDB itself. You can change most of the things you can **show**, by using the related command **set**; for example, you can control what number system is used for displays with **set radix**, or simply inquire which is currently in use with **show radix**.

To display all the settable parameters and their current values, you can use **show** with no arguments; you may also use **info set**. Both commands produce the same display.

Here are three miscellaneous **show** subcommands, all of which are exceptional in lacking corresponding **set** commands:

show version

Show what version of GDB is running. You should include this information in GDB bug-reports. If multiple versions of GDB are in use at your site, you may occasionally want to determine which version of GDB you're running; as GDB evolves, new commands are introduced, and old ones may wither away. The version number is also announced when you start GDB.

show copying

Display information about permission for copying GDB.

show warranty

Display the GNU "NO WARRANTY" statement.

Running programs under GDB

To run a program under GDB, you must first generate debugging information when you compile it. You may start GDB with its arguments, if any, in an environment of your choice. You may redirect your program's input and output, debug an already running process, or kill a child process.

Compiling for debugging

Debugging information is stored in the object file; it describes the data type of each variable or function and the correspondence between source line numbers and addresses in the executable code.

To request debugging information, specify the **-g** option when you run the compiler.

GCC, the GNU C compiler, supports **-g** with or without **-O**, making it possible to debug optimized code. We recommend that you *always* use **-g** whenever you compile a program. You may think your program is correct, but there's no sense in pushing your luck.

When you debug a program compiled with **-g -O**, remember that the optimizer is rearranging your code; the debugger shows you what is really there. Don't be too surprised when the execution path doesn't exactly match your source file! An extreme example: if you define a variable, but never use it, GDB never sees that variable — because the compiler optimizes it out of existence.

Some things don't work as well with **-g -O** as with just **-g**, particularly on machines with instruction scheduling. If in doubt, recompile with **-g** alone, and if this fixes the problem, please report it to us — and include a test case.

Setting the target

When you start the debugger, you need to specify the target to use because the default target isn't supported:

target qnx *com_port_specifier* **|** *host:port* **| pty**

The **pty** option spawns a **pdebug** server on the local machine and connects via a pty.

The **devc-pty** manager must be running on the machine that's running **pdebug**, and a ptyp/ttyp pair must be available.

Here's a sample:

```
(gdb) target qnx 10.109:8000
Remote debugging using 10.109:8000
0x0 in ?? ()
(gdb) sym hello
Reading symbols from hello...done.
(gdb) run /local/src/test/hello
Starting program:  /local/src/test/hello
(gdb)
```

If your communication line is slow, you might need to set the timeout for remote reads:

`set qnxtimeout` *time*

where *time* is the timeout, in seconds. The default is 10 seconds.

Starting your program

`set qnxremotecwd` *path*

Specify the remote process's working directory. You should do this before starting your program.

`run`

`r`

Use the **`run`** command to start your program under GDB. You must first specify the program name with an argument to GDB (see the description of the **`gdb`** utility).

The **`run`** creates an inferior process and makes that process run your program.

The execution of a program is affected by certain information it receives from its superior. GDB provides ways to specify this information, which you must do *before* starting your program. (You can change it after starting your program, but such changes affect your program the *next* time you start it.) This information may be divided into the following categories:

Arguments

Specify the arguments to give your program as the arguments of the **`run`** command. If a shell is available on your target, the shell is used to pass the

arguments, so that you may use normal conventions (such as wildcard expansion or variable substitution) in describing the arguments. In Unix systems, you can control which shell is used with the **SHELL** environment variable. See "Your program's arguments/"

Environment — Your program normally inherits its environment from GDB, but you can use the GDB commands **`set environment`** and **`unset environment`** to change parts of the environment that affect your program. See "Your program's environment."

While input and output redirection work, you can't use pipes to pass the output of the program you're debugging to another program; if you attempt this, GDB is likely to wind up debugging the wrong program.

When you issue the **`run`** command, your program is loaded but doesn't execute immediately. Use the **`continue`** command to start your program. For more information, see "Stopping and continuing." While your program is stopped, you may call functions in your program, using the **`print`** or **`call`** commands. See "Examining data."

If the modification time of your symbol file has changed since the last time GDB read its symbols, GDB discards its symbol table and reads it again. When it does this, GDB tries to retain your current breakpoints.

Your program's arguments

The arguments to your program can be specified by the arguments of the **`run`** command.

A **`run`** command with no arguments uses the same arguments used by the previous **`run`**, or those set by the **`set args`** command.

`set args` Specify the arguments to be used the next time your program is run. If **`set args`** has no arguments, **`run`** executes your program with no arguments. Once you've run your program with arguments, using **`set args`** before the next **`run`** is the only way to run it again without arguments.

`show args` Show the arguments to give your program when it's started.

Your program's environment

The *environment* consists of a set of environment variables and their values. Environment variables conventionally record such things as your user name, your home directory, your terminal type, and your search path for programs to run. Usually you set up environment variables with the shell and they're inherited by all the other programs you run. When debugging, it can be useful to try running your program with a modified environment without having to start GDB over again.

`set qnxinheritenv` *value*

If *value* is 0, the process inherits its environment from GDB. If *value* is 1 (the default), the process inherits its environment from **`pdebug`**.

`path` *directory* Add *directory* to the front of the **`PATH`** environment variable (the search path for executables), for both GDB and your program. You may specify several directory names, separated by a colon (`:`) or whitespace. If *directory* is already in the path, it's moved to the front, so it's searched sooner.

You can use the string **`$cwd`** to refer to the current working directory at the time GDB searches the path. A period (`.`) refers to the directory where you executed the **`path`** command. GDB replaces the period in the *directory* argument by the current path before adding *directory* to the search path.

show paths Display the list of search paths for executables (the **PATH** environment variable).

show environment [*varname*]

Print the value of environment variable *varname* to be given to your program when it starts. If you don't supply *varname*, print the names and values of all environment variables to be given to your program. You can abbreviate **environment** as **env**.

set environment *varname* [=] *value*

Set environment variable *varname* to *value*. The value changes for your program only, not for GDB itself. The *value* may be any string; the values of environment variables are just strings, and any interpretation is supplied by your program itself. The *value* parameter is optional; if it's eliminated, the variable is set to a null value.

For example, this command:

```
set env USER=foo
```

tells a Unix program, when subsequently run, that its user is named **foo**.

unset environment *varname*

Remove variable *varname* from the environment to be passed to your program. This is different from **set env** *varname* **=**, in that **unset environment** removes the variable from the environment, rather than assign it an empty value.

Your program's input and output

By default, the program you run under GDB does input and output to the same terminal that GDB uses. GDB switches the terminal to its own terminal modes to interact with you, but it records the terminal

modes your program was using and switches back to them when you continue running your program.

You can redirect your program's input and/or output using shell redirection with the **run** command. For example,

```
run > outfile
```

starts your program, diverting its output to the file **outfile**.

Debugging an already-running process

attach *process-id*

This command attaches to a running process — one that was started outside GDB. (The **info files** command shows your active targets.) The command takes as its argument a process ID. To find out a process ID, use the **pidin** utility; for more information, see the *Utilities Reference*.

The **attach** command doesn't repeat if you press Enter a second time after executing the command.

To use **attach**, you must have permission to send the process a signal.

When using **attach**, you should first use the **file** command to specify the program running in the process and load its symbol table.

The first thing GDB does after arranging to debug the specified process is to stop it. You can examine and modify an attached process with all the GDB commands that are ordinarily available when you start processes with **run**. You can insert breakpoints; you can step and continue; you can modify storage. If you want the process to continue running, use the **continue** command after attaching GDB to the process.

detach When you've finished debugging the attached process, you can use the **detach** command to release it from GDB control. Detaching the process continues its

execution. After the **detach** command, that process and GDB become completely independent once more, and you're ready to **attach** another process or start one with **run**. The **detach** command doesn't repeat if you press Enter again after executing the command.

If you exit GDB or use the **run** command while you have an attached process, you kill that process. By default, GDB asks for confirmation if you try to do either of these things; you can control whether or not you need to confirm by using the **set confirm** command.

Killing the child process

kill Kill the child process in which your program is running under GDB.

This command is useful if you wish to debug a core dump instead of a running process. GDB ignores any core dump file while your program is running.

The **kill** command is also useful if you wish to recompile and relink your program. With Neutrino, it's possible to modify an executable file while it's running in a process. If you want to run the new version, kill the child process; when you next type **run**, GDB notices that the file has changed, and reads the symbol table again (while trying to preserve your current breakpoint settings).

Debugging programs with multiple threads

In Neutrino, a single program may have more than one *thread* of execution. Each thread has its own registers and execution stack, and perhaps private memory.

GDB provides these facilities for debugging multithreaded programs:

- **thread** *threadno*, a command to switch between threads
- **info threads**, a command to inquire about existing threads
- **thread apply** [*threadno*] [*all*] *args*,

a command to apply a command to a list of threads

- thread-specific breakpoints

The GDB thread debugging facility lets you observe all threads while your program runs — but whenever GDB takes control, one thread in particular is always the focus of debugging. This thread is called the *current thread*. Debugging commands show program information from the perspective of the current thread.

GDB associates its own thread number — always a single integer — with each thread in your program.

`info threads`

Display a summary of all threads currently in your program. GDB displays for each thread (in this order):

1. Thread number assigned by GDB
2. Target system's thread identifier (*systag*)
3. Current stack frame summary for that thread.

An asterisk **`*`** to the left of the GDB thread number indicates the current thread. For example:

```
(gdb) info threads
  3 process 35 thread 27  0x34e5 in sigpause ()
  2 process 35 thread 23  0x34e5 in sigpause ()
* 1 process 35 thread 13  main (argc=1, argv=0x7fffffff8)
    at threadtest.c:68
```

`thread` *threadno*

Make thread number *threadno* the current thread. The command argument *threadno* is the internal GDB thread number, as shown in the first field of the **`info threads`** display. GDB responds by displaying the system identifier of the thread you selected and its current stack frame summary:

```
(gdb) thread 2
[Switching to process 35 thread 23]
0x34e5 in sigpause ()
```

`thread apply` [*threadno*] [**`all`**] *args*

The **`thread apply`** command lets you apply a command to one or more threads. Specify the numbers of the threads that you want affected with the command argument *threadno*. To apply a command to all threads, use **`thread apply all`** *args*.

Whenever GDB stops your program because of a breakpoint or a signal, it automatically selects the thread where that breakpoint or signal happened. GDB alerts you to the context switch with a message of the form **`[Switching to`** *systag***`]`** to identify the thread.

See "Stopping and starting multithreaded programs" for more information about how GDB behaves when you stop and start programs with multiple threads.

See "Setting watchpoints" for information about watchpoints in programs with multiple threads.

Debugging programs with multiple processes

GDB has no special support for debugging programs that create additional processes using the *fork()* function. When a program forks, GDB continues to debug the parent process, and the child process runs unimpeded. If you've set a breakpoint in any code that the child then executes, the child gets a **`SIGTRAP`** signal, which (unless it catches the signal) causes it to terminate.

However, if you want to debug the child process, there's a workaround that isn't too painful:

1. Put a call to *sleep()* in the code that the child process executes after the fork. It may be useful to sleep only if a certain environment variable is set, or a certain file exists, so that the delay doesn't occur when you don't want to run GDB on the child.
2. While the child is sleeping, use the **`pidin`** utility to get its process ID (for more information, see the *Utilities Reference*).

3 Tell GDB (a new invocation of GDB if you're also debugging the parent process) to attach to the child process (see "Debugging an already-running process"). From that point on you can debug the child process just like any other process that you've attached to.

Stopping and continuing

Inside GDB, your program may stop for any of several reasons, such as a signal, a breakpoint, or reaching a new line after a GDB command such as **`step`**. You may then examine and change variables, set new breakpoints or remove old ones, and then continue execution. Usually, the messages shown by GDB provide ample explanation of the status of your program — but you can also explicitly request this information at any time.

`info program`

Display information about the status of your program: whether it's running or not, what process it is, and why it stopped.

Breakpoints, watchpoints, and exceptions

A *breakpoint* makes your program stop whenever a certain point in the program is reached. For each breakpoint, you can add conditions to control in finer detail whether your program stops. You can set breakpoints with the **`break`** command and its variants (see "Setting breakpoints") to specify the place where your program should stop by line number, function name or exact address in the program. In languages with exception handling (such as GNU C++), you can also set breakpoints where an exception is raised (see "Breakpoints and exceptions").

A *watchpoint* is a special breakpoint that stops your program when the value of an expression changes. You must use a different command to set watchpoints (see "Setting watchpoints"), but aside from that, you can manage a watchpoint like any other breakpoint: you enable, disable, and delete both breakpoints and watchpoints using the same commands.

You can arrange to have values from your program displayed automatically whenever GDB stops at a breakpoint. See “Automatic display.”

GDB assigns a number to each breakpoint or watchpoint when you create it; these numbers are successive integers starting with 1. In many of the commands for controlling various features of breakpoints you use the breakpoint number to say which breakpoint you want to change. Each breakpoint may be *enabled* or *disabled*; if disabled, it has no effect on your program until you enable it again.

Setting breakpoints

Use the **break** (**b**) command to set breakpoints. The debugger convenience variable **$bpnum** records the number of the breakpoints you’ve set most recently; see “Convenience variables” for a discussion of what you can do with convenience variables.

You have several ways to say where the breakpoint should go:

break *function*

Set a breakpoint at entry to *function*. When using source languages such as C++ that permit overloading of symbols, *function* may refer to more than one possible place to break. See “Breakpoint menus” for a discussion of that situation.

break +*offset*
break -*offset*

Set a breakpoint some number of lines forward or back from the position at which execution stopped in the currently selected frame.

break *linenum*

Set a breakpoint at line *linenum* in the current source file. That file is the last file whose source text was printed. This breakpoint stops your program just before it executes any of the code on that line.

break *filename*:*linenum*

Set a breakpoint at line *linenum* in source file *filename*.

break *filename*:*function*

Set a breakpoint at entry to *function* found in file *filename*. Specifying a filename as well as a function name is superfluous except when multiple files contain similarly named functions.

break ***address**

Set a breakpoint at address *address*. You can use this to set breakpoints in parts of your program that don't have debugging information or source files.

break When called without any arguments, **break** sets a breakpoint at the next instruction to be executed in the selected stack frame (see "Examining the Stack"). In any selected frame but the innermost, this makes your program stop as soon as control returns to that frame. This is similar to the effect of a **finish** command in the frame inside the selected frame — except that **finish** doesn't leave an active breakpoint. If you use **break** without an argument in the innermost frame, GDB stops the next time it reaches the current location; this may be useful inside loops.

GDB normally ignores breakpoints when it resumes execution, until at least one instruction has been executed. If it didn't do this, you wouldn't be able to proceed past a breakpoint without first disabling the breakpoint. This rule applies whether or not the breakpoint already existed when your program stopped.

break ... if *cond*

Set a breakpoint with condition *cond*; evaluate the expression *cond* each time the breakpoint is reached, and stop only if the value is nonzero — that is, if *cond* evaluates as true. The ellipsis (**...**) stands for one of the

possible arguments described above (or no argument) specifying where to break. For more information on breakpoint conditions, see "Break conditions."

There are several variations on the **break** command, all using the same syntax as above:

tbreak Set a breakpoint enabled only for one stop. The breakpoint is set in the same way as for the **break** command, except that it's automatically deleted after the first time your program stops there. See "Disabling breakpoints."

hbreak Set a hardware-assisted breakpoint. The breakpoint is set in the same way as for the **break** command, except that it requires hardware support (and some target hardware may not have this support).

The main purpose of this is EPROM/ROM code debugging, so you can set a breakpoint at an instruction without changing the instruction.

thbreak Set a hardware-assisted breakpoint enabled only for one stop. The breakpoint is set in the same way as for the **break** command. However, like the **tbreak** command, the breakpoint is automatically deleted after the first time your program stops there. Also, like the **hbreak** command, the breakpoint requires hardware support, which some target hardware may not have. See "Disabling breakpoints" and "Break conditions."

rbreak *regex* Set breakpoints on all functions matching the regular expression *regex*. This command sets an unconditional breakpoint on all matches, printing a list of all breakpoints it set. Once these breakpoints are set, they're treated just like the breakpoints set with the **break** command. You can delete them,

disable them, or make them conditional the same way as any other breakpoint.

When debugging C++ programs, **rbreak** is useful for setting breakpoints on overloaded functions that aren't members of any special classes.

The following commands display information about breakpoints and watchpoints:

info breakpoints [*n*]
info break [*n*]
info watchpoints [*n*]

Print a table of all breakpoints and watchpoints set and not deleted, with the following columns for each breakpoint:

- Breakpoint Numbers.
- Type — breakpoint or watchpoint.
- Disposition — whether the breakpoint is marked to be disabled or deleted when hit.
- Enabled or Disabled — enabled breakpoints are marked with **y**, disabled with **n**.
- Address — where the breakpoint is in your program, as a memory address.
- What — where the breakpoint is in the source for your program, as a file and line number.

If a breakpoint is conditional, **info break** shows the condition on the line following the affected breakpoint; breakpoint commands, if any, are listed after that.

An **info break** command with a breakpoint number *n* as argument lists only that breakpoint. The convenience variable **$_** and the default examining-address for the **x** command are set to the address of the last breakpoint listed (see "Examining memory").

The **info break** command displays the number of times the breakpoint has been hit. This is especially useful in conjunction

with the **ignore** command. You can ignore a large number of breakpoint hits, look at the breakpoint information to see how many times the breakpoint was hit, and then run again, ignoring one less than that number. This gets you quickly to the last hit of that breakpoint.

GDB lets you set any number of breakpoints at the same place in your program. There's nothing silly or meaningless about this. When the breakpoints are conditional, this is even useful (see "Break conditions").

GDB itself sometimes sets breakpoints in your program for special purposes, such as proper handling of **longjmp** (in C programs). These internal breakpoints are assigned negative numbers, starting with **-1**; **info breakpoints** doesn't display them.

You can see these breakpoints with the GDB maintenance command, **maint info breakpoints**.

maint info breakpoints

Using the same format as **info breakpoints**, display both the breakpoints you've set explicitly and those GDB is using for internal purposes. The type column identifies what kind of breakpoint is shown:

- **breakpoint** — normal, explicitly set breakpoint.
- **watchpoint** — normal, explicitly set watchpoint.
- **longjmp** — internal breakpoint, used to handle correctly stepping through **longjmp** calls.
- **longjmp resume** — internal breakpoint at the target of a **longjmp**.
- **until** — temporary internal breakpoint used by the GDB **until** command.
- **finish** — temporary internal breakpoint used by the GDB **finish** command.

Setting watchpoints

You can use a watchpoint to stop execution whenever the value of an expression changes, without having to predict a particular place where this may happen.

Although watchpoints currently execute two orders of magnitude more slowly than other breakpoints, they can help catch errors where in cases where you have no clue what part of your program is the culprit.

`watch` *expr* — Set a watchpoint for an expression. GDB breaks when *expr* is written into by the program and its value changes.

`rwatch` *arg* — Set a watchpoint that breaks when watch *arg* is read by the program. If you use both watchpoints, both must be set with the **`rwatch`** command.

`awatch` *arg* — Set a watchpoint that breaks when *arg* is read and written into by the program. If you use both watchpoints, both must be set with the **`awatch`** command.

`info watchpoints`

This command prints a list of watchpoints and breakpoints; it's the same as **`info break`**.

In multithreaded programs, watchpoints have only limited usefulness. With the current watchpoint implementation, GDB can watch the value of an expression *in a single thread only*. If you're confident that the expression can change due only to the current thread's activity (and if you're also confident that no other thread can become current), then you can use watchpoints as usual. However, GDB may not notice when a noncurrent thread's activity changes the expression.

Breakpoints and exceptions

Some languages, such as GNU C++, implement exception handling. You can use GDB to examine what caused your program to raise an exception and to list the exceptions your program is prepared to handle at a given point in time.

`catch` *exceptions*

You can set breakpoints at active exception handlers by using the **`catch`** command. The *exceptions* argument is a list of names of exceptions to catch.

You can use **`info catch`** to list active exception handlers. See "Information about a frame."

There are currently some limitations to exception handling in GDB:

- If you call a function interactively, GDB normally returns control to you when the function has finished executing. If the call raises an exception, however, the call may bypass the mechanism that returns control to you and cause your program to continue running until it hits a breakpoint, catches a signal that GDB is listening for, or exits.
- You can't raise an exception interactively.
- You can't install an exception handler interactively.

Sometimes **`catch`** isn't the best way to debug exception handling: if you need to know exactly where an exception is raised, it's better to stop *before* the exception handler is called, since that way you can see the stack before any unwinding takes place. If you set a breakpoint in an exception handler instead, it may not be easy to find out where the exception was raised.

To stop just before an exception handler is called, you need some knowledge of the implementation. In the case of GNU C++, exceptions are raised by calling a library function named *__raise_exception()*, which has the following ANSI C interface:

```
void __raise_exception (void **addr, void *id);

/* addr is where the exception identifier is stored.
   id is the exception identifier.  */
```

To make the debugger catch all exceptions before any stack unwinding takes place, set a breakpoint on *__raise_exception()*. See "Breakpoints, watchpoints, and exceptions."

With a conditional breakpoint (see "Break conditions") that depends on the value of *id*, you can stop your program when a specific exception is raised. You can use multiple conditional breakpoints to stop your program when any of a number of exceptions are raised.

Deleting breakpoints

You often need to eliminate a breakpoint or watchpoint once it's done its job and you no longer want your program to stop there. This is called *deleting* the breakpoint. A breakpoint that has been deleted no longer exists and is forgotten.

With the **clear** command you can delete breakpoints according to where they are in your program. With the **delete** command you can delete individual breakpoints or watchpoints by specifying their breakpoint numbers.

You don't have to delete a breakpoint to proceed past it. GDB automatically ignores breakpoints on the first instruction to be executed when you continue execution without changing the execution address.

clear Delete any breakpoints at the next instruction to be executed in the selected stack frame (see "Selecting a frame"). When the innermost frame is selected, this is a good way to delete a breakpoint where your program just stopped.

clear *function*
clear *filename*:*function*

Delete any breakpoints set at entry to *function*.

clear *linenum*
clear *filename*:*linenum*

Delete any breakpoints set at or within the code of the specified line.

delete [**breakpoints**] [*bnums*...]

Delete the breakpoints or watchpoints of the numbers specified as arguments. If no argument is specified, delete all breakpoints (GDB asks for confirmation, unless you've **set confirm off**). You can abbreviate this command as **d**.

Disabling breakpoints

Rather than delete a breakpoint or watchpoint, you might prefer to *disable* it. This makes the breakpoint inoperative as if it had been deleted, but remembers the information on the breakpoint so that you can *enable* it again later.

You disable and enable breakpoints and watchpoints with the **enable** and **disable** commands, optionally specifying one or more breakpoint numbers as arguments. Use **info break** or **info watch** to print a list of breakpoints or watchpoints if you don't know which numbers to use.

A breakpoint or watchpoint can have any of the following states:

Enabled — The breakpoint stops your program. A breakpoint set with the **break** command starts out in this state.

Disabled — The breakpoint has no effect on your program.

Enabled once — The breakpoint stops your program, but then becomes disabled. A breakpoint set with the **tbreak** command starts out in this state.

Enabled for deletion — The breakpoint stops your program, but immediately afterwards it's deleted permanently.

You can use the following commands to enable or disable breakpoints and watchpoints:

`disable` [**`breakpoints`**] [*bnums...*]

Disable the specified breakpoints — or all breakpoints, if none is listed. A disabled breakpoint has no effect but isn't forgotten. All options such as ignore-counts, conditions and commands are remembered in case the breakpoint is enabled again later. You may abbreviate **`disable`** as **`dis`**.

`enable` [**`breakpoints`**] [*bnums...*]

Enable the specified breakpoints (or all defined breakpoints). They become effective once again in stopping your program.

`enable [breakpoints] once` *bnums...*

Enable the specified breakpoints temporarily. GDB disables any of these breakpoints immediately after stopping your program.

`enable [breakpoints] delete` *bnums...*

Enable the specified breakpoints to work once, then die. GDB deletes any of these breakpoints as soon as your program stops there.

Except for a breakpoint set with **`tbreak`** (see "Setting breakpoints"), breakpoints that you set are initially enabled; subsequently, they become disabled or enabled only when you use one of the commands above. (The command **`until`** can set and delete a breakpoint of its own, but it doesn't change the state of your other breakpoints; see "Continuing and stepping.")

Break conditions

The simplest sort of breakpoint breaks every time your program reaches a specified place. You can also specify a *condition* for a breakpoint. A condition is just a Boolean expression in your programming language (see "Expressions"). A breakpoint with a condition evaluates the expression each time your program reaches it, and your program stops only if the condition is *true*.

This is the converse of using assertions for program validation; in that situation, you want to stop when the assertion is violated — that is, when the condition is false. In C, if you want to test an assertion expressed by the condition *assert*, you should set the condition **!** *assert* on the appropriate breakpoint.

Conditions are also accepted for watchpoints; you may not need them, since a watchpoint is inspecting the value of an expression anyhow — but it might be simpler, say, to just set a watchpoint on a variable name, and specify a condition that tests whether the new value is an interesting one.

Break conditions can have side effects, and may even call functions in your program. This can be useful, for example, to activate functions that log program progress, or to use your own print functions to format special data structures. The effects are completely predictable unless there's another enabled breakpoint at the same address. (In that case, GDB might see the other breakpoint first and stop your program without checking the condition of this one.) Note that breakpoint commands are usually more convenient and flexible for the purpose of performing side effects when a breakpoint is reached (see "Breakpoint command lists").

Break conditions can be specified when a breakpoint is set, by using **if** in the arguments to the **break** command. See "Setting breakpoints." They can also be changed at any time with the **condition** command. The **watch** command doesn't recognize the **if** keyword; **condition** is the only way to impose a further condition on a watchpoint.

condition *bnum expression*

Specify *expression* as the break condition for breakpoint or watchpoint number *bnum*. After you set a condition, breakpoint *bnum* stops your program only if the value of *expression* is true (nonzero, in C). When you use **condition**, GDB checks *expression* immediately for syntactic correctness, and to determine whether symbols in it have referents in the context of your breakpoint. GDB doesn't actually evaluate *expression* at

the time the **condition** command is given, however. See "Expressions."

condition *bnum*

Remove the condition from breakpoint number *bnum*. It becomes an ordinary unconditional breakpoint.

A special case of a breakpoint condition is to stop only when the breakpoint has been reached a certain number of times. This is so useful that there's a special way to do it, using the *ignore count* of the breakpoint. Every breakpoint has an ignore count, which is an integer. Most of the time, the ignore count is zero, and therefore has no effect. But if your program reaches a breakpoint whose ignore count is positive, then instead of stopping, it just decrements the ignore count by one and continues. As a result, if the ignore count value is *n*, the breakpoint doesn't stop the next *n* times your program reaches it.

ignore *bnum count*

Set the ignore count of breakpoint number *bnum* to *count*. The next *count* times the breakpoint is reached, your program's execution doesn't stop; other than to decrement the ignore count, GDB takes no action.

To make the breakpoint stop the next time it's reached, specify a count of zero.

When you use **continue** to resume execution of your program from a breakpoint, you can specify an ignore count directly as an argument to **continue**, rather than use **ignore**. See "Continuing and stepping."

If a breakpoint has a positive ignore count and a condition, the condition isn't checked. Once the ignore count reaches zero, GDB resumes checking the condition.

You could achieve the effect of the ignore count with a condition such as **$foo-- <= 0** using a debugger convenience variable that's decremented each time. See "Convenience variables."

Breakpoint command lists

You can give any breakpoint (or watchpoint) a series of commands to execute when your program stops due to that breakpoint. For example, you might want to print the values of certain expressions, or enable other breakpoints.

commands [*bnum*]
... *command-list* **...**
end

Specify a list of commands for breakpoint number *bnum*. The commands themselves appear on the following lines. Type a line containing just **end** to terminate the commands.

To remove all commands from a breakpoint, type **commands** and follow it immediately with **end**; that is, give no commands.

With no *bnum* argument, **commands** refers to the last breakpoint or watchpoint set (not to the breakpoint most recently encountered).

Pressing Enter as a means of repeating the last GDB command is disabled within a *command-list*.

You can use breakpoint commands to start your program up again. Just use the **continue** command, or **step**, or any other command that resumes execution.

Commands in *command-list* that follow a command that resumes execution are ignored. This is because any time you resume execution (even with a simple **next** or **step**), you may encounter another breakpoint — which could have its own command list, leading to ambiguities about which list to execute.

If the first command you specify in a command list is **silent**, the usual message about stopping at a breakpoint isn't printed. This may be desirable for breakpoints that are to print a specific message and then continue. If none of the remaining commands print anything, you see no sign that the breakpoint was reached. The **silent** command is meaningful only at the beginning of a breakpoint command list.

The commands **echo**, **output**, and **printf** allow you to print precisely controlled output, and are often useful in silent breakpoints.

For example, here's how you could use breakpoint commands to print the value of *x* at entry to *foo()* whenever *x* is positive:

```
break foo if x>0
commands
silent
printf "x is %d\n",x
cont
end
```

One application for breakpoint commands is to compensate for one bug so you can test for another. Put a breakpoint just after the erroneous line of code, give it a condition to detect the case in which something erroneous has been done, and give it commands to assign correct values to any variables that need them. End with the **continue** command so that your program doesn't stop, and start with the **silent** command so that no output is produced. Here's an example:

```
break 403
commands
silent
set x = y + 4
cont
end
```

Breakpoint menus

Some programming languages (notably C++) permit a single function name to be defined several times, for application in different contexts. This is called *overloading*. When a function name is overloaded, **break** *function* isn't enough to tell GDB where you want a breakpoint.

If you realize this is a problem, you can use something like **break** *function***(***types***)** to specify which particular version of the function you want. Otherwise, GDB offers you a menu of numbered choices for different possible breakpoints, and waits for your selection with the

prompt **>**. The first two options are always **[0] cancel** and **[1] all**. Typing 1 sets a breakpoint at each definition of *function*, and typing 0 aborts the **break** command without setting any new breakpoints.

For example, the following session excerpt shows an attempt to set a breakpoint at the overloaded symbol *String::after()*. We choose three particular definitions of that function name:

```
(gdb) b String::after
[0] cancel
[1] all
[2] file:String.cc; line number:867
[3] file:String.cc; line number:860
[4] file:String.cc; line number:875
[5] file:String.cc; line number:853
[6] file:String.cc; line number:846
[7] file:String.cc; line number:735
> 2 4 6
Breakpoint 1 at 0xb26c: file String.cc, line 867.
Breakpoint 2 at 0xb344: file String.cc, line 875.
Breakpoint 3 at 0xafcc: file String.cc, line 846.
Multiple breakpoints were set.
Use the "delete" command to delete unwanted
 breakpoints.
(gdb)
```

Continuing and stepping

Continuing means resuming program execution until your program completes normally. In contrast, *stepping* means executing just one more “step” of your program, where “step” may mean either one line of source code, or one machine instruction (depending on what particular command you use). Either when continuing or when stepping, your program may stop even sooner, due to a breakpoint or a signal. (If due to a signal, you may want to use **handle**, or use **signal 0** to resume execution. See “Signals.”)

`continue` [*ignore-count*]
`c` [*ignore-count*]
`fg` [*ignore-count*]

Resume program execution, at the address where your program last stopped; any breakpoints set at that address are bypassed. The optional argument *ignore-count* lets you specify a further number of times to ignore a breakpoint at this location; its effect is like that of **`ignore`** (see "Break conditions").

The argument *ignore-count* is meaningful only when your program stopped due to a breakpoint. At other times, the argument to **`continue`** is ignored.

The synonyms **`c`** and **`fg`** are provided purely for convenience, and have exactly the same behavior as **`continue`**.

To resume execution at a different place, you can use **`return`** (see "Returning from a function") to go back to the calling function; or **`jump`** (see "Continuing at a different address") to go to an arbitrary location in your program.

A typical technique for using stepping is to set a breakpoint (see "Breakpoints, watchpoints, and exceptions") at the beginning of the function or the section of your program where a problem is believed to lie, run your program until it stops at that breakpoint, and then step through the suspect area, examining the variables that are interesting, until you see the problem happen.

`step` Continue running your program until control reaches a different source line, then stop it and return control to GDB. This command is abbreviated **`s`**.

If you use the **step** command while control is within a function that was compiled without debugging information, execution proceeds until control reaches a function that does have debugging information. Likewise, it doesn't step into a function that is compiled without debugging information. To step through functions without debugging information, use the **stepi** command, described below.

The **step** command stops only at the first instruction of a source line. This prevents multiple stops in switch statements, for loops, etc. The **step** command stops if a function that has debugging information is called within the line.

Also, the **step** command enters a subroutine only if there's line number information for the subroutine. Otherwise it acts like the **next** command. This avoids problems when using **cc -gl** on MIPS machines.

step *count* Continue running as in **step**, but do so *count* times. If a breakpoint is reached, or a signal not related to stepping occurs before *count* steps, stepping stops right away.

next [*count*] Continue to the next source line in the current (innermost) stack frame. This is similar to **step**, but function calls that appear within the line of code are executed without stopping. Execution stops when control reaches a different line of code at the original stack level that was executing when you gave the **next** command. This command is abbreviated **n**.

The *count* argument is a repeat count, as for **step**.

The **next** command stops only at the first instruction of a source line. This prevents the multiple stops in switch statements, for loops, etc.

finish Continue running until just after function in the selected stack frame returns. Print the returned value (if any).

Contrast this with the **return** command (see "Returning from a function").

u
until Continue running until a source line past the current line in the current stack frame is reached. This command is used to avoid single-stepping through a loop more than once. It's like the **next** command, except that when **until** encounters a jump, it automatically continues execution until the program counter is greater than the address of the jump.

This means that when you reach the end of a loop after single-stepping though it, **until** makes your program continue execution until it exits the loop. In contrast, a **next** command at the end of a loop simply steps back to the beginning of the loop, which forces you to step through the next iteration.

The **until** command always stops your program if it attempts to exit the current stack frame.

The **until** command may produce somewhat counterintuitive results if the order of machine code doesn't match the order of the source lines. For example, in the following excerpt from a debugging session, the **f** (**frame**) command shows that execution is stopped at line **206**; yet when we use **until**, we get to line **195**:

```
(gdb) f
#0  main (argc=4, argv=0xf7fffae8) at m4.c:206
206                 expand_input();
(gdb) until
195             for ( ; argc > 0; NEXTARG) {
```

This happened because, for execution efficiency, the compiler had generated code for the loop closure

test at the end, rather than the start, of the loop — even though the test in a C **for**-loop is written before the body of the loop. The **until** command appeared to step back to the beginning of the loop when it advanced to this expression; however, it hasn't really gone to an earlier statement — not in terms of the actual machine code.

An **until** command with no argument works by means of single instruction stepping, and hence is slower than **until** with an argument.

until *location*
u *location*

Continue running your program until either the specified location is reached, or the current stack frame returns. The *location* is any of the forms of argument acceptable to **break** (see "Setting breakpoints"). This form of the command uses breakpoints, and hence is quicker than **until** without an argument.

stepi [*count*]
si [*count*]

Execute one machine instruction, then stop and return to the debugger.

It's often useful to do **display/i $pc** when stepping by machine instructions. This makes GDB automatically display the next instruction to be executed, each time your program stops. See "Automatic display."

The *count* argument is a repeat count, as in **step**.

nexti [*count*]
ni [*count*]

Execute one machine instruction, but if it's a function call, proceed until the function returns.

The *count* argument is a repeat count, as in **next**.

Signals

A signal is an asynchronous event that can happen in a program. The operating system defines the possible kinds of signals, and gives each kind a name and a number. The table below gives several examples of signals:

Signal:	Received when:
SIGINT	You type an interrupt, Ctrl – C
SIGSEGV	The program references a place in memory far away from all the areas in use.
SIGALRM	The alarm clock timer goes off (which happens only if your program has requested an alarm).

Some signals, including **SIGALRM**, are a normal part of the functioning of your program. Others, such as **SIGSEGV**, indicate errors; these signals are *fatal* (killing your program immediately) if the program hasn't specified in advance some other way to handle the signal. **SIGINT** doesn't indicate an error in your program, but it's normally fatal so it can carry out the purpose of the interrupt: to kill the program.

GDB has the ability to detect any occurrence of a signal in your program. You can tell GDB in advance what to do for each kind of signal. Normally, it's set up to:

- Ignore signals like **SIGALRM** that don't indicate an error so as not to interfere with their role in the functioning of your program.
- Stop your program immediately whenever an error signal happens.

You can change these settings with the **handle** command.

info signals
info handle

Print a table of all the kinds of signals and how GDB has been told to handle each one. You can use this to see the signal numbers of all the defined types of signals.

handle *signal keywords...*

Change the way GDB handles signal *signal*. The *signal* can be the number of a signal or its name (with or without the **SIG** at the beginning). The *keywords* say what change to make.

The keywords allowed by the **handle** command can be abbreviated. Their full names are:

nostop	GDB shouldn't stop your program when this signal happens. It may still print a message telling you that the signal has come in.
stop	GDB should stop your program when this signal happens. This implies the **print** keyword as well.
print	GDB should print a message when this signal happens.
noprint	GDB shouldn't mention the occurrence of the signal at all. This implies the **nostop** keyword as well.
pass	GDB should allow your program to see this signal; your program can handle the signal, or else it may terminate if the signal is fatal and not handled.
nopass	GDB shouldn't allow your program to see this signal.

When a signal stops your program, the signal isn't visible until you continue. Your program sees the signal then, if **pass** is in effect for the signal in question *at that time*. In other words, after GDB reports a signal, you can use the **handle** command with **pass** or **nopass** to control whether your program sees that signal when you continue.

You can also use the **signal** command to prevent your program from seeing a signal, or cause it to see a signal it normally doesn't see, or to give it any signal at any time. For example, if your program stopped due to some sort of memory reference error, you might store correct values into the erroneous variables and continue, hoping to see more execution; but your program would probably terminate immediately as a result of the fatal signal once it saw the signal. To prevent this, you can continue with **signal 0**. See "Giving your program a signal."

Stopping and starting multithreaded programs

When your program has multiple threads (see "Debugging programs with multiple threads"), you can choose whether to set breakpoints on all threads, or on a particular thread.

break *linespec* **thread** *threadno*
break *linespec* **thread** *threadno* **if** ...

The *linespec* specifies source lines; there are several ways of writing them, but the effect is always to specify some source line.

Use the qualifier **thread** *threadno* with a breakpoint command to specify that you want GDB to stop the program only when a particular thread reaches this breakpoint. The *threadno* is one of the numeric thread identifiers assigned by GDB, shown in the first column of the **info threads** display.

If you don't specify **thread** *threadno* when you set a breakpoint, the breakpoint applies to *all* threads of your program.

You can use the **thread** qualifier on conditional breakpoints as well; in this case, place **thread** *threadno* before the breakpoint condition, like this:

```
(gdb) break frik.c:13 thread 28 if bartab > lim
```

Whenever your program stops under GDB for any reason, *all* threads of execution stop, not just the current thread. This lets you examine the overall state of the program, including switching between threads, without worrying that things may change underfoot.

Conversely, whenever you restart the program, *all* threads start executing. *This is true even when single-stepping* with commands like **`step`** or **`next`**.

In particular, GDB can't single-step all threads in lockstep. Since thread scheduling is up to the Neutrino microkernel (not controlled by GDB), other threads may execute more than one statement while the current thread completes a single step. Moreover, in general, other threads stop in the middle of a statement, rather than at a clean statement boundary, when the program stops.

You might even find your program stopped in another thread after continuing or even single-stepping. This happens whenever some other thread runs into a breakpoint, a signal, or an exception before the first thread completes whatever you requested.

Examining the stack

When your program has stopped, the first thing you need to know is where it stopped and how it got there.

Each time your program performs a function call, information about the call is generated. That information includes the location of the call in your program, the arguments of the call, and the local variables of the function being called. The information is saved in a block of data called a *stack frame*. The stack frames are allocated in a region of memory called the *call stack*.

When your program stops, the GDB commands for examining the stack allow you to see all of this information.

One of the stack frames is *selected* by GDB, and many GDB commands refer implicitly to the selected frame. In particular, whenever you ask GDB for the value of a variable in your program, the value is found in the selected frame. There are special GDB

commands to select whichever frame you're interested in. See "Selecting a frame."

When your program stops, GDB automatically selects the currently executing frame and describes it briefly, similar to the **`frame`** command (see "Information about a frame").

Stack frames

The call stack is divided up into contiguous pieces called *stack frames*, or *frames* for short; each frame is the data associated with one call to one function. The frame contains the arguments given to the function, the function's local variables, and the address at which the function is executing.

When your program is started, the stack has only one frame, that of the function *main()*. This is called the *initial* frame or the *outermost* frame. Each time a function is called, a new frame is made. Each time a function returns, the frame for that function invocation is eliminated. If a function is recursive, there can be many frames for the same function. The frame for the function in which execution is actually occurring is called the *innermost* frame. This is the most recently created of all the stack frames that still exist.

Inside your program, stack frames are identified by their addresses. A stack frame consists of many bytes, each of which has its own address; each kind of computer has a convention for choosing one byte whose address serves as the address of the frame. Usually this address is kept in a register called the *frame pointer register* while execution is going on in that frame.

GDB assigns numbers to all existing stack frames, starting with 0 for the innermost frame, 1 for the frame that called it, and so on upward. These numbers don't really exist in your program; they're assigned by GDB to give you a way of designating stack frames in GDB commands.

Some compilers provide a way to compile functions so that they operate without stack frames. (For example, the **`gcc`** option **`-fomit-frame-pointer`** generates functions without a frame.)

This is occasionally done with heavily used library functions to reduce the time required to set up the frame. GDB has limited facilities for dealing with these function invocations. If the innermost function invocation has no stack frame, GDB nevertheless regards it as though it had a separate frame, which is numbered 0 as usual, allowing correct tracing of the function call chain. However, GDB has no provision for frameless functions elsewhere in the stack.

`frame` *args*
: The **`frame`** command lets you move from one stack frame to another, and to print the stack frame you select. The *args* may be either the address of the frame or the stack frame number. Without an argument, **`frame`** prints the current stack frame.

`select-frame`
: The **`select-frame`** command lets you move from one stack frame to another without printing the frame. This is the silent version of **`frame`**.

Backtraces

A backtrace is a summary of how your program got where it is. It shows one line per frame, for many frames, starting with the currently executing frame (frame 0), followed by its caller (frame 1), and on up the stack.

`backtrace`
`bt`
: Print a backtrace of the entire stack, with one line per frame, for all frames in the stack.

  You can stop the backtrace at any time by typing the system interrupt character, normally Ctrl – C.

`backtrace` *n*
`bt` *n*
: Similar, but print only the innermost *n* frames.

`backtrace -`*n*
`bt -`*n*
: Similar, but print only the outermost *n* frames.

The names **where** and **info stack** (**info s**) are additional aliases for **backtrace**.

Each line in the backtrace shows the frame number and the function name. The program counter value is also shown — unless you use **set print address off**. The backtrace also shows the source filename and line number, as well as the arguments to the function. The program counter value is omitted if it's at the beginning of the code for that line number.

Here's an example of a backtrace. It was made with the command **bt 3**, so it shows the innermost three frames:

```
#0  m4_traceon (obs=0x24eb0, argc=1, argv=0x2b8c8)
    at builtin.c:993
#1  0x6e38 in expand_macro (sym=0x2b600) at macro.c:242
#2  0x6840 in expand_token (obs=0x0, t=177664, td=0xf7fffb08)
    at macro.c:71
(More stack frames follow...)
```

The display for frame 0 doesn't begin with a program counter value, indicating that your program has stopped at the beginning of the code for line **993** of **builtin.c**.

Selecting a frame

Most commands for examining the stack and other data in your program work on whichever stack frame is selected at the moment. Here are the commands for selecting a stack frame; all of them finish by printing a brief description of the stack frame just selected.

frame *n*
f *n*
: Select frame number *n*. Recall that frame 0 is the innermost (currently executing) frame, frame 1 is the frame that called the innermost one, and so on. The highest-numbered frame is the one for **main**.

frame *addr*
f *addr*
: Select the frame at address *addr*. This is useful mainly if the chaining of stack frames has been damaged by a bug, making it impossible for GDB to

assign numbers properly to all frames. In addition, this can be useful when your program has multiple stacks and switches between them.

On the MIPS architecture, **frame** needs two addresses: a stack pointer and a program counter.

up *n*
Move *n* frames up the stack. For positive numbers, this advances toward the outermost frame, to higher frame numbers, to frames that have existed longer. The default for *n* is 1.

down *n*
Move *n* frames down the stack. For positive numbers, this advances toward the innermost frame, to lower frame numbers, to frames that were created more recently. The default for *n* is 1. You may abbreviate **down** as **do**.

All of these commands end by printing two lines of output describing the frame. The first line shows the frame number, the function name, the arguments, and the source file and line number of execution in that frame. The second line shows the text of that source line.

For example:

```
(gdb) up
#1  0x22f0 in main (argc=1, argv=0xf7fffbf4, env=0xf7fffbfc)
    at env.c:10
10              read_input_file (argv[i]);
```

After such a printout, the **list** command with no arguments prints ten lines centered on the point of execution in the frame. See "Printing source lines."

up-silently *n*
down-silently *n*

These two commands are variants of **up** and **down**; they differ in that they do their work silently, without causing display of the new frame. They're intended primarily for use in GDB command scripts, where the output might be unnecessary and distracting.

Information about a frame

There are several other commands to print information about the selected stack frame:

`frame`
`f`

When used without any argument, this command doesn't change which frame is selected, but prints a brief description of the currently selected stack frame. It can be abbreviated **`f`**. With an argument, this command is used to select a stack frame. See "Selecting a frame."

`info frame`
`info f`

This command prints a verbose description of the selected stack frame, including:

- the address of the frame
- the address of the next frame down (called by this frame)
- the address of the next frame up (caller of this frame)
- the language in which the source code corresponding to this frame is written
- the address of the frame's arguments
- the program counter saved in it (the address of execution in the caller frame)
- which registers were saved in the frame

The verbose description is useful when something has gone wrong that has made the stack format fail to fit the usual conventions.

`info frame` *addr*
`info f` *addr*

Print a verbose description of the frame at address *addr*, without selecting that frame. The selected frame remains unchanged by this command. This

requires the same kind of address (more than one for some architectures) that you specify in the **frame** command. See "Selecting a frame."

info args Print the arguments of the selected frame, each on a separate line.

info locals Print the local variables of the selected frame, each on a separate line. These are all variables (declared either static or automatic) accessible at the point of execution of the selected frame.

info catch Print a list of all the exception handlers that are active in the current stack frame at the current point of execution. To see other exception handlers, visit the associated frame (using the **up**, **down**, or **frame** commands); then type **info catch**. See "Breakpoints and exceptions."

MIPS machines and the function stack

MIPS-based computers use an unusual stack frame, which sometimes requires GDB to search backward in the object code to find the beginning of a function.

To improve response time — especially for embedded applications, where GDB may be restricted to a slow serial line for this search — you may want to limit the size of this search, using one of these commands:

set heuristic-fence-post *limit*

Restrict GDB to examining at most *limit* bytes in its search for the beginning of a function. A value of 0 (the default) means there's no limit. However, except for 0, the larger the limit the more bytes **heuristic-fence-post** must search and therefore the longer it takes to run.

show heuristic-fence-post

Display the current limit.

These commands are available *only* when GDB is configured for debugging programs on MIPS processors.

Examining source files

GDB can print parts of your program's source, since the debugging information recorded in the program tells GDB what source files were used to build it. When your program stops, GDB spontaneously prints the line where it stopped. Likewise, when you select a stack frame (see "Selecting a frame"), GDB prints the line where execution in that frame has stopped. You can print other portions of source files by explicit command.

Printing source lines

To print lines from a source file, use the **`list`** (**`l`**) command. By default, ten lines are printed. There are several ways to specify what part of the file you want to print. Here are the forms of the **`list`** command most commonly used:

`list` *linenum*	Print lines centered around line number *linenum* in the current source file.
`list` *function*	Print lines centered around the beginning of function *function*.
`list`	Print more lines. If the last lines printed were printed with a **`list`** command, this prints lines following the last lines printed; however, if the last line printed was a solitary line printed as part of displaying a stack frame (see "Examining the Stack"), this prints lines centered around that line.
`list -`	Print lines just before the lines last printed.

By default, GDB prints ten source lines with any of these forms of the **`list`** command. You can change this using **`set listsize`**:

set listsize *count*

Make the **list** command display *count* source lines (unless the **list** argument explicitly specifies some other number).

show listsize

Display the number of lines that **list** prints.

Repeating a **list** command with Enter discards the argument, so it's equivalent to typing just **list**. This is more useful than listing the same lines again. An exception is made for an argument of **-**; that argument is preserved in repetition so that each repetition moves up in the source file.

In general, the **list** command expects you to supply zero, one or two *linespecs*. Linespecs specify source lines; there are several ways of writing them but the effect is always to specify some source line. Here's a complete description of the possible arguments for **list**:

list *linespec*	Print lines centered around the line specified by *linespec*.
list *first*,*last*	Print lines from *first* to *last*. Both arguments are linespecs.
list , *last*	Print lines ending with *last*.
list *first***,**	Print lines starting with *first*.
list +	Print lines just after the lines last printed.
list -	Print lines just before the lines last printed.
list	As described in the preceding table.

Here are the ways of specifying a single source line — all the kinds of *linespec*:

number	Specifies line *number* of the current source file. When a **list** command has two linespecs, this refers to the same source file as the first linespec.

+*offset* Specifies the line *offset* lines after the last line printed. When used as the second linespec in a **`list`** command that has two, this specifies the line *offset* lines down from the first linespec.

-*offset* Specifies the line *offset* lines before the last line printed.

filename:*number*

Specifies line *number* in the source file *filename*.

function Specifies the line that begins the body of the function *function*. For example: in C, this is the line with the open brace, **`}`**.

filename:*function*

Specifies the line of the open brace that begins the body of *function* in the file *filename*. You need the filename with a function name only to avoid ambiguity when there are identically named functions in different source files.

***address** Specifies the line containing the program address *address*. The *address* may be any expression.

Searching source files

The commands for searching through the current source file for a regular expression are:

`forward-search` *regexp*
`search` *regexp*
`fo` *regexp*

Check each line, starting with the one following the last line listed, for a match for *regexp*, listing the line found.

reverse-search *regexp*
rev *regexp*

Check each line, starting with the one before the last line listed and going backward, for a match for *regexp*, listing the line found.

Specifying source directories

Executable programs sometimes don't record the directories of the source files from which they were compiled, just the names. Even when they do, the directories could be moved between the compilation and your debugging session. GDB has a list of directories to search for source files; this is called the *source path*. Each time GDB wants a source file, it tries all the directories in the list, in the order they're present in the list, until it finds a file with the desired name.

The executable search path *isn't* used for this purpose. Neither is the current working directory, unless it happens to be in the source path.

If GDB can't find a source file in the source path, and the object program records a directory, GDB tries that directory too. If the source path is empty, and there's no record of the compilation directory, GDB looks in the current directory as a last resort.

Whenever you reset or rearrange the source path, GDB clears out any information it has cached about where source files are found and where each line is in the file.

When you start GDB, its source path is empty. To add other directories, use the **directory** command.

directory *dirname ...*
dir *dirname ...*

Add directory *dirname* to the front of the source path. Several directory names may be given to this command, separated by colons (**:**) or whitespace. You may specify a directory that is already in the

source path; this moves it forward, so GDB searches it sooner.

You can use the string **$cdir** to refer to the compilation directory (if one is recorded), and **$cwd** to refer to the current working directory. Note that **$cwd** isn't the same as a period (**.**); the former tracks the current working directory as it changes during your GDB session, while the latter is immediately expanded to the current directory at the time you add an entry to the source path.

directory Reset the source path to empty again. This requires confirmation.

show directories

Print the source path: show which directories it contains.

If your source path is cluttered with directories that are no longer of interest, GDB may sometimes cause confusion by finding the wrong versions of source. You can correct the situation as follows:

1. Use **directory** with no argument to reset the source path to empty.
2. Use **directory** with suitable arguments to reinstall the directories you want in the source path. You can add all the directories in one command.

Source and machine code

You can use the command **info line** to map source lines to program addresses (and vice versa), and the command **disassemble** to display a range of addresses as machine instructions. When run under GNU Emacs mode, the **info line** command causes the arrow to point to the line specified. Also, **info line** prints addresses in symbolic form as well as hex.

`info line` *linespec*

Print the starting and ending addresses of the compiled code for source line *linespec*. You can specify source lines in any of the ways understood by the **`list`** command (see "Printing source lines").

For example, we can use **`info line`** to discover the location of the object code for the first line of function **`m4_changequote`**:

```
(gdb) info line m4_changecom
Line 895 of "builtin.c" starts at pc 0x634c and ends at 0x6350.
```

We can also inquire (using **`*`***addr* as the form for *linespec*) what source line covers a particular address:

```
(gdb) info line *0x63ff
Line 926 of "builtin.c" starts at pc 0x63e4 and ends at 0x6404.
```

After **`info line`**, the default address for the **`x`** command is changed to the starting address of the line, so that **`x/i`** is sufficient to begin examining the machine code (see "Examining memory"). Also, this address is saved as the value of the convenience variable **`$_`** (see "Convenience variables").

`disassemble`

This specialized command dumps a range of memory as machine instructions. The default memory range is the function surrounding the program counter of the selected frame. A single argument to this command is a program counter value; GDB dumps the function surrounding this value. Two arguments specify a range of addresses (first inclusive, second exclusive) to dump.

We can use **`disassemble`** to inspect the object code range shown in the last **`info line`** example (the example shows SPARC machine instructions):

```
(gdb) disas 0x63e4 0x6404
Dump of assembler code from 0x63e4 to 0x6404:
0x63e4 <builtin_init+5340>:     ble 0x63f8 <builtin_init+5360>
0x63e8 <builtin_init+5344>:     sethi %hi(0x4c00), %o0
0x63ec <builtin_init+5348>:     ld [%i1+4], %o0
0x63f0 <builtin_init+5352>:     b 0x63fc <builtin_init+5364>
0x63f4 <builtin_init+5356>:     ld [%o0+4], %o0
0x63f8 <builtin_init+5360>:     or %o0, 0x1a4, %o0
0x63fc <builtin_init+5364>:     call 0x9288 <path_search>
0x6400 <builtin_init+5368>:     nop
End of assembler dump.
```

`set assembly-language` *instruction-set*

This command selects the instruction set to use when disassembling the program via the **`disassemble`** or **`x/i`** commands. It's useful for architectures that have more than one native instruction set.

Currently it's defined only for the Intel x86 family. You can set *instruction-set* to either **`i386`** or **`i8086`**. The default is **`i386`**.

Shared libraries

You can use the following commands when working with shared libraries:

`sharedlibrary` [*regexp*]

Load shared object library symbols for files matching the given regular expression, *regexp*. If *regexp* is omitted, GDB tries to load symbols for all loaded shared libraries.

`info sharedlibrary`

Display the status of the loaded shared object libraries.

The following parameters apply to shared libraries:

`set solib-search-path` *dir*[:*dir*...]

Set the search path for loading shared library symbols files that don't have an absolute path. This path overrides the **PATH** and **LD_LIBRARY_PATH** environment variables.

set solib-absolute-prefix *prefix*

Set the prefix for loading absolute shared library symbol files.

set auto-solib-add *value*

Make the loading of shared library symbols automatic or manual:

- If *value* is nonzero, symbols from all shared object libraries are loaded automatically when the inferior process (i.e. the one being debugged) begins execution, or when the dynamic linker informs GDB that a new library has been loaded.
- If *value* is zero, symbols must be loaded manually with the **sharedlibrary** command.

You can query the settings of these parameters with the **show solib-search-path**, **show solib-absolute-prefix**, and **show auto-solib-add** commands.

Examining data

The usual way to examine data in your program is with the **print** (**p**) command or its synonym **inspect**. It evaluates and prints the value of an expression of the language your program is written in.

print *exp*
print /*f exp*

exp is an expression (in the source language). By default, the value of *exp* is printed in a format appropriate to its data type; you can choose a different format by specifying **/***f*, where *f* is a letter specifying the format; see "Output formats."

print
print /*f*

If you omit *exp*, GDB displays the last value again (from the *value history*; see "Value history"). This lets you conveniently inspect the same value in an alternative format.

A lower-level way of examining data is with the **x** command. It examines data in memory at a specified address and prints it in a specified format. See “Examining memory.”

If you’re interested in information about types, or about how the fields of a structure or class are declared, use the **ptype** *exp* command rather than **print**. See “Examining the symbol table.”

Expressions

The **print** command and many other GDB commands accept an expression and compute its value. Any kind of constant, variable or operator defined by the programming language you’re using is valid in an expression in GDB. This includes conditional expressions, function calls, casts and string constants. It unfortunately doesn’t include symbols defined by preprocessor **#define** commands.

GDB supports array constants in expressions input by the user. The syntax is **{***element, element...***}**. For example, you can use the command **print {1, 2, 3}** to build up an array in memory that is *malloc*’d in the target program.

Because C is so widespread, most of the expressions shown in examples in this manual are in C. In this section, we discuss operators that you can use in GDB expressions regardless of your programming language.

Casts are supported in all languages, not just in C, because it’s useful to cast a number into a pointer in order to examine a structure at that address in memory.

GDB supports these operators, in addition to those common to programming languages:

@	Binary operator for treating parts of memory as arrays. See “Artificial arrays”, for more information.
::	Lets you specify a variable in terms of the file or function where it’s defined. See “Program variables.”

{*type***}** *addr* Refers to an object of type *type* stored at address *addr* in memory. The *addr* may be any expression whose value is an integer or pointer (but parentheses are required around binary operators, just as in a cast). This construct is allowed regardless of what kind of data is normally supposed to reside at *addr*.

Program variables

The most common kind of expression to use is the name of a variable in your program.

Variables in expressions are understood in the selected stack frame (see “Selecting a frame”); they must be either:

- global (or static)

  Or:

- visible according to the scope rules of the programming language from the point of execution in that frame

This means that in the function:

```
foo (a)
     int a;
{
  bar (a);
  {
    int b = test ();
    bar (b);
  }
}
```

you can examine and use the variable *a* whenever your program is executing within the function *foo()*, but you can use or examine the variable *b* only while your program is executing inside the block where *b* is declared.

There’s an exception: you can refer to a variable or function whose scope is a single source file even if the current execution point isn’t in this file. But it’s possible to have more than one such variable or function with the same name (in different source files). If that

happens, referring to that name has unpredictable effects. If you wish, you can specify a static variable in a particular function or file, using the colon-colon notation:

file`::`*variable*
function`::`*variable*

Here *file* or *function* is the name of the context for the static *variable*. In the case of filenames, you can use quotes to make sure GDB parses the filename as a single word. For example, to print a global value of **`x`** defined in **`f2.c`**:

```
(gdb) p 'f2.c'::x
```

This use of **`::`** is very rarely in conflict with the very similar use of the same notation in C++. GDB also supports use of the C++ scope resolution operator in GDB expressions.

Occasionally, a local variable may appear to have the wrong value at certain points in a function, such as just after entry to a new scope, and just before exit.

You may see this problem when you're stepping by machine instructions. This is because, on most machines, it takes more than one instruction to set up a stack frame (including local variable definitions); if you're stepping by machine instructions, variables may appear to have the wrong values until the stack frame is completely built. On exit, it usually also takes more than one machine instruction to destroy a stack frame; after you begin stepping through that group of instructions, local variable definitions may be gone.

Artificial arrays

It's often useful to print out several successive objects of the same type in memory; a section of an array, or an array of dynamically determined size for which only a pointer exists in the program.

You can do this by referring to a contiguous span of memory as an *artificial array*, using the binary operator `@`. The left operand of `@`

should be the first element of the desired array and be an individual object. The right operand should be the desired length of the array. The result is an array value whose elements are all of the type of the left operand. The first element is actually the left operand; the second element comes from bytes of memory immediately following those that hold the first element, and so on. For example, if a program says:

```
int *array = (int *) malloc (len * sizeof (int));
```

you can print the contents of **`array`** with:

```
p *array@len
```

The left operand of `@` must reside in memory. Array values made with `@` in this way behave just like other arrays in terms of subscripting, and are coerced to pointers when used in expressions. Artificial arrays most often appear in expressions via the value history (see "Value history"), after printing one out.

Another way to create an artificial array is to use a cast. This reinterprets a value as if it were an array. The value need not be in memory:

```
(gdb) p/x (short[2])0x12345678
$1 = {0x1234, 0x5678}
```

As a convenience, if you leave the array length out — as in (*type*[])*value* — gdb calculates the size to fill the value as **`sizeof(`***value***`)/sizeof(`***type***`)**. For example:

```
(gdb) p/x (short[])0x12345678
$2 = {0x1234, 0x5678}
```

Sometimes the artificial array mechanism isn't quite enough; in moderately complex data structures, the elements of interest may not actually be adjacent — for example, if you're interested in the values of pointers in an array. One useful workaround in this situation is to use a convenience variable (see "Convenience variables") as a counter in an expression that prints the first interesting value, and then repeat

that expression via Enter. For instance, suppose you have an array *dtab* of pointers to structures, and you're interested in the values of a field *fv* in each structure. Here's an example of what you might type:

```
set $i = 0
p dtab[$i++]->fv
Enter
Enter
...
```

Output formats

By default, GDB prints a value according to its data type. Sometimes this isn't what you want. For example, you might want to print a number in hex, or a pointer in decimal. Or you might want to view data in memory at a certain address as a character string or as an instruction. To do these things, specify an *output format* when you print a value.

The simplest use of output formats is to say how to print a value already computed. This is done by starting the arguments of the **`print`** command with a slash and a format letter. The format letters supported are:

`x` Regard the bits of the value as an integer, and print the integer in hexadecimal.

`d` Print as integer in signed decimal.

`u` Print as integer in unsigned decimal.

`o` Print as integer in octal.

`t` Print as integer in binary. The letter **`t`** stands for **`two`**. (The letter **`b`** can't be used because these format letters are also used with the **`x`** command, where **`b`** stands for **`byte`**. See "Examining memory.")

`a` Print as an address, both absolute in hexadecimal and as an offset from the nearest preceding symbol. You can use this

format used to discover where (in what function) an unknown address is located:

```
(gdb) p/a 0x54320
$3 = 0x54320 <_initialize_vx+396>
```

c Regard as an integer and print it as a character constant.

f Regard the bits of the value as a floating point number and print using typical floating point syntax.

For example, to print the program counter in hex (see “Registers”), type:

```
p/x $pc
```

No space is required before the slash; this is because command names in GDB can’t contain a slash.

To reprint the last value in the value history with a different format, you can use the **print** command with just a format and no expression. For example, **p/x** reprints the last value in hex.

Examining memory

You can use the command **x** (for “examine”) to examine memory in any of several formats, independently of your program’s data types.

x/*nfu addr*
x *addr*
x Use the **x** command to examine memory.

The *n, f*, and *u* are all optional parameters that specify how much memory to display and how to format it; *addr* is an expression giving the address where you want to start displaying memory. If you use defaults for *nfu,* you need not type the slash **/**. Several commands set convenient defaults for *addr*.

n The repeat count is a decimal integer; the default is 1. It specifies how much memory (counting by units *u*) to display.

f The display format is one of the formats used by **`print`**, **`s`** (null-terminated string), or **`i`** (machine instruction). The default is **`x`** (hexadecimal) initially. The default changes each time you use either **`x`** or **`print`**.

u The unit size is any of:

- **`b`** — bytes.
- **`h`** — halfwords (two bytes).
- **`w`** — words (four bytes). This is the initial default.
- **`g`** — giant words (eight bytes).

Each time you specify a unit size with **`x`**, that size becomes the default unit the next time you use **`x`**. (For the **`s`** and **`i`** formats, the unit size is ignored and isn't normally written.)

addr The address where you want GDB to begin displaying memory. The expression need not have a pointer value (though it may); it's always interpreted as an integer address of a byte of memory. See "Expressions" for more information on expressions. The default for *addr* is usually just after the last address examined — but several other commands also set the default address: **`info breakpoints`** (to the address of the last breakpoint listed), **`info line`** (to the starting address of a line), and **`print`** (if you use it to display a value from memory).

For example, **`x/3uh 0x54320`** is a request to display three halfwords (**`h`**) of memory, formatted as unsigned decimal integers (**`u`**), starting at address **`0x54320`**. The **`x/4xw $sp`** command prints the four words (**`w`**) of memory above the stack pointer (here, **`$sp`**; see "Registers") in hexadecimal (**`x`**).

Since the letters indicating unit sizes are all distinct from the letters specifying output formats, you don't have to remember whether unit size or format comes first; either order works. The output

specifications **4xw** and **4wx** mean exactly the same thing. (However, the count *n* must come first; **wx4** doesn't work.)

Even though the unit size *u* is ignored for the formats **s** and **i**, you might still want to use a count *n*; for example, **3i** specifies that you want to see three machine instructions, including any operands. The command **disassemble** gives an alternative way of inspecting machine instructions; see "Source and machine code."

All the defaults for the arguments to **x** are designed to make it easy to continue scanning memory with minimal specifications each time you use **x**. For example, after you've inspected three machine instructions with **x/3i** *addr*, you can inspect the next seven with just **x/7**. If you use Enter to repeat the **x** command, the repeat count *n* is used again; the other arguments default as for successive uses of **x**.

The addresses and contents printed by the **x** command aren't saved in the value history because there's often too much of them and they would get in the way. Instead, GDB makes these values available for subsequent use in expressions as values of the convenience variables **$_** and **$__**. After an **x** command, the last address examined is available for use in expressions in the convenience variable **$_** The contents of that address, as examined, are available in the convenience variable **$__**.

If the **x** command has a repeat count, the address and contents saved are from the last memory unit printed; this isn't the same as the last address printed if several units were printed on the last line of output.

Automatic display

If you find that you want to print the value of an expression frequently (to see how it changes), you might want to add it to the *automatic display list* so that GDB prints its value each time your program stops. Each expression added to the list is given a number to identify it; to remove an expression from the list, you specify that number. The automatic display looks like this:

```
2: foo = 38
3: bar[5] = (struct hack *) 0x3804
```

This display shows item numbers, expressions and their current values. As with displays you request manually using **x** or **print**, you can specify the output format you prefer; in fact, **display** decides whether to use **print** or **x** depending on how elaborate your format specification is — it uses **x** if you specify a unit size, or one of the two formats (**i** and **s**) that are supported only by **x**; otherwise it uses **print**.

display *exp*
: Add the expression *exp* to the list of expressions to display each time your program stops. See "Expressions." The **display** command doesn't repeat if you press Enter again after using it.

display/*fmt exp*
: For *fmt* specifying only a display format and not a size or count, add the expression *exp* to the auto-display list but arrange to display it each time in the specified format *fmt*. See "Output formats."

display/*fmt addr*
: For *fmt* **i** or **s**, or including a unit-size or a number of units, add the expression *addr* as a memory address to be examined each time your program stops. Examining means in effect doing **x/***fmt addr*. See "Examining memory."

For example, **display/i $pc** can be helpful, to see the machine instruction about to be executed each time execution stops (**$pc** is a common name for the program counter; see "Registers").

undisplay *dnums...*
delete display *dnums...*
: Remove item numbers *dnums* from the list of expressions to display.

  The **undisplay** command doesn't repeat if you press Enter after using it. (Otherwise you'd just get the error **No display number ...**.)

`disable display` *dnums...*

Disable the display of item numbers *dnums*. A disabled display item isn't printed automatically, but isn't forgotten; it may be enabled again later.

`enable display` *dnums...*

Enable the display of item numbers *dnums*. It becomes effective once again in auto display of its expression, until you specify otherwise.

`display` Display the current values of the expressions on the list, just as is done when your program stops.

`info display`

Print the list of expressions previously set up to display automatically, each one with its item number, but without showing the values. This includes disabled expressions, which are marked as such. It also includes expressions that wouldn't be displayed right now because they refer to automatic variables not currently available.

If a display expression refers to local variables, it doesn't make sense outside the lexical context for which it was set up. Such an expression is disabled when execution enters a context where one of its variables isn't defined.

For example, if you give the command **`display last_char`** while inside a function with an argument *last_char*, GDB displays this argument while your program continues to stop inside that function. When it stops where there's no variable *last_char*, the display is disabled automatically. The next time your program stops where *last_char* is meaningful, you can enable the display expression once again.

Print settings

GDB provides the following ways to control how arrays, structures, and symbols are printed.

These settings are useful for debugging programs in any language:

`set print address`
`set print address on`

GDB prints memory addresses showing the location of stack traces, structure values, pointer values, breakpoints, and so forth, even when it also displays the contents of those addresses. The default is **`on`**. For example, this is what a stack frame display looks like with **`set print address on`**:

```
(gdb) f
#0  set_quotes (lq=0x34c78 "<<", rq=0x34c88 ">>")
    at input.c:530
530         if (lquote != def_lquote)
```

`set print address off`

Don't print addresses when displaying their contents. For example, this is the same stack frame displayed with **`set print address off`**:

```
(gdb) set print addr off
(gdb) f
#0  set_quotes (lq="<<", rq=">>") at input.c:530
530         if (lquote != def_lquote)
```

You can use **`set print address off`** to eliminate all machine-dependent displays from the GDB interface. For example, with **`print address off`**, you should get the same text for backtraces on all machines — whether or not they involve pointer arguments.

`show print address`

Show whether or not addresses are to be printed.

When GDB prints a symbolic address, it normally prints the closest earlier symbol plus an offset. If that symbol doesn't uniquely identify the address (for example, it's a name whose scope is a single source file), you may need to clarify. One way to do this is with **`info line`**, for example **`info line *0x4537`**. Alternately, you can set GDB to print the source file and line number when it prints a symbolic address:

`set print symbol-filename on`

Tell GDB to print the source filename and line number of a symbol in the symbolic form of an address.

`set print symbol-filename off`

Don't print source filename and line number of a symbol. This is the default.

`show print symbol-filename`

Show whether or not GDB prints the source filename and line number of a symbol in the symbolic form of an address.

Another situation where it's helpful to show symbol filenames and line numbers is when disassembling code; GDB shows you the line number and source file that correspond to each instruction.

Also, you may wish to see the symbolic form only if the address being printed is reasonably close to the closest earlier symbol:

`set print max-symbolic-offset` *max-offset*

Tell GDB to display the symbolic form of an address only if the offset between the closest earlier symbol and the address is less than *max-offset*. The default is 0, which tells GDB to always print the symbolic form of an address if any symbol precedes it.

`show print max-symbolic-offset`

Ask how large the maximum offset is that GDB prints in a symbolic address.

If you have a pointer and you aren't sure where it points, try **set print symbol-filename on**. Then you can determine the name and source file location of the variable where it points, using **p/a** *pointer*. This interprets the address in symbolic form. For example, here GDB shows that a variable *ptt* points at another variable *t*, defined in **hi2.c**:

```
(gdb) set print symbol-filename on
(gdb) p/a ptt
$4 = 0xe008 <t in hi2.c>
```

For pointers that point to a local variable, **p/a** doesn't show the symbol name and filename of the referent, even with the appropriate **set print** options turned on.

Other settings control how different kinds of objects are printed:

set print array
set print array on

Pretty print arrays. This format is more convenient to read, but uses more space. The default is off.

set print array off

Return to compressed format for arrays.

show print array

Show whether compressed or pretty format is selected for displaying arrays.

set print elements *number-of-elements*

Set a limit on how many elements of an array GDB prints. If GDB is printing a large array, it stops printing after it has printed the number of elements set by the **set print elements** command. This limit also applies to the display of strings. Setting *number-of-elements* to zero means that the printing is unlimited.

show print elements

Display the number of elements of a large array that GDB prints. If the number is 0, the printing is unlimited.

set print null-stop

Cause GDB to stop printing the characters of an array when the first NULL is encountered. This is useful when large arrays actually contain only short strings.

set print pretty on

Cause GDB to print structures in an indented format with one member per line, like this:

```
$1 = {
  next = 0x0,
  flags = {
    sweet = 1,
    sour = 1
  },
  meat = 0x54 "Pork"
}
```

set print pretty off

Cause GDB to print structures in a compact format, like this:

```
$1 = {next = 0x0, flags = {sweet = 1, sour = 1}, \
meat = 0x54 "Pork"}
```

This is the default format.

show print pretty

Show which format GDB is using to print structures.

set print sevenbit-strings on

Print using only seven-bit characters; if this option is set, GDB displays any eight-bit characters (in strings or character values) using the notation *nnn*. This setting is best if you're working in English (ASCII) and you use the high-order bit of characters as a marker or "meta" bit.

`set print sevenbit-strings off`

Print full eight-bit characters. This lets you use more international character sets, and is the default.

`show print sevenbit-strings`

Show whether or not GDB is printing only seven-bit characters.

`set print union on`

Tell GDB to print unions that are contained in structures. This is the default setting.

`set print union off`

Tell GDB not to print unions that are contained in structures.

`show print union`

Ask GDB whether or not it prints unions that are contained in structures. For example, given the declarations:

```
typedef enum {Tree, Bug} Species;
typedef enum {Big_tree, Acorn, Seedling} Tree_forms;
typedef enum {Caterpillar, Cocoon, Butterfly}
             Bug_forms;

struct thing {
  Species it;
  union {
    Tree_forms tree;
    Bug_forms bug;
  } form;
};

struct thing foo = {Tree, {Acorn}};
```

with **`set print union on`** in effect, **`p foo`** prints:

```
$1 = {it = Tree, form = {tree = Acorn, bug = Cocoon}}
```

and with **`set print union off`** in effect, it prints:

```
$1 = {it = Tree, form = {...}}
```

These settings are of interest when debugging C++ programs:

`set print demangle`
`set print demangle on`

Print C++ names in their source form rather than in the encoded ("mangled") form passed to the assembler and linker for type-safe linkage. The default is **`on`**.

`show print demangle`

Show whether C++ names are printed in mangled or demangled form.

`set print asm-demangle`
`set print asm-demangle on`

Print C++ names in their source form rather than their mangled form, even in assembler code printouts such as instruction disassemblies. The default is off.

`show print asm-demangle`

Show whether C++ names in assembly listings are printed in mangled or demangled form.

`set demangle-style` *style*

Choose among several encoding schemes used by different compilers to represent C++ names. The choices for *style* are:

- **`auto`** Allow GDB to choose a decoding style by inspecting your program.
- **`gnu`** Decode based on the GNU C++ compiler (**`g++`**) encoding algorithm. This is the default.
- **`lucid`** Decode based on the Lucid C++ compiler (**`lcc`**) encoding algorithm.
- **`arm`** Decode using the algorithm in the *C++ Annotated Reference Manual*.

  This setting alone isn't sufficient to allow debugging **`cfront`**-generated executables. GDB would require further enhancement to permit that.

foo Show the list of formats.

show demangle-style

Display the encoding style currently in use for decoding C++ symbols.

set print object
set print object on

When displaying a pointer to an object, identify the *actual* (derived) type of the object rather than the *declared* type, using the virtual function table.

set print object off

Display only the declared type of objects, without reference to the virtual function table. This is the default setting.

show print object

Show whether actual, or declared, object types are displayed.

set print static-members
set print static-members on

Print static members when displaying a C++ object. The default is on.

set print static-members off

Don't print static members when displaying a C++ object.

show print static-members

Show whether C++ static members are printed, or not.

set print vtbl
set print vtbl on

Pretty print C++ virtual function tables. The default is off.

set print vtbl off

Don't pretty print C++ virtual function tables.

show print vtbl

Show whether C++ virtual function tables are pretty printed, or not.

Value history

Values printed by the **print** command are saved in the GDB *value history*. This lets you refer to them in other expressions. Values are kept until the symbol table is reread or discarded (for example with the **file** or **symbol-file** commands). When the symbol table changes, the value history is discarded, since the values may contain pointers back to the types defined in the symbol table.

The values printed are given *history numbers*, which you can use to refer to them. These are successive integers starting with 1. The **print** command shows you the history number assigned to a value by printing **$***num* **=** before the value; here *num* is the history number.

To refer to any previous value, use **$** followed by the value's history number. The way **print** labels its output is designed to remind you of this. Just **$** refers to the most recent value in the history, and **$$** refers to the value before that. **$$***n* refers to the *n*th value from the end; **$$2** is the value just prior to **$$**, **$$1** is equivalent to **$$**, and **$$0** is equivalent to **$**.

For example, suppose you have just printed a pointer to a structure and want to see the contents of the structure. It suffices to type:

```
p *$
```

If you have a chain of structures where the component **next** points to the next one, you can print the contents of the next one with this:

```
p *$.next
```

You can print successive links in the chain by repeating this command — which you can do by just typing Enter.

The history records values, not expressions. If the value of **x** is 4 and you type these commands:

```
print x
set x=5
```

then the value recorded in the value history by the **print** command remains 4 even though the value of **x** has changed.

show values

Print the last ten values in the value history, with their item numbers. This is like **p $$9** repeated ten times, except that **show values** doesn't change the history.

show values *n*

Print ten history values centered on history item number *n*.

show values +

Print ten history values just after the values last printed. If no more values are available, **show values +** produces no display.

Pressing Enter to repeat **show values** *n* has exactly the same effect as **show values +**.

Convenience variables

GDB provides *convenience variables* that you can use within GDB to hold on to a value and refer to it later. These variables exist entirely within GDB; they aren't part of your program, and setting a convenience variable has no direct effect on further execution of your program. That's why you can use them freely.

Convenience variables are prefixed with **$**. Any name preceded by **$** can be used for a convenience variable, unless it's one of the predefined machine-specific register names (see "Registers"). Value

history references, in contrast, are *numbers* preceded by **$**. See "Value history."

You can save a value in a convenience variable with an assignment expression, just as you'd set a variable in your program. For example:

```
set $foo = *object_ptr
```

saves in $*foo* the value contained in the object pointed to by *object_ptr*.

Using a convenience variable for the first time creates it, but its value is **void** until you assign a new value. You can alter the value with another assignment at any time.

Convenience variables have no fixed types. You can assign to a convenience variable any type of value, including structures and arrays, even if that variable already has a value of a different type. The convenience variable, when used as an expression, has the type of its current value.

show convenience

Print a list of convenience variables used so far, and their values. Abbreviated **show con**.

One of the ways to use a convenience variable is as a counter to be incremented or a pointer to be advanced. For example, to print a field from successive elements of an array of structures:

```
set $i = 0
print bar[$i++]->contents
```

Repeat that command by pressing Enter.

Some convenience variables are created automatically by GDB and given values likely to be useful:

$_** The variable **$_ is automatically set by the **x** command to the last address examined (see

"Examining memory"). Other commands that provide a default address for **x** to examine also set **$_** to that address; these commands include **info line** and **info breakpoint**. The type of **$_** is **void *** except when set by the **x** command, in which case it's a pointer to the type of **$__**

$__** The variable **$__ is automatically set by the **x** command to the value found in the last address examined. Its type is chosen to match the format in which the data was printed.

$_exitcode The variable **$_exitcode** is automatically set to the exit code when the program being debugged terminates.

Registers

You can refer to machine register contents, in expressions, as variables with names starting with **$**. The names of registers are different for each machine; use **info registers** to see the names used on your machine.

info registers

Print the names and values of all registers except floating-point registers (in the selected stack frame).

info all-registers

Print the names and values of all registers, including floating-point registers.

info registers *regname* ...

Print the value of each specified register *regname*. As discussed in detail below, register values are normally relative to the selected stack frame. The *regname* may be any register name valid on the machine you're using, with or without the initial **$**.

GDB has four “standard” register names that are available (in expressions) on most machines — whenever they don’t conflict with an architecture’s canonical mnemonics for registers:

$pc Program counter.

$sp Stack pointer.

$fp A register that contains a pointer to the current stack frame.

$ps A register that contains the processor status.

For example, you could print the program counter in hex with:

```
p/x $pc
```

or print the instruction to be executed next with:

```
x/i $pc
```

or add four to the stack pointer with:

```
set $sp += 4
```

This is a way of removing one word from the stack, on machines where stacks grow downward in memory (most machines, nowadays). This assumes that the innermost stack frame is selected; setting **$sp** isn’t allowed when other stack frames are selected. To pop entire frames off the stack, regardless of machine architecture, use the Enter key.

Whenever possible, these four standard register names are available on your machine even though the machine has different canonical mnemonics, so long as there’s no conflict. The **info registers** command shows the canonical names.

GDB always considers the contents of an ordinary register as an integer when the register is examined in this way. Some machines

have special registers that can hold nothing but floating point; these registers are considered to have floating point values. There's no way to refer to the contents of an ordinary register as floating point value (although you can *print* it as a floating point value with **`print/f $`***regname*).

Some registers have distinct "raw" and "virtual" data formats. This means that the data format in which the register contents are saved by the operating system isn't the same one that your program normally sees. For example, the registers of the 68881 floating point coprocessor are always saved in "extended" (raw) format, but all C programs expect to work with "double" (virtual) format. In such cases, GDB normally works with the virtual format only (the format that makes sense for your program), but the **`info registers`** command prints the data in both formats.

Normally, register values are relative to the selected stack frame (see "Selecting a frame"). This means that you get the value that the register would contain if all stack frames farther in were exited and their saved registers restored. In order to see the true contents of hardware registers, you must select the innermost frame (with **`frame 0`**).

However, GDB must deduce where registers are saved, from the machine code generated by your compiler. If some registers aren't saved, or if GDB is unable to locate the saved registers, the selected stack frame makes no difference.

Floating point hardware

Depending on the configuration, GDB may be able to give you more information about the status of the floating point hardware.

`info float` Display hardware-dependent information about the floating point unit. The exact contents and layout vary depending on the floating point chip. Currently, **`info float`** is supported on x86 machines.

Examining the symbol table

The commands described in this section allow you to inquire about the symbols (names of variables, functions and types) defined in your program. This information is inherent in the text of your program and doesn't change as your program executes. GDB finds it in your program's symbol table, in the file indicated when you started GDB (see the description of the **gdb** utility).

Occasionally, you may need to refer to symbols that contain unusual characters, which GDB ordinarily treats as word delimiters. The most frequent case is in referring to static variables in other source files (see "Program variables"). Filenames are recorded in object files as debugging symbols, but GDB ordinarily parses a typical filename, like **foo.c**, as the three words **foo**, **.**, and **c**. To allow GDB to recognize **foo.c** as a single symbol, enclose it in single quotes. For example:

```
p 'foo.c'::x
```

looks up the value of *x* in the scope of the file **foo.c**.

info address *symbol*

Describe where the data for *symbol* is stored. For a register variable, this says which register it's kept in. For a nonregister local variable, this prints the stack-frame offset at which the variable is always stored.

Note the contrast with **print &***symbol*, which doesn't work at all for a register variable, and for a stack local variable prints the exact address of the current instantiation of the variable.

whatis *exp*

Print the data type of expression *exp*. The *exp* expression isn't actually evaluated, and any side-effecting operations (such as assignments or function calls) inside it don't take place. See "Expressions."

whatis Print the data type of **$**, the last value in the value history.

ptype *typename*

Print a description of data type *typename*, which may be the name of a type, or for C code it may have the form:

- **class** *class-name*
- **struct** *struct-tag*
- **union** *union-tag*
- **enum** *enum-tag*

ptype *exp*
ptype Print a description of the type of expression *exp*. The **ptype** command differs from **whatis** by printing a detailed description, instead of just the name of the type. For example, for this variable declaration:

```
struct complex {double real; double imag;} v;
```

the two commands give this output:

```
(gdb) whatis v
type = struct complex
(gdb) ptype v
type = struct complex {
    double real;
    double imag;
}
```

As with **whatis**, using **ptype** without an argument refers to the type of **$**, the last value in the value history.

info types *regexp*
info types

Print a brief description of all types whose name matches *regexp* (or all types in your program, if you supply no argument). Each complete typename is

matched as though it were a complete line; thus, **`i type value`** gives information on all types in your program whose name includes the string **`value`**, but **`i type ^value$`** gives information only on types whose complete name is **`value`**.

This command differs from **`ptype`** in two ways: first, like **`whatis`**, it doesn't print a detailed description; second, it lists all source files where a type is defined.

`info source`

Show the name of the current source file — that is, the source file for the function containing the current point of execution — and the language it was written in.

`info sources`

Print the names of all source files in your program for which there is debugging information, organized into two lists: files whose symbols have already been read, and files whose symbols are read when needed.

`info functions`

Print the names and data types of all defined functions.

`info functions` *regexp*

Print the names and data types of all defined functions whose names contain a match for regular expression *regexp*. Thus, **`info fun step`** finds all functions whose names include **`step`**; **`info fun ^step`** finds those whose names start with **`step`**.

`info variables`

Print the names and data types of all variables that are declared outside of functions (i.e. excluding local variables).

`info variables` *regexp*

Print the names and data types of all variables (except for local variables) whose names contain a match for regular expression *regexp*.

Some systems allow individual object files that make up your program to be replaced without stopping and restarting your program. If you're running on one of these systems, you can allow GDB to reload the symbols for automatically relinked modules:

- **`set symbol-reloading on`** — replace symbol definitions for the corresponding source file when an object file with a particular name is seen again.
- **`set symbol-reloading off`** — don't replace symbol definitions when reencountering object files of the same name. This is the default state; if you aren't running on a system that permits automatically relinking modules, you should leave **`symbol-reloading`** off, since otherwise GDB may discard symbols when linking large programs, that may contain several modules (from different directories or libraries) with the same name.
- **`show symbol-reloading`** — show the current **`on`** or **`off`** setting.

`maint print symbols` *filename*
`maint print psymbols` *filename*
`maint print msymbols` *filename*

Write a dump of debugging symbol data into the file *filename*. These commands are used to debug the GDB symbol-reading code. Only symbols with debugging data are included.

- If you use **`maint print symbols`**, GDB includes all the symbols for which it has already

collected full details: that is, *filename* reflects symbols for only those files whose symbols GDB has read. You can use the command **`info sources`** to find out which files these are.

- If you use **`maint print psymbols`** instead, the dump shows information about symbols that GDB only knows partially — that is, symbols defined in files that GDB has skimmed, but not yet read completely.
- Finally, **`maint print msymbols`** dumps just the minimal symbol information required for each object file from which GDB has read some symbols.

Altering execution

Once you think you've found an error in your program, you might want to find out for certain whether correcting the apparent error would lead to correct results in the rest of the run. You can find the answer by experimenting, using the GDB features for altering execution of the program.

For example, you can store new values in variables or memory locations, give your program a signal, restart it at a different address, or even return prematurely from a function.

Assignment to variables

To alter the value of a variable, evaluate an assignment expression. See "Expressions". For example,

```
print x=4
```

stores the value 4 in the variable *x* and then prints the value of the assignment expression (which is 4).

If you aren't interested in seeing the value of the assignment, use the **`set`** command instead of the **`print`** command. The **`set`** command is

really the same as **print** except that the expression's value isn't printed and isn't put in the value history (see "Value history"). The expression is evaluated only for its effects.

If the beginning of the argument string of the **set** command appears identical to a **set** subcommand, use the **set variable** command instead of just **set**. This command is identical to **set** except for its lack of subcommands. For example, if your program has a variable *width*, you get an error if you try to set a new value with just **set width=13**, because GDB has the command **set width**:

```
(gdb) whatis width
type = double
(gdb) p width
$4 = 13
(gdb) set width=47
Invalid syntax in expression.
```

The invalid expression, of course, is **=47**. In order to actually set the program's variable *width*, use:

```
(gdb) set var width=47
```

GDB allows more implicit conversions in assignments than C; you can freely store an integer value into a pointer variable or vice versa, and you can convert any structure to any other structure that is the same length or shorter.

To store values into arbitrary places in memory, use the **{...}** construct to generate a value of specified type at a specified address (see "Expressions"). For example, **{int}0x83040** refers to memory location **0x83040** as an integer (which implies a certain size and representation in memory), and:

```
set {int}0x83040 = 4
```

stores the value 4 in that memory location.

Continuing at a different address

Ordinarily, when you continue your program, you do so at the place where it stopped, with the **`continue`** command. You can instead continue at an address of your own choosing, with the following commands:

`jump` *linespec* — Resume execution at line *linespec*. Execution stops again immediately if there's a breakpoint there. See "Printing source lines" for a description of the different forms of *linespec*.

The **`jump`** command doesn't change the current stack frame, or the stack pointer, or the contents of any memory location or any register other than the program counter. If line *linespec* is in a different function from the one currently executing, the results may be bizarre if the two functions expect different patterns of arguments or of local variables. For this reason, the **`jump`** command requests confirmation if the specified line isn't in the function currently executing. However, even bizarre results are predictable if you're well acquainted with the machine-language code of your program.

`jump *`*`address`* — Resume execution at the instruction at *address*.

You can get much the same effect as the **`jump`** command by storing a new value in the register **`$pc`**. The difference is that this doesn't start your program running; it only changes the address of where it *will* run when you continue. For example:

```
set $pc = 0x485
```

makes the next **`continue`** command or stepping command execute at address **`0x485`**, rather than at the address where your program stopped. See "Continuing and stepping."

The most common occasion to use the **jump** command is to back up — perhaps with more breakpoints set — over a portion of a program that has already executed, in order to examine its execution in more detail.

Giving your program a signal

signal< *signal*

Resume execution where your program stopped, but immediately give it the given *signal*. The *signal* can be the name or number of a signal. For example, on many systems **signal 2** and **signal SIGINT** are both ways of sending an interrupt signal.

Alternatively, if *signal* is zero, continue execution without giving a signal. This is useful when your program stopped on account of a signal and would ordinary see the signal when resumed with the **continue** command; **signal 0** causes it to resume without a signal.

The **signal** command doesn't repeat when you press Enter a second time after executing the command.

Invoking the **signal** command isn't the same as invoking the **kill** utility from the shell. Sending a signal with **kill** causes GDB to decide what to do with the signal depending on the signal handling tables (see "Signals"). The **signal** command passes the signal directly to your program.

Returning from a function

return
return *expression*

You can cancel the execution of a function call with the **return** command. If you give an *expression* argument, its value is used as the function's return value.

When you use **return**, GDB discards the selected stack frame (and all frames within it). You can think of this as making the discarded

frame return prematurely. If you wish to specify a value to be returned, give that value as the argument to **`return`**.

This pops the selected stack frame (see “Selecting a frame”) and any other frames inside it, leaving its caller as the innermost remaining frame. That frame becomes selected. The specified value is stored in the registers used for returning values of functions.

The **`return`** command doesn’t resume execution; it leaves the program stopped in the state that would exist if the function had just returned. In contrast, the **`finish`** command (see “Continuing and stepping”) resumes execution until the selected stack frame returns naturally.

Calling program functions

`call` *expr* Evaluate the expression *expr* without displaying **`void`** returned values.

You can use this variant of the **`print`** command if you want to execute a function from your program, but without cluttering the output with **`void`** returned values. If the result isn’t void, it’s printed and saved in the value history.

A user-controlled variable, *call_scratch_address*, specifies the location of a scratch area to be used when GDB calls a function in the target. This is necessary because the usual method of putting the scratch area on the stack doesn’t work in systems that have separate instruction and data spaces.

Patching programs

By default, GDB opens the file containing your program’s executable code (or the core file) read-only. This prevents accidental alterations to machine code; but it also prevents you from intentionally patching your program’s binary.

If you’d like to be able to patch the binary, you can specify that explicitly with the **`set write`** command. For example, you might

want to turn on internal debugging flags, or even to make emergency repairs.

`set write on`
`set write off`

If you specify **`set write on`**, GDB opens executable and core files for both reading and writing; if you specify **`set write off`** (the default), GDB opens them read-only.

If you've already loaded a file, you must load it again (using the **`exec-file`** or **`core-file`** command) after changing **`set write`** for your new setting to take effect.

`show write` Display whether executable files and core files are opened for writing as well as reading.

Appendix E

ARM Memory Management

In this appendix. . .

This appendix describes various features and restrictions related to the Neutrino implementation on ARM/Xscale processors:

- restrictions and issues that don't apply to other processor ports, and may need to be taken into consideration when porting code to ARM/Xscale targets.
- ARM-specific features that you can use to work around some of the restrictions imposed by the Neutrino ARM implementation

For an overview of how Neutrino manages memory, see the introduction to the Finding Memory Errors chapter of the IDE *User's Guide*.

ARM-specific restrictions and issues

This section describes the major restrictions and issues raised by the Neutrino implementation on ARM/Xscale:

- behavior of _NTO_TCTL_IO
- implications of the ARM/Xscale cache architecture

_NTO_TCTL_IO behavior

Device drivers in Neutrino use *ThreadCtl()* with the _NTO_TCTL_IO flag to obtain I/O privileges. This mechanism allows direct access to I/O ports and the ability to control processor interrupt masking.

On ARM platforms, all I/O access is memory-mapped, so this flag is used primarily to allow manipulation of the processor interrupt mask.

Normal user processes execute in the processor's User mode, and the processor silently ignores any attempts to manipulate the interrupt mask in the CPSR register (i.e. they don't cause any protection violation, and simply have no effect on the mask).

The _NTO_TCTL_IO flag makes the calling thread execute in the processor's System mode. This is a privileged mode that differs only from the Supervisor mode in its use of banked registers.

This means that such privileged user processes execute with all the access permission of kernel code:

- They can directly access kernel memory:
  - They fault if they attempt to write to read-only memory.
  - They don't fault if they write to writable mappings. This includes kernel data and also the mappings for page tables.
- They can circumvent the regular permission control for user mappings:
  - They don't fault if they write to read-only user memory.

The major consequence of this is that buggy programs using _NTO_TCTL_IO can corrupt kernel memory.

Implications of the ARM Cache Architecture

All currently supported ARM/Xscale processors implement a virtually indexed cache. This has a number of software-visible consequences:

- Whenever any virtual-to-physical address translations are changed, the cache must be flushed, because the contents of the cache no longer identify the same physical memory. This would typically have to be performed:
  - when memory is unmapped (to prevent stale cache data)
  - during a context switch (since all translations have now changed).

  The Neutrino implementation does perform this flushing when memory is unmapped, but it avoids the context-switch penalty by using the "Fast Context Switch Extension" implemented by some ARM MMUs. This is described below.
- Shared memory accessed via different virtual addresses may need to be made uncached, because the cache would contain different entries for each virtual address range. If any of these mappings are writable, it causes a coherency problem because modifications

made through one mapping aren't visible through the cache entries for other mappings.

- Memory accessed by external bus masters (e.g. DMA) may need to be made uncached:
  - If the DMA writes to memory, it will be more up to date than a cache entry that maps that memory. CPU access would get stale data from the cache.
  - If the DMA reads from memory, it may be stale if there is a cache entry that maps that memory. DMA access would get stale data from memory.

  An alternative to making such memory uncached is to modify all drivers that perform DMA access to explicitly synchronize memory when necessary:
  - before a DMA read from memory: clean and invalidate cache entries
  - after a DMA write to memory: invalidate cache entries

As mentioned, Neutrino uses the MMU Fast Context Switch Extension (FCSE) to avoid cache-flushing during context switches. Since the cost of this cache-flushing can be significant (potentially many thousands of cycles), this is crucial to a microkernel system like Neutrino because context switches are much more frequent than in a monolithic (e.g. UNIX-like) OS:

- Message passing involves context switching between sender and receiver.
- Interrupt handling involves context switching to the driver address space.

The FCSE implementation works by splitting the 4 GB virtual address space into a number of 32 MB slots. Each address space appears to have a virtual address space range of 0 - 32 MB, but the MMU transparently remaps this to a a "real" virtual address by putting the slot index into the top 7 bits of the virtual address.

For example, consider two processes: process 1 has slot index 1; process 2 has slot index 2. Each process appears to have an address space 0 - 32 MB, and their code uses those addresses for execution, loads and stores.

In reality, the virtual addresses seen by the MMU (cache and TLB) are:

- Process 1: **0x00000000-0x01FFFFFF** is mapped to **0x02000000-0x03FFFFFF**.
- Process2: **0x00000000-0x01FFFFFF** is mapped to **0x04000000-0x07FFFFFF**.

This mechanism imposes a number of restrictions:

- Each process address space is limited to 32 MB in size. This space contains all the code, data, heap, thread stacks and shared objects mapped by the process.
- The FCSE remapping uses the top 7 bits of the address space, which means there can be at most 128 slots. In practice, some of the 4 GB virtual space is required for the kernel, so the real number is lower.

  The current limit is 63 slots:

  - Slot 0 is never used.
  - Slots 64-127 (**0x80000000-0xFFFFFFFF**) are used by the kernel and the ARM-specific *shm_ctl()* support described below.

  Since each process typically has its own address space, this imposes a hard limit of at most 63 different processes.
- Because the MMU transparently remaps each process's virtual address, shared memory objects must be mapped uncached, since they're always mapped at different virtual addresses.

  Strictly speaking, this is required only if at least one writable mapping exists, but the current VM implementation doesn't track this, and unconditionally makes all mappings uncached.

The consequence of this is that performance of memory accesses to shared memory object mappings will be bound by the uncached memory performance of the system.

ARM-specific features

This section describes the ARM-specific behavior of certain operations that are provided via a processor-independent interface:

- *shm_ctl()* operations for defining special memory object properties

shm_ctl() behavior

The Neutrino implementation on ARM uses various *shm_ctl()* flags to provide some workarounds for the restrictions imposed by the MMU FCSE implementation, to provide a "global" address space above **`0x80000000`** that lets processes map objects that wouldn't otherwise fit into the (private) 32 MB process-address space.

The following flags supplied to *shm_ctl()* create a shared memory object that you can subsequently *mmap()* with special properties:

- You can use SHMCTL_PHYS to create an object that maps a physical address range that's greater than 32 MB. A process that maps such an object gets a (unique) mapping of the object in the "global address space."
- You can use SHMCTL_GLOBAL to create an object whose "global address space" mapping is the same for all processes. This address is allocated when the object is first mapped, and subsequent maps receive the virtual address allocated by the first mapping.

  Since all mappings of these objects share the same virtual address, there are a number of artifacts caused by *mmap()*:

  - If PROT_WRITE is specified, the mappings are made writable. This means all processes that have mapped now have writable access even if they initially mapped it PROT_READ only.
  - If PROT_READ only is specified, the mappings aren't changed. If this is the first *mmap()*, the mappings are made read-only, otherwise the mappings are unchanged.

- If PROT_NOCACHE isn't specified, the mappings are allowed to be cacheable since all processes share the same virtual address, and hence no cache aliases will exist.

- SHMCTL_LOWERPROT causes a *mmap()* of the object to have user-accessible mappings. By default, system-level mappings are created, which allow access only by threads that used _NTO_TCTL_IO.

  Specifying this flag allows *any* process in the system to access the object, because the virtual address is visible to all processes.

To create these special mappings:

1. Create and initialize the object:

```
fd = shm_open(name, ...)
shm_ctl(fd, ...)
```

   Note that you must be **root** to use *shm_ctl()*.

2. Map the object:

```
fd = shm_open(name, ...)
mmap( ..., fd, ...)
```

   Any process that can use *shm_open()* on the object can map it, not just the process that created the object.

The following table summarizes the effect of the various combinations of flags passed to *shm_ctl()*:

Flags	Object type	Effect of *mmap()*
SHMCTL_ANON	Anonymous memory (not contiguous)	Mapped into normal process address space. PROT_NOCACHE is forced.

continued...

Flags	Object type	Effect of *mmap()*
SHMCTL_ANON | SHMCTL_PHYS	Anonymous memory (physically contiguous)	Mapped into normal process address space. PROT_NOCACHE is forced.
SHMCTL_ANON | SHMCTL_GLOBAL	Anonymous memory (not contiguous)	Mapped into global address space. PROT_NOCACHE isn't forced. All processes receive the same mapping.
SHMCTL_ANON | SHMCTL_GLOBAL | SHMCTL_PHYS	Anonymous memory (not contiguous)	Mapped into global address space. PROT_NOCACHE isn't forced. All processes receive the same mapping.
SHMCTL_PHYS	Physical memory range	Mapped into global address space. PROT_NOCACHE is forced. Processes receive unique mappings.
SHMCTL_PHYS | SHMCTL_GLOBAL	Physical memory range	Mapped into global address space. PROT_NOCACHE isn't forced. All processes receive the same mapping.

Note that by default, *mmap()* creates privileged access mappings, so the caller must have _NTO_TCTL_IO privilege to access them.

Flags may specify SHMCTL_LOWERPROT to create user-accessible mappings. However, this allows any process to access these mappings if they're in the global address space.

Appendix F

Advanced Qnet Topics

In this appendix. . .

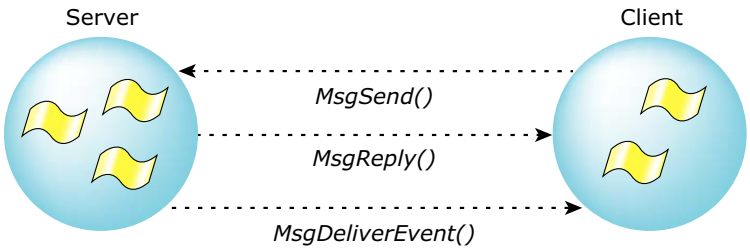
Low-level discussion on Qnet principles

The Qnet protocol extends interprocess communication (IPC) transparently over a network of microkernels. This is done by taking advantage of the Neutrino's message-passing paradigm. Message passing is the central theme of Neutrino that manages a group of cooperating processes by routing messages. This enhances the efficiency of all transactions among all processes throughout the system.

As we found out in the "How does it work?" section of the Transparent Distributed Processing Using Qnet chapter, many POSIX and other function calls are built on this message passing. For example, the *write()* function is built on the *MsgSendv()* function. In this section, you'll find several things, e.g. how Qnet works at the message passing level; how node names are resolved to node numbers, and how that number is used to create a connection to a remote node.

In order to understand how message passing works, consider two processes that wish to communicate with each other: a client process and a server process. First we consider a single-node case, where both client and server reside in the same machine. In this case, the client simply creates a connection (via *ConnectAttach()*) to the server, and then sends a message (perhaps via *MsgSend()*).

The Qnet protocol extends this message passing over to a network. For example, consider the case of a simple network with two machines: one contains the client process, the other contains the server process. The code required for client-server communication is identical (it uses same API) to the code in the single-node case. The client creates a connection to the server and sends the server a message. The only difference in the network case is that the client specifies a different node descriptor for the *ConnectAttach()* function call in order to indicate the server's node. See the diagram below to understand how message passing works.



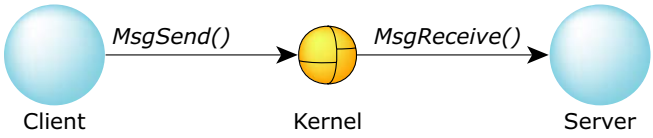
Each node in the network is assigned a unique name that becomes its identifier. This is what we call a *node descriptor*. This name is the only visible means to determine whether the OS is running as a network or as a standalone operating system.

Details of Qnet data communication

As mentioned before, Qnet relies on the message passing paradigm of Neutrino. Before any message pass, however, the application (e.g. the client) must establish a connection to the server using the low-level *ConnectAttach()* function call:

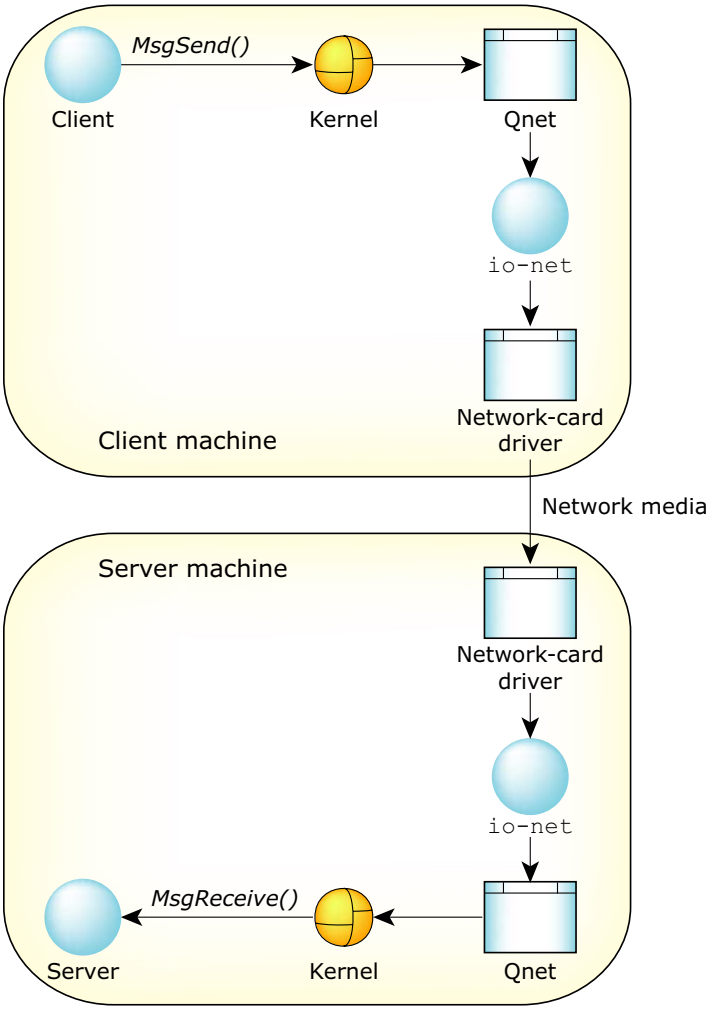
```
ConnectAttach(nd, pid, chid, index, flags);
```

In the above call, *nd* is the node descriptor that identifies each node uniquely. The node descriptor is the only visible means to determine whether the Neutrino is running as a network or as a standalone operating system. If *nd* is zero, you're specifying a local server process, and you'll get local message passing from the client to the server, carried out by the local kernel as shown below:



When you specify a nonzero value for *nd*, the application transparently passes message to a server on another machine, and connects to a server on another machine. This way, Qnet not only

builds a network of trusted machines, it lets all these machines share their resources with little overhead.



The advantage of this approach lies in using the same API. The key design features are:

- The kernel puts the user data directly into (and out of) the network card's buffers - there's no copying of the payload.

- There are no context switches as the packet travels from (and to) the kernel from the network card.

These features maximize performance for large payloads and minimize turnaround time for small packets.

Node descriptors

The <sys/netmgr.h> header file

The **<sys/netmgr.h>** header defines the ND_LOCAL_NODE macro as zero. You can use it any time that you're dealing with node descriptors to make it obvious that you're talking about the local node.

As discussed, node descriptors represent machines, but they also include *Quality of Service* information. If you want to see if two node descriptors refer to the same machine, you can't just arithmetically compare the descriptors for equality; use the *ND_NODE_CMP()* macro instead:

- If the return value from the macro is zero, the descriptors refer to the same node.
- If the value is less than 0, the first node is "less than" the second.
- If the value is greater than 0, the first node is "greater than" the second.

This is similar to the way that *strcmp()* and *memcmp()* work. It's done this way in case you want to do any sorting that's based on node descriptors.

The **<sys/netmgr.h>** header file also defines the following networking functions:

- *netmgr_strtond()*
- *netmgr_ndtostr()*
- *netmgr_remote_nd()*

netmgr_strtond()

```
int netmgr_strtond(const char *nodename, char **endstr);
```

This function converts the string pointed at by *nodename* into a node descriptor, which it returns. If there's an error, *netmgr_strtond()* returns -1 and sets *errno*. If the *endstr* parameter is non-NULL, *netmgr_strtond()* sets **endstr* to point at the first character beyond the end of the node name. This function accepts all three forms of node name — simple, directory, and FQNN (Fully Qualified NodeName). FQNN identifies a Neutrino node using a unique name on a network. The FQNN consists of the nodename and the node domain.

netmgr_ndtostr()

```
int netmgr_ndtostr(unsigned flags,
                   int nd,
                   char *buf,
                   size_t maxbuf);
```

This function converts the given node descriptor into a string and stores it in the memory pointed to by *buf*. The size of the buffer is given by *maxbuf*. The function returns the actual length of the node name (even if the function had to truncate the name to get it to fit into the space specified by *maxbuf*), or -1 if an error occurs (*errno* is set).

The *flags* parameter controls the conversion process, indicating which pieces of the string are to be output. The following bits are defined:

ND2S_DIR_SHOW,
ND2S_DIR_HIDE

> Show or hide the network directory portion of the string. If you don't set either of these bits, the string includes the network directory portion if the node isn't in the default network directory.

ND2S_QOS_SHOW,
ND2S_QOS_HIDE

Show or hide the quality of service portion of the string. If you don't specify either of these bits, the string includes the quality of service portion if it isn't the default QoS for the node.

ND2S_NAME_SHOW,
ND2S_NAME_HIDE

Show or hide the node name portion of the string. If you don't specify either of these bits, the string includes the name if the node descriptor doesn't represent the local node.

ND2S_DOMAIN_SHOW,
ND2S_DOMAIN_HIDE

Show or hide the node domain portion of the string. If you don't specify either of these bits, and a network directory portion is included in the string, the node domain is included if it isn't the default for the output network directory. If you don't specify either of these bits, and the network directory portion isn't included in the string, the node domain is included if the domain isn't in the default network directory.

By combining the above bits in various combinations, all sorts of interesting information can be extracted, for example:

ND2S_NAME_SHOW

A name that's useful for display purposes.

ND2S_DIR_HIDE | ND2S_NAME_SHOW | ND2S_DOMAIN_SHOW
A name that you can pass to another node and know that it's referring to the same machine (i.e. the FQNN).

ND2S_DIR_SHOW | ND2S_NAME_HIDE | ND2S_DOMAIN_HIDE with ND_LOCAL_NODE
The default network directory.

ND2S_DIR_HIDE | NDS2_QOS_SHOW | ND2S_NAME_HIDE | ND2S_DOMAIN_HIDE with ND_LOCAL_NODE
The default Quality of Service for the node.

netmgr_remote_nd()

```
int netmgr_remote_nd(int remote_nd, int local_nd);
```

This function takes the *local_nd* node descriptor (which is relative to this node) and returns a new node descriptor that refers to the same machine, but is valid only for the node identified by *remote_nd*. The function can return -1 in some cases (e.g. if the *remote_nd* machine can't talk to the *local_nd* machine).

Booting over the network

Overview

Unleash the power of Qnet to boot your computer (i.e. client) over the network! You can do it when your machine doesn't have a local disk or large flash. In order to do this, you first need the GRUB executable. GRUB is the generic boot loader that runs at computer startup and is responsible for loading the OS into memory and starting to execute it.

During booting, you need to load the GRUB executable into the memory of your machine, by using:

- a GRUB floppy or CD (i.e. local copy of GRUB)

  Or:

- Network card boot ROM (e.g. PXE, bootp downloads GRUB from server)

Neutrino doesn't ship GRUB. To get GRUB:

1. Go to **www.gnu.org/software/grub** website.
2. Download the GRUB executable.
3. Create a floppy or CD with GRUB on it, or put the GRUB binary on the server for downloading by a network boot ROM.

Here's what the PXE boot ROM does to download the OS image:

- The network card of your computer broadcasts a DHCP request.

- The DHCP server responds with the relevant information, such as IP address, netmask, location of the **pxegrub** server, and the menu file.
- The network card then sends a TFTP request to the **pxegrub** server to transfer the OS image to the client.

Here's an example to show the different steps to boot your client using PXE boot ROM:

Creating directory and setting up configuration files

Create a new directory on your DHCP server machine called **/tftpboot** and run **make install**. Copy the **pxegrub** executable image from **/opt/share/grub/i386-pc** to the **/tftpboot** directory.

Modify the **/etc/dhcpd.conf** file to allow the network machine to download the **pxegrub** image and configuration menu, as follows:

```
# dhcpd.conf
#
# Sample configuration file for PXE dhcpd
#

subnet 192.168.0.0 netmask 255.255.255.0 {
  range 192.168.0.2 192.168.0.250;
  option broadcast-address 192.168.0.255;
  option domain-name-servers 192.168.0.1;
}

# Hosts which require special configuration options can be listed in
# host statements.   If no address is specified, the address will be
# allocated dynamically (if possible), but the host-specific information
# will still come from the host declaration.

host testpxe {
  hardware ethernet 00:E0:29:88:0D:D3;         # MAC address of system to boot
  fixed-address 192.168.0.3;                   # This line is optional
  option option-150 "(nd)/tftpboot/menu.1st";  # Tell grub to use Menu file
  filename "/tftpboot/pxegrub";                # Location of PXE grub image
}
# End dhcpd.conf
```

If you're using an ISC 3 DHCP server, you may have to add a definition of code 150 at the top of the **dhcpd.conf** file as follows:

```
option pxe-menu code 150 = text;
```

Then instead of using **option option-150**, use:

```
option pxe-menu "(nd)/tftpboot/menu.1st";)
```

Here's an example of the **menu.1st** file:

```
# menu.1st start

default 0                           # default OS image
to load
timeout 3                           # seconds to pause
before loading default image
title Neutrino Bios image           # text displayed in menu
kernel (nd)/tftpboot/bios.ifs       # OS image
title Neutrino ftp image            # text for second OS image
kernel (nd)/tftpboot/ftp.ifs        # 2nd OS image (optional)

# menu.1st end
```

Building an OS image

In this section, there is a functional buildfile that you can use to create an OS image that can be loaded by GRUB without a hard disk or any local storage.

Create the image by typing the following:

```
$ mkifs -vvv build.txt build.img
$ cp build.img /tftpboot
```

Here is the buildfile:

In a real buildfile, you can't use a backslash (\) to break a long line into shorter pieces, but we've done that here, just to make the buildfile easier to read.

```
[virtual=x86,elf +compress] boot = {
    startup-bios

    PATH=/proc/boot:/bin:/usr/bin:/sbin:/usr/sbin: \
    /usr/local/bin:/usr/local/sbin \
    LD_LIBRARY_PATH=/proc/boot: \
    /lib:/usr/lib:/lib/dll  procnto
}

[+script] startup-script = {
    procmgr_symlink ../../proc/boot/libc.so.2 /usr/lib/ldqnx.so.2

    #
    # do magic required to set up PnP and pci bios on x86
    #
    display_msg Do the BIOS magic ...
    seedres
    pci-bios
    waitfor /dev/pci

    #
    # A really good idea is to set hostname and domain
    # before qnet is started
    #
    setconf _CS_HOSTNAME aboyd
    setconf _CS_DOMAIN   ott.qnx.com

    #
    # If you do not set the hostname to something
    # unique before qnet is started, qnet will try
    # to create and set the hostname to a hopefully
    # unique string constructed from the ethernet
    # address, which will look like EAc07f5e
    # which will probably work, but is pretty ugly.
    #

    #
    # start io-net, network driver and qnet
    #
    # NB to help debugging, add verbose=1 after -pqnet below
    #
    display_msg Starting io-net and speedo driver and qnet ...
    io-net -dspeedo -pqnet

    display_msg Waiting for ethernet driver to initialize ...
    waitfor /dev/io-net/en0 60

    display_msg Waiting for Qnet to initialize ...
    waitfor /net 60

    #
    # Now that we can fetch executables from the remote server
```

```
    # we can run devc-con and ksh, which we do not include in
    # the image, to keep the size down
    #
    # In our example, the server we are booting from
    # has the hostname qpkg and the SAME domain: ott.qnx.com
    #
    # We clean out any old bogus connections to the qpkg server
    # if we have recently rebooted quickly, by fetching a trivial
    # executable which works nicely as a sacrificial lamb
    #
    /net/qpkg/bin/true

    #
    # now print out some interesting techie-type information
    #
    display_msg hostname:
    getconf _CS_HOSTNAME
    display_msg domain:
    getconf _CS_DOMAIN
    display_msg uname -a:
    uname -a

    #
    # create some text consoles
    #
    display_msg .
    display_msg Starting 3 text consoles which you can flip
    display_msg between by holding ctrl alt + OR ctrl alt -
    display_msg .
    devc-con -n3
    waitfor /dev/con1

    #
    # start up some command line shells on the text consoles
    #
    reopen /dev/con1
    [+session] TERM=qansi HOME=/ PATH=/bin:/usr/bin:\
    /usr/local/bin:/sbin:/usr/sbin:/usr/local/sbin:\
    /proc/boot ksh &

    reopen /dev/con2
    [+session] TERM=qansi HOME=/ PATH=/bin:/usr/bin:\
    /usr/local/bin:/sbin:/usr/sbin:\
    /usr/local/sbin:/proc/boot ksh &

    reopen /dev/con3
    [+session] TERM=qansi HOME=/ PATH=/bin:\
    /usr/bin:/usr/local/bin:/sbin:/usr/sbin:\
    /usr/local/sbin:/proc/boot ksh &

    #
    # startup script ends here
    #
}

#
# Lets create some links in the virtual file system so that
# applications are fooled into thinking there's a local hard disk
#
```

```
#
# Make /tmp point to the shared memory area
#
[type=link] /tmp=/dev/shmem

#
# Redirect console (error) messages to con1
#
[type=link] /dev/console=/dev/con1

#
# Now for the diskless qnet magic.  In this example, we are booting
# using a server which has the hostname qpkg.  Since we do not have
# a hard disk, we will create links to point to the servers disk
#
[type=link] /bin=/net/qpkg/bin
[type=link] /boot=/net/qpkg/boot
[type=link] /etc=/net/qpkg/etc
[type=link] /home=/net/qpkg/home
[type=link] /lib=/net/qpkg/lib
[type=link] /opt=/net/qpkg/opt
[type=link] /pkgs=/net/qpkg/pkgs
[type=link] /root=/net/qpkg/root
[type=link] /sbin=/net/qpkg/sbin
[type=link] /usr=/net/qpkg/usr
[type=link] /var=/net/qpkg/var
[type=link] /x86=/

#
# these are essential shared libraries which must be in the
# image for us to start io-net, the ethernet driver and qnet
#
libc.so
devn-speedo.so
npm-qnet.so

#
# copy code and data for all following executables
# which will be located in /proc/boot in the image
#
[data=copy]

seedres
pci-bios
setconf
io-net
waitfor

# uncomment this for debugging
# getconf
```

Booting the client

With your DHCP server running, boot the client machine using the PXE ROM. The client machine attempts to obtain an IP address from the DHCP server and load **`pxegrub`**. If successful, it should display a menu of available images to load. Select your option for the OS image. If you don't select any available option, the BIOS image is loaded after 3 seconds. You can also use the arrow keys to select the downloaded OS image.

If all goes well, you should now be running your OS image.

Troubleshooting

If the boot is unsuccessful, troubleshoot as follows:

Make sure your:

- DHCP server is running and is configured correctly
- **`TFTP`** isn't commented out of the **`/etc/inetd.conf`** file
- all users can read **`pxegrub`** and the OS image
- **`inetd`** is running

What doesn't work ...

- Qnet's functionality is limited when applications create a shared-memory region. That only works when the applications run on the same machine.
- Server calls such as *MsgReply()*, *MsgError()*, *MsgWrite()*, *MsgRead()*, and *MsgDeliverEvent()* behave differently for local and network cases. In the local case, these calls are *non blocking*, whereas in the network case, these calls *block*. In the non blocking scenario, a lower priority thread won't run; in the network case, a lower priority thread can run.
- The **`mq`** isn't working.

- Cross-endian doesn't work. Qnet doesn't support communication between a big-endian machine and a little-endian machine. However, it works between machines of different processor types (e.g. MIPS, PPC) that are of same endian. For cross-endian development, use NFS.
- The *ConnectAttach()* function appears to succeed the first time, even if the remote node is nonoperational or is turned off. In this case, it *should* report a failure, but it doesn't. For efficiency, *ConnectAttach()* is paired up with *MsgSend()*, which in turn reports the error. For the first transmission, packets from both *ConnectAttach()* and *MsgSend()* are transmitted together.
- Qnet isn't appropriate for broadcast or multicast applications. Since you're sending messages on specific channels that target specific applications, you can't send messages to more than one node or manager at the same time.

Glossary

A20 gate

On x86-based systems, a hardware component that forces the A20 address line on the bus to zero, regardless of the actual setting of the A20 address line on the processor. This component is in place to support legacy systems, but the QNX Neutrino OS doesn't require any such hardware. Note that some processors, such as the 386EX, have the A20 gate hardware built right into the processor itself — our IPL will disable the A20 gate as soon as possible after startup.

adaptive

Scheduling algorithm whereby a thread's priority is decayed by 1. See also **FIFO**, **round robin**, and **sporadic**.

atomic

Of or relating to atoms. :-)

In operating systems, this refers to the requirement that an operation, or sequence of operations, be considered *indivisible*. For example, a thread may need to move a file position to a given location and read data. These operations must be performed in an atomic manner; otherwise, another thread could preempt the original thread and move the file position to a different location, thus causing the original thread to read data from the second thread's position.

attributes structure

Structure containing information used on a per-resource basis (as opposed to the **OCB**, which is used on a per-open basis).

This structure is also known as a **handle**. The structure definition is fixed (**`iofunc_attr_t`**), but may be extended. See also **mount structure**.

bank-switched

A term indicating that a certain memory component (usually the device holding an **image**) isn't entirely addressable by the processor. In this case, a hardware component manifests a small portion (or "window") of the device onto the processor's address bus. Special

commands have to be issued to the hardware to move the window to different locations in the device. See also **linearly mapped**.

base layer calls

Convenient set of library calls for writing resource managers. These calls all start with *resmgr_*()*. Note that while some base layer calls are unavoidable (e.g. *resmgr_pathname_attach()*), we recommend that you use the **POSIX layer calls** where possible.

BIOS/ROM Monitor extension signature

A certain sequence of bytes indicating to the BIOS or ROM Monitor that the device is to be considered an "extension" to the BIOS or ROM Monitor — control is to be transferred to the device by the BIOS or ROM Monitor, with the expectation that the device will perform additional initializations.

On the x86 architecture, the two bytes 0x55 and 0xAA must be present (in that order) as the first two bytes in the device, with control being transferred to offset 0x0003.

block-integral

The requirement that data be transferred such that individual structure components are transferred in their entirety — no partial structure component transfers are allowed.

In a resource manager, directory data must be returned to a client as **block-integral** data. This means that only complete `struct dirent` structures can be returned — it's inappropriate to return partial structures, assuming that the next _IO_READ request will "pick up" where the previous one left off.

bootable

An image can be either bootable or **nonbootable**. A bootable image is one that contains the startup code that the IPL can transfer control to.

bootfile

The part of an OS image that runs the **startup code** and the Neutrino microkernel.

budget

In **sporadic** scheduling, the amount of time a thread is permitted to execute at its normal priority before being dropped to its low priority.

buildfile

A text file containing instructions for **`mkifs`** specifying the contents and other details of an **image**, or for **`mkefs`** specifying the contents and other details of an embedded filesystem image.

canonical mode

Also called edited mode or "cooked" mode. In this mode the character device library performs line-editing operations on each received character. Only when a line is "completely entered" — typically when a carriage return (CR) is received — will the line of data be made available to application processes. Contrast **raw mode**.

channel

A kernel object used with message passing.

In QNX Neutrino, message passing is directed towards a **connection** (made to a channel); threads can receive messages from channels. A thread that wishes to receive messages creates a channel (using *ChannelCreate()*), and then receives messages from that channel (using *MsgReceive()*). Another thread that wishes to send a message to the first thread must make a connection to that channel by "attaching" to the channel (using *ConnectAttach()*) and then sending data (using *MsgSend()*).

CIFS

Common Internet File System (aka SMB) — a protocol that allows a client workstation to perform transparent file access over a network to a Windows 95/98/NT server. Client file access calls are converted to

CIFS protocol requests and are sent to the server over the network. The server receives the request, performs the actual filesystem operation, and sends a response back to the client.

CIS

Card Information Structure — a data block that maintains information about flash configuration. The CIS description includes the types of memory devices in the regions, the physical geometry of these devices, and the partitions located on the flash.

combine message

A resource manager message that consists of two or more messages. The messages are constructed as combine messages by the client's C library (e.g. *stat()*, *readblock()*), and then handled as individual messages by the resource manager.

The purpose of combine messages is to conserve network bandwidth and/or to provide support for atomic operations. See also **connect message** and **I/O message**.

connect message

In a resource manager, a message issued by the client to perform an operation based on a pathname (e.g. an **`io_open`** message). Depending on the type of connect message sent, a context block (see **OCB**) may be associated with the request and will be passed to subsequent I/O messages. See also **combine message** and **I/O message**.

connection

A kernel object used with message passing.

Connections are created by client threads to "connect" to the channels made available by servers. Once connections are established, clients can *MsgSendv()* messages over them. If a number of threads in a process all attach to the same channel, then the one connection is shared among all the threads. Channels and connections are identified within a process by a small integer.

The key thing to note is that connections and file descriptors (**FD**) are one and the same object. See also **channel** and **FD**.

context

Information retained between invocations of functionality.

When using a resource manager, the client sets up an association or **context** within the resource manager by issuing an *open()* call and getting back a file descriptor. The resource manager is responsible for storing the information required by the context (see **OCB**). When the client issues further file-descriptor based messages, the resource manager uses the OCB to determine the context for interpretation of the client's messages.

cooked mode

See **canonical mode**.

core dump

A file describing the state of a process that terminated abnormally.

critical section

A code passage that *must* be executed "serially" (i.e. by only one thread at a time). The simplest from of critical section enforcement is via a **mutex**.

deadlock

A condition in which one or more threads are unable to continue due to resource contention. A common form of deadlock can occur when one thread sends a message to another, while the other thread sends a message to the first. Both threads are now waiting for each other to reply to the message. Deadlock can be avoided by good design practices or massive kludges — we recommend the good design approach.

device driver

A process that allows the OS and application programs to make use of the underlying hardware in a generic way (e.g. a disk drive, a network interface). Unlike OSs that require device drivers to be tightly bound into the OS itself, device drivers for QNX Neutrino are standard processes that can be started and stopped dynamically. As a result, adding device drivers doesn't affect any other part of the OS — drivers can be developed and debugged like any other application. Also, device drivers are in their own protected address space, so a bug in a device driver won't cause the entire OS to shut down.

DNS

Domain Name Service — an Internet protocol used to convert ASCII domain names into IP addresses. In QNX native networking, **dns** is one of **Qnet**'s builtin resolvers.

dynamic bootfile

An OS image built on the fly. Contrast **static bootfile**.

dynamic linking

The process whereby you link your modules in such a way that the Process Manager will link them to the library modules before your program runs. The word "dynamic" here means that the association between your program and the library modules that it uses is done *at load time*, not at linktime. Contrast **static linking**. See also **runtime loading**.

edge-sensitive

One of two ways in which a **PIC** (Programmable Interrupt Controller) can be programmed to respond to interrupts. In edge-sensitive mode, the interrupt is "noticed" upon a transition to/from the rising/falling edge of a pulse. Contrast **level-sensitive**.

edited mode

See **canonical mode**.

EOI

End Of Interrupt — a command that the OS sends to the PIC after processing all Interrupt Service Routines (ISR) for that particular interrupt source so that the PIC can reset the processor's In Service Register. See also **PIC** and **ISR**.

EPROM

Erasable Programmable Read-Only Memory — a memory technology that allows the device to be programmed (typically with higher-than-operating voltages, e.g. 12V), with the characteristic that any bit (or bits) may be individually programmed from a 1 state to a 0 state. To change a bit from a 0 state into a 1 state can only be accomplished by erasing the *entire* device, setting *all* of the bits to a 1 state. Erasing is accomplished by shining an ultraviolet light through the erase window of the device for a fixed period of time (typically 10-20 minutes). The device is further characterized by having a limited number of erase cycles (typically 10e5 - 10e6). Contrast **flash** and **RAM**.

event

A notification scheme used to inform a thread that a particular condition has occurred. Events can be signals or pulses in the general case; they can also be unblocking events or interrupt events in the case of kernel timeouts and interrupt service routines. An event is delivered by a thread, a timer, the kernel, or an interrupt service routine when appropriate to the requestor of the event.

FD

File Descriptor — a client must open a file descriptor to a resource manager via the *open()* function call. The file descriptor then serves as a handle for the client to use in subsequent messages. Note that a file descriptor is the exact same object as a connection ID (*coid*, returned by *ConnectAttach()*).

FIFO

First In First Out — a scheduling algorithm whereby a thread is able to consume CPU at its priority level without bounds. See also **adaptive**, **round robin**, and **sporadic**.

flash memory

A memory technology similar in characteristics to **EPROM** memory, with the exception that erasing is performed electrically instead of via ultraviolet light, and, depending upon the organization of the flash memory device, erasing may be accomplished in blocks (typically 64k bytes at a time) instead of the entire device. Contrast **EPROM** and **RAM**.

FQNN

Fully Qualified NodeName — a unique name that identifies a QNX Neutrino node on a network. The FQNN consists of the nodename plus the node domain tacked together.

garbage collection

Aka space reclamation, the process whereby a filesystem manager recovers the space occupied by deleted files and directories.

HA

High Availability — in telecommunications and other industries, HA describes a system's ability to remain up and running without interruption for extended periods of time.

handle

A pointer that the resource manager base library binds to the pathname registered via *resmgr_attach()*. This handle is typically used to associate some kind of per-device information. Note that if you use the *iofunc_*()* **POSIX layer calls**, you must use a particular *type* of handle — in this case called an **attributes structure**.

image

In the context of embedded QNX Neutrino systems, an “image” can mean either a structure that contains files (i.e. an OS image) or a structure that can be used in a read-only, read/write, or read/write/reclaim FFS-2-compatible filesystem (i.e. a flash filesystem image).

interrupt

An event (usually caused by hardware) that interrupts whatever the processor was doing and asks it do something else. The hardware will generate an interrupt whenever it has reached some state where software intervention is required.

interrupt handler

See **ISR**.

interrupt latency

The amount of elapsed time between the generation of a hardware interrupt and the first instruction executed by the relevant interrupt service routine. Also designated as “T_{il}”. Contrast **scheduling latency**.

interrupt service routine

See **ISR**.

interrupt service thread

A thread that is responsible for performing thread-level servicing of an interrupt.

Since an **ISR** can call only a very limited number of functions, and since the amount of time spent in an ISR should be kept to a minimum, generally the bulk of the interrupt servicing work should be done by a thread. The thread attaches the interrupt (via *InterruptAttach()* or *InterruptAttachEvent()*) and then blocks (via *InterruptWait()*), waiting for the ISR to tell it to do something (by returning an event of type SIGEV_INTR). To aid in minimizing

scheduling latency, the interrupt service thread should raise its priority appropriately.

I/O message

A message that relies on an existing binding between the client and the resource manager. For example, an _IO_READ message depends on the client's having previously established an association (or **context**) with the resource manager by issuing an *open()* and getting back a file descriptor. See also **connect message**, **context**, **combine message**, and **message**.

I/O privileges

A particular right, that, if enabled for a given thread, allows the thread to perform I/O instructions (such as the x86 assembler **`in`** and **`out`** instructions). By default, I/O privileges are disabled, because a program with it enabled can wreak havoc on a system. To enable I/O privileges, the thread must be running as **`root`**, and call *ThreadCtl()*.

IPC

Interprocess Communication — the ability for two processes (or threads) to communicate. QNX Neutrino offers several forms of IPC, most notably native messaging (synchronous, client/server relationship), POSIX message queues and pipes (asynchronous), as well as signals.

IPL

Initial Program Loader — the software component that either takes control at the processor's reset vector (e.g. location 0xFFFFFFF0 on the x86), or is a BIOS extension. This component is responsible for setting up the machine into a usable state, such that the startup program can then perform further initializations. The IPL is written in assembler and C. See also **BIOS extension signature** and **startup code**.

IRQ

Interrupt Request — a hardware request line asserted by a peripheral to indicate that it requires servicing by software. The IRQ is handled by the **PIC**, which then interrupts the processor, usually causing the processor to execute an **Interrupt Service Routine (ISR)**.

ISR

Interrupt Service Routine — a routine responsible for servicing hardware (e.g. reading and/or writing some device ports), for updating some data structures shared between the ISR and the thread(s) running in the application, and for signalling the thread that some kind of event has occurred.

kernel

See **microkernel**.

level-sensitive

One of two ways in which a **PIC** (Programmable Interrupt Controller) can be programmed to respond to interrupts. If the PIC is operating in level-sensitive mode, the IRQ is considered active whenever the corresponding hardware line is active. Contrast **edge-sensitive**.

linearly mapped

A term indicating that a certain memory component is entirely addressable by the processor. Contrast **bank-switched**.

message

A parcel of bytes passed from one process to another. The OS attaches no special meaning to the content of a message — the data in a message has meaning for the sender of the message and for its receiver, but for no one else.

Message passing not only allows processes to pass data to each other, but also provides a means of synchronizing the execution of several processes. As they send, receive, and reply to messages, processes

undergo various “changes of state” that affect when, and for how long, they may run.

microkernel

A part of the operating system that provides the minimal services used by a team of optional cooperating processes, which in turn provide the higher-level OS functionality. The microkernel itself lacks filesystems and many other services normally expected of an OS; those services are provided by optional processes.

mount structure

An optional, well-defined data structure (of type **`iofunc_mount_t`**) within an *iofunc_*()* structure, which contains information used on a per-mountpoint basis (generally used only for filesystem resource managers). See also **attributes structure** and **OCB**.

mountpoint

The location in the pathname space where a resource manager has “registered” itself. For example, the serial port resource manager registers mountpoints for each serial device (**`/dev/ser1`**, **`/dev/ser2`**, etc.), and a CD-ROM filesystem may register a single mountpoint of **`/cdrom`**.

mutex

Mutual exclusion lock, a simple synchronization service used to ensure exclusive access to data shared between threads. It is typically acquired (*pthread_mutex_lock()*) and released (*pthread_mutex_unlock()*) around the code that accesses the shared data (usually a **critical section**). See also **critical section**.

name resolution

In a QNX Neutrino network, the process by which the **Qnet** network manager converts an **FQNN** to a list of destination addresses that the transport layer knows how to get to.

name resolver

Program code that attempts to convert an **FQNN** to a destination address.

NDP

Node Discovery Protocol — proprietary QNX Software Systems protocol for broadcasting name resolution requests on a QNX Neutrino LAN.

network directory

A directory in the pathname space that's implemented by the **Qnet** network manager.

Neutrino

Name of an OS developed by QNX Software Systems.

NFS

Network FileSystem — a TCP/IP application that lets you graft remote filesystems (or portions of them) onto your local namespace. Directories on the remote systems appear as part of your local filesystem and all the utilities you use for listing and managing files (e.g. **`ls`**, **`cp`**, **`mv`**) operate on the remote files exactly as they do on your local files.

NMI

Nonmaskable Interrupt — an interrupt that can't be masked by the processor. We don't recommend using an NMI!

Node Discovery Protocol

See **NDP**.

node domain

A character string that the **Qnet** network manager tacks onto the nodename to form an **FQNN**.

nodename

A unique name consisting of a character string that identifies a node on a network.

nonbootable

A nonbootable OS image is usually provided for larger embedded systems or for small embedded systems where a separate, configuration-dependent setup may be required. Think of it as a second “filesystem” that has some additional files on it. Since it’s nonbootable, it typically won’t contain the OS, startup file, etc. Contrast **bootable**.

OCB

Open Control Block (or Open Context Block) — a block of data established by a resource manager during its handling of the client’s *open()* function. This context block is bound by the resource manager to this particular request, and is then automatically passed to all subsequent I/O functions generated by the client on the file descriptor returned by the client’s *open()*.

package filesystem

A virtual filesystem manager that presents a customized view of a set of files and directories to a client. The “real” files are present on some medium; the package filesystem presents a virtual view of selected files to the client.

pathname prefix

See **mountpoint**.

pathname space mapping

The process whereby the Process Manager maintains an association between resource managers and entries in the pathname space.

persistent

When applied to storage media, the ability for the medium to retain information across a power-cycle. For example, a hard disk is a persistent storage medium, whereas a ramdisk is not, because the data is lost when power is lost.

Photon microGUI

The proprietary graphical user interface built by QNX Software Systems.

PIC

Programmable Interrupt Controller — hardware component that handles IRQs. See also **edge-sensitive**, **level-sensitive**, and **ISR**.

PID

Process ID. Also often *pid* (e.g. as an argument in a function call).

POSIX

An IEEE/ISO standard. The term is an acronym (of sorts) for Portable Operating System Interface — the "X" alludes to "UNIX", on which the interface is based.

POSIX layer calls

Convenient set of library calls for writing resource managers. The POSIX layer calls can handle even more of the common-case messages and functions than the **base layer calls**. These calls are identified by the *iofunc_*()* prefix. In order to use these (and we strongly recommend that you do), you must also use the well-defined POSIX-layer **attributes** (`iofunc_attr_t`), **OCB** (`iofunc_ocb_t`), and (optionally) **mount** (`iofunc_mount_t`) structures.

preemption

The act of suspending the execution of one thread and starting (or resuming) another. The suspended thread is said to have been "preempted" by the new thread. Whenever a lower-priority thread is

actively consuming the CPU, and a higher-priority thread becomes READY, the lower-priority thread is immediately preempted by the higher-priority thread.

prefix tree

The internal representation used by the Process Manager to store the pathname table.

priority inheritance

The characteristic of a thread that causes its priority to be raised or lowered to that of the thread that sent it a message. Also used with mutexes. Priority inheritance is a method used to prevent **priority inversion**.

priority inversion

A condition that can occur when a low-priority thread consumes CPU at a higher priority than it should. This can be caused by not supporting priority inheritance, such that when the lower-priority thread sends a message to a higher-priority thread, the higher-priority thread consumes CPU *on behalf of* the lower-priority thread. This is solved by having the higher-priority thread inherit the priority of the thread on whose behalf it's working.

process

A nonschedulable entity, which defines the address space and a few data areas. A process must have at least one **thread** running in it — this thread is then called the first thread.

process group

A collection of processes that permits the signalling of related processes. Each process in the system is a member of a process group identified by a process group ID. A newly created process joins the process group of its creator.

process group ID

The unique identifier representing a process group during its lifetime. A process group ID is a positive integer. The system may reuse a process group ID after the process group dies.

process group leader

A process whose ID is the same as its process group ID.

process ID (PID)

The unique identifier representing a process. A PID is a positive integer. The system may reuse a process ID after the process dies, provided no existing process group has the same ID. Only the Process Manager can have a process ID of 1.

pty

Pseudo-TTY — a character-based device that has two “ends”: a master end and a slave end. Data written to the master end shows up on the slave end, and vice versa. These devices are typically used to interface between a program that expects a character device and another program that wishes to use that device (e.g. the shell and the **`telnet`** daemon process, used for logging in to a system over the Internet).

pulses

In addition to the synchronous Send/Receive/Reply services, QNX Neutrino also supports fixed-size, nonblocking messages known as pulses. These carry a small payload (four bytes of data plus a single byte code). A pulse is also one form of **event** that can be returned from an ISR or a timer. See *MsgDeliverEvent()* for more information.

Qnet

The native network manager in QNX Neutrino.

QoS

Quality of Service — a policy (e.g. **`loadbalance`**) used to connect nodes in a network in order to ensure highly dependable transmission. QoS is an issue that often arises in high-availability (**HA**) networks as well as realtime control systems.

RAM

Random Access Memory — a memory technology characterized by the ability to read and write any location in the device without limitation. Contrast **flash** and **EPROM**.

raw mode

In raw input mode, the character device library performs no editing on received characters. This reduces the processing done on each character to a minimum and provides the highest performance interface for reading data. Also, raw mode is used with devices that typically generate binary data — you don't want any translations of the raw binary stream between the device and the application. Contrast **canonical mode**.

replenishment

In **sporadic** scheduling, the period of time during which a thread is allowed to consume its execution **budget**.

reset vector

The address at which the processor begins executing instructions after the processor's reset line has been activated. On the x86, for example, this is the address 0xFFFFFFF0.

resource manager

A user-level server program that accepts messages from other programs and, optionally, communicates with hardware. QNX Neutrino resource managers are responsible for presenting an interface to various types of devices, whether actual (e.g. serial ports, parallel ports, network cards, disk drives) or virtual (e.g. **`/dev/null`**, a network filesystem, and pseudo-ttys).

In other operating systems, this functionality is traditionally associated with **device drivers**. But unlike device drivers, QNX Neutrino resource managers don't require any special arrangements with the kernel. In fact, a resource manager looks just like any other user-level program. See also **device driver**.

RMA

Rate Monotonic Analysis — a set of methods used to specify, analyze, and predict the timing behavior of realtime systems.

round robin

Scheduling algorithm whereby a thread is given a certain period of time to run. Should the thread consume CPU for the entire period of its timeslice, the thread will be placed at the end of the ready queue for its priority, and the next available thread will be made READY. If a thread is the only thread READY at its priority level, it will be able to consume CPU again immediately. See also **adaptive**, **FIFO**, and **sporadic**.

runtime loading

The process whereby a program decides *while it's actually running* that it wishes to load a particular function from a library. Contrast **static linking**.

scheduling latency

The amount of time that elapses between the point when one thread makes another thread READY and when the other thread actually gets some CPU time. Note that this latency is almost always at the control of the system designer.

Also designated as "T_{sl}". Contrast **interrupt latency**.

session

A collection of process groups established for job control purposes. Each process group is a member of a session. A process belongs to the session that its process group belongs to. A newly created process

joins the session of its creator. A process can alter its session membership via *setsid()*. A session can contain multiple process groups.

session leader

A process whose death causes all processes within its process group to receive a SIGHUP signal.

software interrupts

Similar to a hardware interrupt (see **interrupt**), except that the source of the interrupt is software.

sporadic

Scheduling algorithm whereby a thread's priority can oscillate dynamically between a "foreground" or normal priority and a "background" or low priority. A thread is given an execution **budget** of time to be consumed within a certain **replenishment** period. See also **adaptive**, **FIFO**, and **round robin**.

startup code

The software component that gains control after the IPL code has performed the minimum necessary amount of initialization. After gathering information about the system, the startup code transfers control to the OS.

static bootfile

An image created at one time and then transmitted whenever a node boots. Contrast **dynamic bootfile**.

static linking

The process whereby you combine your modules with the modules from the library to form a single executable that's entirely self-contained. The word "static" implies that it's not going to change — *all* the required modules are already combined into one.

system page area

An area in the kernel that is filled by the startup code and contains information about the system (number of bytes of memory, location of serial ports, etc.) This is also called the SYSPAGE area.

thread

The schedulable entity under QNX Neutrino. A thread is a flow of execution; it exists within the context of a **process**.

timer

A kernel object used in conjunction with time-based functions. A timer is created via *timer_create()* and armed via *timer_settime()*. A timer can then deliver an **event**, either periodically or on a one-shot basis.

timeslice

A period of time assigned to a **round-robin** or **adaptive** scheduled thread. This period of time is small (on the order of tens of milliseconds); the actual value shouldn't be relied upon by any program (it's considered bad design).

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