Embedded Xinu Documentation

Release master

Douglas Comer, Dennis Brylow, and others

March 03, 2015

Contents

CHAPTER 1

Introduction

Note: This documentation, generated from files distributed with the Embedded Xinu source code, is currently under development as a replacement for the Embedded Xinu Wiki (http://xinu.mscs.mu.edu).

Embedded Xinu is an ongoing research and implementation project in the area of Operating Systems and Embedded Systems. Its original goal was to re-implement and port the *Xinu Operating System* to several embedded MIPS platforms, such as the Linksys WRT54GL router. Since then, Embedded Xinu has been ported to other platforms, such as the *QEMU MIPSel virtual environment* and the *Raspberry Pi*; see *the list of supported platforms*. Although Embedded Xinu is still being developed and ported to new platforms, a laboratory environment and curriculum materials are already in use for courses in Operating Systems, Hardware Systems, Embedded Systems, Networking, and Compilers at Marquette University and other colleges/universities.

The Embedded Xinu project was conceived and is supervised by Dr. Dennis Brylow and is being conducted by both graduate and undergraduate students in the *Systems Laboratory* in the Math, Statistics, & Computer Science department of Marquette University in Milwaukee, Wisconsin. The first major phase of work on Embedded Xinu began in the Summer of 2006.

Our project partners include Dr. Bina Ramamurthy at University of Buffalo (with whom we shared an NSF CCLI grant), Dr. Paul Ruth at University of Mississippi, and Dr. Doug Comer (father of Xinu) at Purdue University.

1.1 Getting started

To get started by downloading, compiling, and running Embedded Xinu, see *Getting started with Embedded Xinu*.

For information about the features of Embedded Xinu, see *Components and Features (platform independent)*.

Information about specific platforms is also available:

- *ARM ports (including Raspberry Pi)*
- *MIPS ports (including Linksys routers)*

1.2 Teaching with Embedded Xinu

For curriculum guidance on adopting or adapting Embedded Xinu for undergraduate coursework, see *Teaching with Embedded Xinu*.

For information about building an Embedded Xinu laboratory environment, see *Building an Embedded Xinu laboratory*.

1.3 Supported platforms

These are all the platforms on which Embedded Xinu currently runs.

Platform	Status	Comments	*PLATFORM value*	*Cross-target*
Linksys WRT54GL	Supported	This is our primary development platform, on which Xinu has been tested thoroughly.	`wrt54gl`	`mipsel`
Linksys WRT54G v8	Supported	Tested and running at the Embedded Xinu Lab. Supported via same code as WRT54GL.	`wrt54gl`	`mipsel`
Linksys WRT54G v4	Probably Supported	The v4 is apparently the version on which WRT54GL is based, and so although the Embedded Xinu Lab has not explicitly tested it, it probably works.	`wrt54gl`	`mipsel`
Linksys WRT160NL	Supported	Newer model of WRT54GL. Full O/S teaching core functioning, including wired network interface.	`wrt160nl`	`mips`
Linksys E2100L	Supported	Full O/S teaching core functioning, including wired network interface.	`e2100l`	`mips`
ASUS WL-330gE	Not actively maintained	This platform was working in the past but is no longer being actively maintained or tested.	`wl330ge`	`mipsel`
mipsel-qemu	Supported	Full O/S teaching core functioning, network support in progress.	`mipsel-qemu`	`mipsel`
Raspberry Pi	Supported	Core operating system including wired networking is functional.	`arm-rpi`	`arm-none-eabi`
arm-qemu	Supported	Core operating system, excluding wired networking, is functional.	`arm-qemu`	`arm-none-eabi`

1.4 The original Xinu

The original **Xinu** (**"Xinu is not unix"**) is a small, academic operating system to teach the concepts of operating systems to students. Developed at Purdue University by Dr. Douglas E. Comer in the early 1980s for the LSI-11 platform, it has now been ported to a variety of platforms.

Embedded Xinu is an update of this project which attempts to modernize the code base and port the system to modern RISC architectures such as MIPS, while keeping the original goals of teaching operating system concepts to students.

Note: Most places in this documentation that simply say "Xinu" or "XINU" are actually talking about Embedded Xinu.

CHAPTER 2

Getting started with Embedded Xinu

This section describes how to download and compile *Embedded Xinu*, assuming you are using a UNIX operating system such as Linux or Mac OS X, or at least a UNIX-compatible environment such as Cygwin.

2.1 Downloading the source code

Stable versions of Embedded Xinu may be downloaded from http://xinu-os.org/Downloads.

The development version (recommended, as of this writing) is stored in a repository using the git source code management system. To download it, install git and run the following command:

```
$ git clone https://github.com/xinu-os/xinu
```

You then should have a copy of the source:

```
$ cd xinu
$ ls -F
apps/    compile/  docs/     lib/     loader/   mem/ README.md  system/
AUTHORS  device/   include/  LICENSE  mailbox/  network/  shell/ test/
```

Note that Embedded Xinu is licensed under a BSD-style license; see the copyright information in the source distribution for more details.

2.2 Choosing a platform

See the *list of platforms supported by Embedded Xinu*.

Note: Each supported platform corresponds to a subdirectory of `compile/platforms/`.

If you do not have "real embedded hardware" available and simply would like to try out Embedded Xinu from your laptop or desktop, you can use either the *mipsel-qemu* or the *arm-qemu* ports, each of which runs in the QEMU system emulator.

2.3 Setting up a cross-compiler

Since most of Embedded Xinu's supported platforms do not share the same processor architecture as an x86 workstation, building Embedded Xinu typically requires an appropriate cross compiler for the C programming language. The processor architecture of each Embedded Xinu platform is listed under *Cross-target* in the *list of supported platforms*; note that this is the value to pass to `--target` when configuring binutils and gcc.

Currently, only the gcc compiler is supported. (clang does not yet work!)

2.3.1 Option 1: Install cross-compiler from repository

Some Linux distributions already have popular cross compilers available in their software repositories. When available, this can be used as a quick alternative to building from source.

2.3.2 Option 2: Build cross-compiler from source

This section documents how to build and install binutils and gcc from source in a cross-compiler configuration.

Native development environment

Before you can build anything from source, you first need appropriate development tools for your native platform, such as **gcc** and **make**.

- On Linux systems, these tools can be found in the software repositories under various names and groupings, depending on the Linux distribution.
- On Windows via Cygwin, these tools can be found under the "devel" category when you run the setup program.
- On Mac OS X, these tools come with Xcode.

binutils

Before building the C compiler itself, the corresponding binary utilities including the assembler and linker must be installed.

Note: Good practice when building any software package is to use a normal user account, and only acquire root privileges with `sudo` for installation (step 6 below).

1. Download a recent release of GNU binutils, for example:

```
$ wget ftp://ftp.gnu.org/gnu/binutils/binutils-2.23.tar.gz
```

2. Untar the binutils source:

```
$ tar xvf binutils-2.23.tar.gz
```

3. Create and enter a build directory:

```
$ mkdir binutils-2.23-build
$ cd binutils-2.23-build
```

4. Configure binutils for the appropriate target, for example:

```
$ ../binutils-2.23/configure --prefix=/opt/mipsel-dev --target=mipsel \
        --disable-nls
```

The argument given to `--prefix` is the location into which to install the binutils, and is of your choosing. Typical locations would be a subdirectory of `/opt` or `/usr/local`. (Note that installing into these locations requires `sudo` privilege in step 6. Normally, it is also possible to install software into a user's home directory, which does not require the `sudo` privilege.)

The argument given to `--target` is the target which the binutils will target, and must be set appropriately for the desired Embedded Xinu platform, as shown under *Cross-target* in the *list of supported platforms*.

`--disable-nls` simply saves time and space by not supporting any human languages other than English. You can skip this option if you want.

5. Build binutils:

```
$ make
```

6. Install binutils:

```
$ sudo make install
```

gcc

1. Download a recent release of the GNU Compiler Collection, for example:

```
$ wget ftp://ftp.gnu.org/gnu/gcc/gcc-4.8.2/gcc-4.8.2.tar.bz2
```

2. Untar the gcc source:

```
$ tar xvf gcc-4.8.2.tar.bz2
```

3. Create and enter a build directory:

```
$ mkdir gcc-4.8.2-build
$ cd gcc-4.8.2-build
```

4. Configure gcc for the appropriate target, for example:

```
$ ../gcc-4.8.2/configure --prefix=/opt/mipsel-dev --target=mipsel \
          --enable-languages=c,c++ --without-headers --disable-nls
```

`--prefix` and `--target` must be exactly the same as those chosen for the binutils installation.

`--enable-languages=c,c++` ensures that only C and C++ compilers are built, not the compilers for other languages such as Ada and Fortran that are also supported by the GNU Compiler Collection. Note:

Embedded Xinu does not actually contain C++ code, so if desired this could be stripped down to simply `--enable-languages=c`.

`--without-headers` is needed when there is no libc (standard C library) installed for the target platform, as is the case here.

`--disable-nls` simply saves time and space by not supporting any human languages other than English. You can skip this option if you want.

5. Build gcc:

```
$ make all-gcc all-target-libgcc
```

Tip: gcc can take a while to build (upwards of half an hour). You can add the argument `-jN` to **make**, where N is an integer, to run multiple compilation jobs in parallel.

---

6. Install gcc:

```
$ sudo make install-gcc install-target-libgcc
```

Testing the cross compiler

First, for convenience you may wish to make the cross-utilities available under their unqualified names by updating `$PATH`, for example:

```
export PATH="$PATH:/opt/mipsel-dev/bin"
```

The above should go in a shell startup file such as `$HOME/.bashrc`.

Test the compiler by creating a file `test.c`:

```
void f(void)
{
}
```

and compiling it with, for example:

```
mipsel-gcc -c test.c
```

This should succeed and produce a file `test.o` without any error messages.

2.4 Compiling Embedded Xinu

Having built a cross-compiler if needed, compiling Embedded Xinu now requires running **make** to process the `Makefile` in the `compile/` directory and specifying an appropriate `PLATFORM`, for example:

```
$ make -C compile PLATFORM=wrt54gl
```

Additional details follow.

2.4.1 Makefile variables

Several variables can be defined on the **make** command line to customize the build.

- `PLATFORM` specifies the name of a directory in `compile/platforms/` that is the Embedded Xinu platform for which to build the kernel.

- `COMPILER_ROOT` specifies the location of the executables for the compiler and binutils necessary to compile, assemble, and link code for the target platform. `COMPILER_ROOT` must include any target prefix that the executables may be prefixed with. Example for ARM-based platforms: `/opt/arm-dev/bin/arm-none-eabi-`. Or, if the executables are on your `$PATH`, you could simply specify, for example, `arm-none-eabi-`; however, that (or the corresponding prefix for a non-ARM-based `PLATFORM`) is already the default.
- `DETAIL` can be defined as `-DDETAIL` to enable certain debugging messages in Embedded Xinu.
- `VERBOSE` can be defined to any value to cause the build system to print the actual command lines executed when compiling, linking, assembling, etc.

To override any of the above variables, you must pass it as an argument to **make**, like in the following example:

```
$ make PLATFORM=arm-rpi
```

2.4.2 Makefile targets

The following Makefile targets are available:

- **xinu.boot** Compile Embedded Xinu normally. This is the default target.
- **debug** Same as xinu.boot, but include debugging information.
- **docs** Generate the Doxygen documentation for Embedded Xinu. This requires that Doxygen is installed. Note: to eliminate irrelevant details in the documentation, the documentation is parameterized by platform; therefore, the exact documentation that's generated will depend on the current setting of `PLATFORM` (see *Makefile variables*).
- **clean** Remove all object files.
- **docsclean** Remove documentation generated by `make docs`.
- **realclean** Remove all generated files of any kind.

The above covers the important targets, but see the `compile/Makefile` for a few additional targets that are available.

Note: Older versions of Embedded Xinu had a `make depend` target to generate header dependency information. This has been removed because this information is now generated automatically. That is, if you modify a header, the appropriate source files will now be recompiled automatically.

2.5 Next steps

Typically, after *compiling Embedded Xinu*, a file `xinu.boot` containing the kernel binary is produced. Actually running this file is largely platform-dependent. Just a few examples are:

- Raspberry Pi: See *Booting the Raspberry Pi* and *Downloading, compiling, and running XinuPi*.
- Mipsel-QEMU: See *mipsel-qemu*.
- ARM-QEMU See *arm-qemu*.

Places to go next:

- *Components and Features (platform independent)*
- *Teaching with Embedded Xinu*

2.6 Other resources

- GCC Cross-Compiler (OSDev Wiki)

CHAPTER 3

Components and Features (platform independent)

This is the documentation for major *Embedded Xinu* components and features relevant to multiple platforms. Platform-specific documentation can be found in *MIPS ports (including Linksys routers)* and *ARM ports (including Raspberry Pi)*.

3.1 Preemptive multitasking

Like virtually all modern operating systems, XINU supports **preemptive multitasking**, which makes it appear that multiple threads are executing at the same time on the same processor. Support for preemptive multitasking consists of support for multiple threads combined with a preemption mechanism.

3.1.1 Multiple threads

XINU supports multiple threads, but only one can execute at a time. A **thread context** refers to the saved state of a thread, primarily CPU registers. XINU platforms must implement two functions to allow creating new threads and switching between threads using their thread contexts:

- `setupStack()`, which is responsible for setting up the stack of a new thread to include an initial thread context and procedure arguments. This routine is typically implemented in C. It is called internally by `create()`, located in system/create.c. For an example, see system/arch/arm/setupStack.c.
- `ctxsw()`, which is responsible for switching between threads. More specifically, this routine must save the thread context of the current thread and restore the thread context of the new thread. This routine is always implemented in assembly language. For an example, see system/arch/arm/ctxsw.S.

Since different CPU architectures use different registers and calling conventions, the size and format of a thread context varies depending on the CPU architecture. Note that since thread contexts are created in both `setupStack()` and `ctxsw()`, these two routines must create contexts that are compatible, at least to the extent that `ctxsw()` can either start a new thread or resume an existing thread.

Other articles describe this in more detail for specific architectures:

- *Preemptive multitasking (ARM)*

3.1.2 Preemption

Preemption occurs when the timer interrupt occurs and XINU attempts to reschedule the currently executing thread, which results in a call to `ctxsw()`, described above, that may switch to a different thread context. (We say *may* because the code is written such that `ctxsw()` is called when the same thread is rescheduled to itself, in which

case `ctxsw()` restores the saved context immediately and is a no-op.) The means of generating a timer interrupt is platform-dependent and may even differ among platforms that share the same CPU architecture. For an example, see *BCM2835 System Timer*, which is used in the *Raspberry Pi*, an ARM-based platform.

3.2 Shell

The **XINU shell**, or **xsh**, is a subsystem that acts as a simple command-line interface for human interaction with the operating system. It is implemented in shell/.

3.2.1 How it works

Starting a shell

Note: This section explains how to programatically start a shell. By default, this is already done by system/main.c.

An instance of the XINU shell can be started by creating a thread to execute the shell() procedure. This procedure is declared as follows:

```
thread shell(int indescrp, int outdescrp, int errdescrp);
```

The shell will read and execute commands from the character device specified by `indescrp`. It shell will send any output written to stdout by the executed shell commands to the device specified by `outdescrp`, and any output written to stderr to to the device specified by `errdescrp`.

A typical instance of spawning a shell, as seen in system/main.c, is:

```
ready(create
          ((void *)shell, INITSTK, INITPRIO, "SHELL0", 3,
                     CONSOLE, CONSOLE, CONSOLE), RESCHED_NO);
```

The above uses the `CONSOLE` device for all input and output, which typically is set up as *TTY device* that wraps around the first serial port, or UART:

```
open(CONSOLE, SERIAL0);
```

If additional input or output devices, such as keyboards, framebuffers, or additional serial ports are available, additional shell threads may be started on them.

Reading and executing commands

When a user enters a command at the shell, the lexan() function divides the string of input into tokens. Command name, arguments, quoted strings, backgrounding, and redirection tokens are all recognized and divided by lexan().

After the command is parsed, the shell uses the tokens to properly execute the given command. The shell first checks for the backgrounding ampersand ('&'), which should only appear as the last token. The shell is designed to handle redirection, but does not currently do so since XINU's file system is in development.

Next, the command is looked up in the command table defined at the top of shell/shell.c. Each entry in the command table follows the format of command name, is the command built-in (ie can the command run in the background), and the function that executes the command: `{"command_name", TRUE / FALSE, xsh_function},`.

Built-in commands are executed by calling the function that implements the command. All other commands are executed by creating a new process. If the user did not include the backgrounding flag in the input, the shell waits until the command process has completed before asking for more input.

3.2.2 List of commands

Although the actual shell commands available in a given build of XINU depend on the platform and enabled features, some of the important ones are listed below:

Command	Description
clear	clears the shell's output
exit	quits the shell
help	displays the list of supported commands, or displays help about a specific command
kill	kills the specified thread
memstat	displays the current memory usage and prints the free list
memdump	dumps a region of memory
ps	displays a table of running processes
reset	soft resets the system
sleep	puts the executing thread to sleep for the specified time
test	does nothing by default, but developers can temporarily add code here
testsuite	run a series of tests to see if the system is functioning properly
uartstat	display information about a UART

A full list of commands can be obtained from the shell by running the `help` command. Help on a specific command can be obtained using `COMMAND --help` or `help COMMAND`.

3.2.3 Adding commands

The shell is designed to be expandable, allowing users to add their own commands. The code that runs the shell (shell/shell.c) and the command parser (shell/lexan.c) do not need to change when a new command is added. The majority of the work goes into writing the actual command. After the command is written, three items must be added to the system:

- the function prototype needs to be added to the header file (include/shell.h),
- the command table (shell/shell.c) must be updated, and
- the make file (shell/Makerules) must build the file containing the function.

Writing the function

The command should be given its own C source file in the shell/ directory, following the naming convention `xsh_command.c`. All command files should include `kernel.h` and `shell.h`, along with any other headers necessary for the command. Function names for commands follow the same naming convention as the source file: `xsh_command`. The method signature for a command is:

```
shellcmd xsh_command(int nargs, char *args[])
```

Within the command, arguments are accessed via the `args` array. The command name is located in `arg[0]`. Subsequent arguments, up to `nargs` are accessed via `arg[n]`. Error checking of arguments is the responsibility of the command function. It is good practice to check for the correct number of arguments; remember the command name is counted in `nargs`, so a command without any arguments should have `nargs == 1`. Although not required, command functions should also allow for an argument of `--help` as `arg[1]`. This argument should cause the command to print out usage information. When a user types `help COMMAND` in the shell, the `COMMAND` is called with the `--help` argument.

Additional code within the command function depends on what the command does. After the command is completed it should return `OK`.

Add to command table

After the command function is written, the command needs to be added to the command table so the shell is aware of the command. The command table is an array of `centry` (command entry) structures defined in `shell/shell.c`. Each entry in the command table follows the format of command name, is the command built-in (ie can the command run in the background), and the function that executes the command: `{"command_name", TRUE / FALSE, xsh_function},`.

Add to header and makefile

To complete the process, add the function prototype to the shell header file `include/shell.h`:

```
shellcmd xsh_command(int, char *[]);
```

Lastly, add the command function source file to the makefile (`shell/Makerules`) under the `C_FILES` group to ensure the command is compiled into the XINU boot image.

Example

We will run through a brief implementation of adding an echo command to the system.

Write the function

Begin by creating the source file in `shell/xsh_echo.c`. Since all commands take the same arguments (as passed by the shell), we get:

```
#include <kernel.h>
#include <stdio.h>
#include <string.h>

/**
 * Shell command echos input text to standard out.
 * @param stdin descriptor of input device
 * @param stdout descriptor of output device
 * @param stderr descriptor of error device
 * @param args array of arguments
 * @return OK for success, SYSERR for syntax error
 */
shellcmd xsh_echo(int nargs, char *args[])
{
    int i;  /* counter for looping through arguments */

    /* Output help, if '--help' argument was supplied */
    if (nargs == 2 && strcmp(args[1], "--help") == 0)
    {
        fprintf(stdout, "Usage: clear\n");
        fprintf(stdout, "Clears the terminal.\n");
        fprintf(stdout, "\t--help\t display this help and exit\n");
        return SYSERR;
    }

    /* loop through the arguments printing each as it is displayed */
    for ( i = 1; i < nargs; i++ )
    {
        fprintf(stdout, "%s ", args[i]);
```

```
    }

    /* Just so the next prompt doesn't run on to this line */
    fprintf(stdout, "\n");

    /* there were no errors so, return OK */
    return OK;
}
```

Add the function to the command table

While we are in the shell/ directory, we'll modify the command table found at the top of shell/shell.c. Since we are adding the echo command, we'll most likely want the user input at the shell to be "`echo`," this is not a builtin function (FALSE), and the function that supports this is xsh_echo. Giving us the entry:

```
{ "echo", FALSE, xsh_echo }
```

Add the function prototype to the include file

Next we must add the prototype of the function to the shell include file in include/shell.h. This is simply done by adding the line:

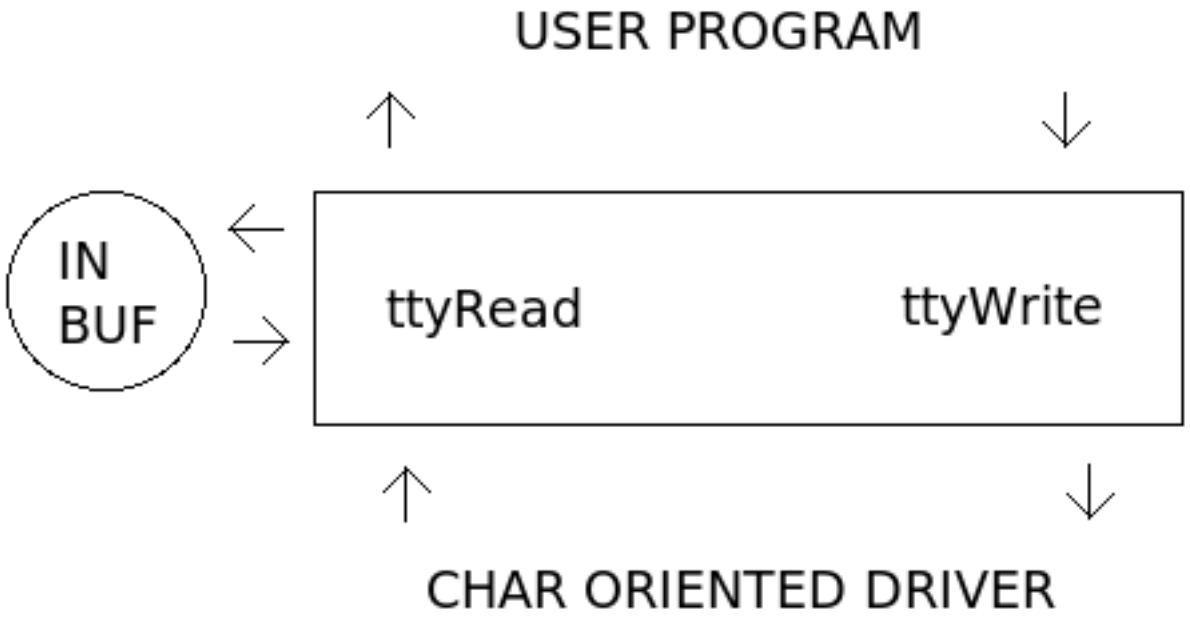
```
shellcmd xsh_echo(int, char *[]);
```

Add the file to the Makefile

Finally (and most importantly) we add the function to the Makefile to make sure that it is built by the compiler. We do this by finding the line beginning with "`C_FILES =`" in `shell/Makerules` and adding xsh_echo.c to the end of it.

Compile and run, and you should now have a working implementation of the `echo` command on your XINU system!

3.3 TTY driver



XINU's TTY driver, located in device/tty/, serves as an intermediary device between hardware device drivers and user applications to provide line buffering of input and cooking of input and output. The driver is purely software oriented and makes no direct communication with physical hardware. Instead, the TTY driver relies on an underlying device driver to communicate directly with the hardware. The *XINU Shell* utilizes a TTY device to line buffer and cook user input read from another device, such as a UART.

3.3.1 Open & Close

ttyOpen(), which should be called via open(), associates a TTY with an underlying char-oriented hardware device. The underlying device driver must provide both `getc()` and `putc()` functions for the TTY to obtain input and send output character by character. The device should already be opened and initialized before the TTY is opened. When a TTY is opened, its device control block, input buffer, and flags are initialized. No input flags are set when a TTY device is opened. The `TTY_ONLCR` output flag is set when a TTY device is opened.

ttyClose(), which should be called via close(), disassociates a TTY from its underlying device and resets the TTY's device control block.

3.3.2 Read

The TTY driver reads characters from an underlying device driver using the devices `getc()` function. Input is first buffered in the TTY driver's circular buffer before being copied to the user buffer supplied as a parameter in the `ttyRead()` function call.

The ttyRead() function begins by checking the `ieof` flag to determine if the EOF character (Control+D) was read during the last call to `ttyRead()` If the `ieof` flag is set, the function returns the `EOF` constant, defined in `stddef.h`. `EOF` is only returned once for each EOF character read by the TTY driver. A call made to `ttyRead()` after `EOF` was returned, will result in an attempt to read more characters from the underlying device driver.

If the `TTY_IRAW` flag is set, the TTY driver performs no line buffering or line editing (input cooking). The user buffer is first filled from any data remaining in the TTY driver's input buffer from the last `ttyRead()` call. The remaining portion of the user supplied buffer is filled by reading characters from the underlying device driver.

The TTY driver performs line buffering and line editing (input cooking) when the `TTY_IRAW` flag is not set. Characters are read from the underlying device driver until a line delimiter is read or the TTY driver's input buffer is full. Lines may be terminated with the newline (LF or `'\n'`) or end of file (EOF or ASCII character 0x04) characters. If the `TTY_ECHO` flag is set, each character is output as it is read.

Special handling is required for some characters to perform line editing (input cooking). If the TTY driver's input buffer contains characters, backspace (BS or `'\b'`) and delete (DEL or ASCII character 0x7F) remove the last character from the TTY's input buffer. The newline and carriage return (CR or `'\r'`) characters are cooked if certain input flags are set. The end of file character causes the `ieof` flag to be set. Any other unprintable characters are ignored.

After a line of input is buffered in the TTY's device driver, the user supplied buffer is filled from the TTY's input buffer. If the end of file character was the only character read, the `EOF` constant is returned. Otherwise, the number of characters read into the user buffer is returned.

The TTY driver has the following input flags:

- `TTY_IRAW` - reads input unbuffered and uncooked
- `TTY_INLCR` - converts `'\n'` to `'\r'`
- `TTY_IGNCR` - ignores `'\r'`
- `TTY_ICRNL` - converts `'\r'` to `'\n'`
- `TTY_ECHO` - echoes input

3.3.3 Write

The TTY driver does not buffer output; in ttyWrite(), it writes characters directly to an underlying device driver. The TTY driver cooks newlines (LF or `'\n'`) and carriage returns (CR or `'\r'`) if certain output flags are set.

The TTY driver has the following output flags:

- `TTY_ONLCR` - converts `'\n'` to `'\r\n'`
- `TTY_OCRNL` - converts `'\r'` to `'\n'`

3.3.4 Control

The TTY driver has four control functions: two to set and clear input flags and two to set and clear output flags. Each of control functions returns the previous state of the flags being changed. These are implemented in ttyControl() and should be called via control().

3.4 Memory management

Memory management is an important aspect of any operating system. As such, XINU makes use of some aspects of the underlying hardware to build up a simple-to-understand memory management system.

3.4.1 Memory allocators

XINU maintains two memory allocators that work in tandem to provide dynamic memory to both kernel and user software. The first allocator is the kernel allocator which allocates small chunks of memory from the global memory heap as needed by the kernel. The second allocator is a user allocator, that allocates memory from a per-thread memory heap as needed by user processes.

Kernel allocator

The most basic memory allocator in the system is the kernel allocator which uses the `memget` and `memfree` functions. This operates on the global kernel heap that uses the `memlist` global variable. In this allocator the kernel developer is trusted to keep track of the accounting information for memory blocks. This makes a rather straightforward API.

```
void *memptr = memget(nbytes);
memfree(memptr, nbytes);
```

As can be seen in the above API, the allocation function takes a single parameter (`nbytes`) which is the number of bytes requested. The deallocation function takes two parameters (`memptr` and `nbytes`), where `memptr` is the memory address allocated via the `memget` function and `nbytes` is the number of bytes requested with the original call.

User allocator

Unlike the kernel allocator, the user allocator does not trust the programmer to remember the amount of memory requested and instead stores the accounting information immediately before the allocated memory. To the programmer the API for user memory is simply:

```
void *memptr = malloc(nbytes);
free(memptr);
```

This allocator works on a per-thread memory list of free memory, this allows memory to be owned by the calling thread and prevents other threads from having access to the memory. This forms the basis of memory protection.

When a request for memory comes in to the allocator, it attempts to satisfy the request with free memory that has already been allocated to thread. If that fails, the allocator will then attempt to acquire memory from the region allocator (described below). Since the region allocator works at page granularity, any excess memory is inserted into the thread's free memory list for future requests. When a block of memory is free'd, the memory is returned to the thread's free memory list.

It is not until the thread is killed that the memory is removed from the thread's protection domain and made available to the region allocator.

Region allocator

The region allocator works beneath the user allocator and is initialized during the boot process. During system boot XINU uses `UHEAP_SIZE` as defined in `xinu.conf` to allocate memory for the user heap. This memory is allocated via the kernel `memget()` function and is then passed to the `memRegionInit()` function. Once the region allocator is initialized, the only user level interface to the region allocator is hidden behind the `malloc` and `free` routines.

3.4.2 Memory protection

Note: This section applies to MIPS platforms only.

Since XINU has limited resources to work with it does not provide a virtual memory system. It does take advantage of separate address spaces for each user thread running in the system, which provides simple memory protection for low overhead costs. As such, when allocating pages to the thread via the user allocator those pages will be mapped to the protection domain of the currently running thread. These protection domains are inserted into a single global page table, that hold all the page table entries and the address space identifier of the protected page.

In the memory protection subsystem, the default behaviour is to map all the kernel pages (i.e. pages that are not in the user heap), to every thread in the system as read only. This allows all threads to read from kernel data, but prevents overwriting of that data.

Translation lookaside buffer

Note: This section applies to MIPS platforms only.

To facilitate memory protection, XINU uses the translation lookaside buffer (TLB) built into the MIPS processors of the WRT54GL series of routers. When a piece of software attempts to access memory in the *user segment*, a TLB load or store exception will occur. When this occurs the processor jumps to a specific exception handler which allows the kernel to look up the page table entry, check if the faulting thread is in the same memory space as the entry, and load the entry into the TLB. If there is no mapping or the thread is not in the same address space, a memory protection violation occurs and the thread is killed.

3.5 Message passing

Message passing is one method used by XINU threads for interprocess communication. It allows threads to send individual messages to other threads by using the system calls `send`, `receive`, and `recvclr`. Each thread has memory allocated for a single message in its thread control block specifically for messages sent and received using this method. This form of message passing should not be confused with the mailbox messaging queue system also used for interprocess communication.

Upon creation, each thread is allocated memory in its thread control block for two fields which apply to this message passing system: a 4 byte (`int` type) message box to contain a single message sent to this thread, and a one byte flag (`bool` type) to signal if there is an unreceived message waiting in that thread's message box.

Threads use the functions `send(tid_typ tid, int msg)`, `receive()`, and `recvclr()` to utilize this system of message passing.

`send(tid_typ tid, int msg)` delivers the message passed in as the parameter `msg` to the message box in the thread control block of the thread with a thread id of `tid`, also passed in as a parameter. `send` will always yield the processor by calling reschedule if the receiving thread was in a state of waiting to receive a message (`THRRECV`).

`receive()` returns the message waiting in the message box of the thread control block of the thread which called `receive`. If there is no message waiting for the thread then the thread will go into a state of waiting to receive a message (`THRRECV`) until a message is passed to the thread.

`recvclr()` is a non-blocking version of `receive()`. If there is a message waiting in the message box of the thread control block of the thread which called `receive` it returns the message. If there is no message waiting for the thread, then it will simply return `OK`, signifying that there was no message waiting for the thread. Notice that this does not block the thread that called `receive` and will always immediately return either the message or `OK`.

3.6 Mailboxes

In XINU, a **mailbox** is a messaging queue used for interprocess communication. Mailboxes should not to be confused with the single *message passing* capability built into the thread control block which uses send() and receive().

XINU allows for a finite number of mailboxes to be created. Each mailbox is identified by a number. Any number of processes can send and receive messages from the mailbox, provided the processes know the correct mailbox number.

When a new mailbox is created (allocated) a maximum number of messages allowed in the queue must be specified. Memory for the messages is allocated when the mailbox is created. Once the mailbox message queue is full, processes

that attempt to send a message must wait for space in the queue. If the queue is empty, processes that attempt to receive a message must wait for a message to be enqueued. A message is 4 bytes long (`int` type).

When a mailbox is deleted all remaining messages in the queue are destroyed. Processes waiting to send or receive are released from the wait state.

3.7 Standard C Library

3.7.1 Overview

The XINU C library, or **libxc**, is a "minimal" standard C library distributed with XINU. It is intended to be easy to understand rather than high-performance or fully standards compliant. However, the functions that are implemented are mostly the same as the standard versions except as documented below.

3.7.2 API

For the sake of reducing redundancy, the full API (functions and macros) provided by libxc is not documented on this page. Instead, every function implemented in the lib/libxc directory has a detailed comment describing its behavior. Note that every C source file in this directory implements a separate externally visible function.

The library headers are:

Header	Description
ctype.h	Character types
limits.h	Limits of integer types
stdarg.h	Variable argument lists
stdint.h	Fixed-width integer types
stdio.h	Standard input and output
stdlib.h	Standard library definitions
string.h	String operators

stddef.h is also present and defines some XINU-specific types in addition to the standard `offsetof`, `size_t`, and `NULL`.

3.7.3 Deviations from standard behavior

For various reasons (usually simplicity), libxc deviates from other C libraries in the following ways:

- Many standard functions (and some headers) are simply not implemented. Examples: Floating-point mathematics functions; `setjmp()` and `longjmp()`; wide character support; locale support; time functions; complex arithmetic.
- Formatted printing and scanning support only a limited range of format specifiers. See _doscan() and _doprnt() for more information.

- The ctype functions declared in include/ctype.h do not handle `EOF` (end-of-file) as specified by C99.
- `putc()` is not implemented in libxc. In Xinu it's actually a "system call", and its arguments are reversed compared to the standard `putc()`. Use `fputc()` or `putchar()` to get standard behavior.
- The stdio functions do not buffer the output like a standard implementation would; instead they write directly to a device descriptor (rather than a `FILE` stream).
- strlcpy() is implemented, even though this is technically a nonstandard BSD extension. We do this because several places in XINU were incorrectly calling strncpy() when they expected behavior equivalent to strlcpy().

3.7.4 Platform-specific overrides

Sometimes, one would like to build the C library with optimized implementations of certain functions, usually string functions like memcpy() or strlen() written in assembly language for a particular architecture. In line with the goals of XINU, this is discouraged because this makes it more difficult for people to understand the code and find where a given function is actually defined for a given platform.

If you nevertheless still wish to do this, please do not modify the code in libxc itself unless absolutely necessary. Instead, define a variable `LIBXC_OVERRIDE_CFILES` in the platform-specific platformVars file (e.g. `compile/platforms/$(PLATFORM)/platformVars`) that is a list of C source files in libxc that should not be compiled. For example, if you override `memcpy()`, then you would specify:

```
LIBXC_OVERRIDE_CFILES := memcpy.c
```

in platformVars. You then need to provide your own implementation of the corresponding function(s), but please do it in a platform-specific directory (e.g. `system/platforms/$(PLATFORM)`) instead of in here.

This method still has the limitation that the replacement function(s) will not be included in `libxc.a` itself, only in the kernel as a whole. However, this is inconsequential for XINU where everything gets linked into a single kernel image.

3.7.5 References

- C standard library - Wikipedia
- C99 standard
- Brian Kernighan and Dennis Ritchie. *The C Programming Language*, second edition. Prentice Hall.

3.8 Networking

This is the documentation for *Embedded Xinu*'s networking subsystem, including the files under network/ as well as certain protocols implemented as device drivers (e.g. device/tcp/ and device/udp/).

3.8.1 Networking stack design

The new network stack design does not have a NET device. The read and write device function paradigm does not map well to the network stack. TCP, UDP, and RAW sockets do not read from a network device, rather a network receive thread calls a chain of receive functions to process the packet at each layer in the network stack. A write function does not work well for sending a packet since the final destination of the packet is not known until the IP and/or ARP layers. The write device function assumes the thread calling write knows exactly which device to which the data should be written. A table of netif structures (separate from devtab, the table of devices) is still maintained to

store configuration and accounting information for each underlying device (ETH, etc.) with which the network stack is receiving and sending packets.

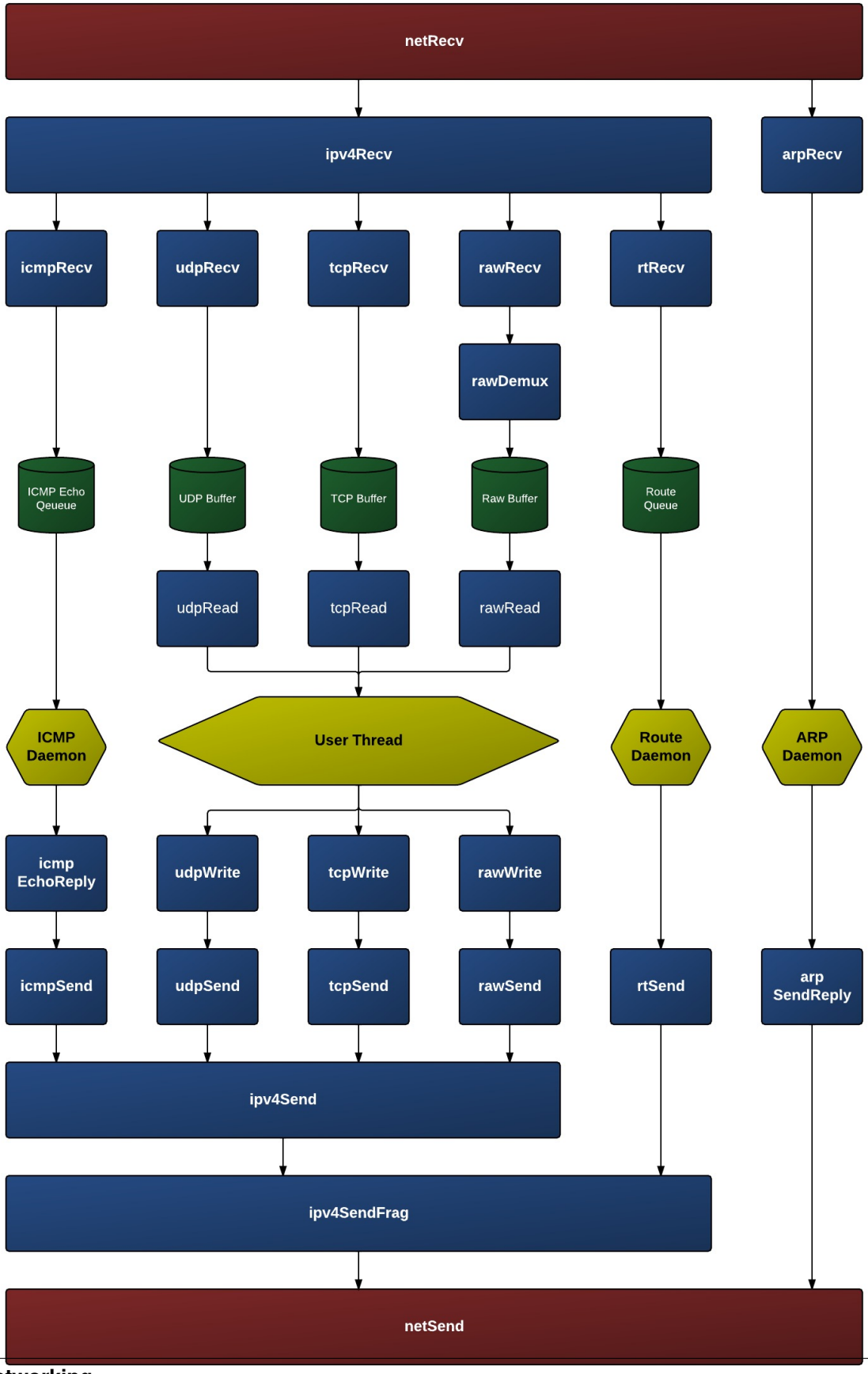
A network interface is setup using the netUp() function. An underlying device, IP address, mask, and gateway must be provided when calling `netUp()`.

Note: `netUp()` does not have *DHCP* built into it. Instead, for DHCP configuration dhcpClient() should be called before calling `netUp()`. The DHCP client will interact directly with the underlying device (ETH, etc.) without using the network stack in order to acquire IPv4 information.

Network receive threads continually read incoming packets from an underlying device. Each network interface has one or more network receive threads running. The `netRecv()` function includes an infinite loop which reads a packet from the underlying device and calls `ipv4Recv()` or `arpRecv()` depending on the type of the packet. The packet is read into a buffer declared as a local variable within the netRecv function. At the IP layer `ipv4Recv()` calls `tcpRecv()`, `udpRecv()`, `rawRecv()`, or passes the packet to a routing thread. No sending of packets should ever occur under a network receive thread. For protocols in which an incoming packet may generate the need to send a reply packet, the protocol must have a separate thread for sending. For example, if an incoming TCP packet contains data which needs to be acknowledge, and `tcpRecv()` should set a flag or send a message to a TCP monitor thread which will proceed to send the acknowledgement.

A global buffer pool is allocated for storing outgoing packets. One pool exists for use by all network interfaces. When sending a packet, the sending function (ex. `tcpSend()`) obtains a buffer from the pool, calls the appropriate lower-level send function (ex. `ipv4Send()`), and, after the function returns, returns the buffer to the pool.

The network stack is designed to treat the Xinu backend as both a router and a multi-homed host. Packets received on any of a backend's network interfaces may be destined for the backend or may need to be routed to another network destination. The network layer (IP layer) determines how to handle incoming packets. In the function `ipv4Recv()`, the destination of an IP packet is compared against the IP address and broadcast address for every active network interface. If the destination address of the IP packet matches the IP address of the interface on which it was received or the IP address of any other network interface, the packet is passed to the appropriate transport layer receive function (`udpRecv()`, `tcpRecv()`, etc.). IP packets whose destination does not match with one of the active network interfaces are passed to the routing module of the network stack, i.e. the function `rtRecv()` is called. In `rtRecv()` the packet is copied into a buffer from the global buffer pool and placed on a queue for a routing thread to process. Currently, the network stack does not use a selective drop algorithm when the router is overloaded; once the queue of packets to route is full, all subsequent packets which require routing are dropped. A routing thread processes each packet on the routing queue. If no route is known, the packet is dropped; otherwise the TTL is decrement, the checksum is recalculated and the `netSend()` function is called. Packets being sent from the transport layer (`udpSend()`, `tcpSend()`, etc) are not passed to the routing thread. The transport layer calls `ipv4Send()` which performs a route table lookup, sets up the IP packet header and calls `netSend()`.


netRecv
ipv4Recv
arpRecv
icmpRecv
udpRecv
tcpRecv
rawRecv
rtRecv
rawDemux
ICMP Echo Qeueue
UDP Buffer
TCP Buffer
Raw Buffer
Route Queue
udpRead
tcpRead
rawRead
ICMP Daemon
User Thread
Route Daemon
ARP Daemon
icmp EchoReply
udpWrite
tcpWrite
rawWrite
icmpSend
udpSend
tcpSend
rawSend
rtSend
arp SendReply
ipv4Send
ipv4SendFrag
netSend

3.8.2 ARP

As part of its *networking subsystem*, XINU supports the **Address Resolution Protocol** (**ARP**), which allows protocol addresses (e.g. IPv4 addresses) to be translated into hardware addresses (e.g. MAC addresses).

ARP daemon

The ARP daemon is run automatically on start up and waits for incoming ARP packets. Incoming packets are filtered through netRecv() and ARP requests/replies are sent on to the ARP Daemon.

Use of ARP when sending packets

Callers of netSend() do not need to specify `hwaddr`, the hardware address of the destination computer, and can leave this parameter as `NULL`. In such cases arpLookup() is called to try to map the destination protocol address to a hardware address. This first searches the ARP table, but if the relevant entry is not found, an ARP request is sent. In the latter case, the calling thread is put to sleep until the ARP daemon wakes it up after receiving the corresponding reply, or until a designated timeout has elapsed.

Shell commands

To print the ARP table, run the **arp** command from the *XINU shell*:

```
xsh@supervoc$ arp

Address                 HWaddress               Interface
192.168.6.10            52:54:03:02:B1:06       ETH0
192.168.6.101           00:16:B6:28:7D:4F       ETH0
192.168.6.130           00:25:9C:3A:87:53       ETH0
```

Currently there is no way to add/remove entries or clear the ARP table manually.

Resources

- RFC826

3.8.3 Routing

As part of its *Networking subsystem*, XINU supports IPv4 routing.

At the center of the routing module is the *routing daemon*, which repeatedly retrieves packets from a *mailbox* on which packets can be placed using rtRecv() and routes them to their destinations (or sends special packets such as *ICMP* unreachable packets) by calling rtSend(). To route packets, the routing daemon makes use of a routing table. Routing table entries can be programatically added and removed with rtAdd() and rtRemove(), respectively. The shell command **route** relies on both these functions.

Add a Route

To add a route to the route entry table use **route add** with the following parameters:

```
route add <destination> <gateway> <mask> <interface>
```

Example:

```
route add 192.168.6.0 192.168.1.100 255.255.255.0 ETH0
```

Relevant source code: xsh_route(), rtAdd()

Delete a Route

To delete a route from the route entry table, use **route del** with the destination as the third parameter:

```
route del <destination>
```

Example:

```
route del 192.168.6.0
```

Relevant source code: xsh_route(), rtRemove().

Debugging

The routing subsystem contains *Trace statements* for debugging. To enable, uncomment the following line in include/route.h, and optionally change the device (such as TTY1) to which messages will be logged:

```
// #define TRACE_RT TTY1
```

3.8.4 ICMP

As part of its *Networking subsystem*, XINU supports the **Internet Control Message Protocol** (**ICMP**). The support can be found in the network/icmp/ directory. This module features an ICMP daemon that runs on start up and responds to ICMP echo requests(pings). The module implements the function icmpEchoRequest(), which is used by the **ping** *shell command* to send ICMP echo requests to the specified IPv4 address.

Note that order to either send or reply to ICMP echo packets, the network interface needs to be brought up (e.g. by using the **netup** at the shell).

Resources

- RFC792

3.8.5 TCP

XINU supports the **Transmission Control Protocol** (**TCP**). The support can be found in the device/tcp/ directory. Note that this is *not* in the network/ directory; this is because the TCP module is designed to provide **TCP devices** that can be controlled using the generic XINU device functions such as `open()`, `control()`, `read()`, `write()`, `close()`.

Debugging

The TCP module contains *Trace statements* for debugging. To enable, uncomment the following line in include/tcp.h, and optionally change the device (such as TTY1) to which messages will be logged:

```
// #define TRACE_TCP  TTY1
```

Example - TCP Echo Test

About

This is a simple TCP usage example. It is an echo test client that sends a message to the echo server and then prints out the reply. The echo protocol is defined in RFC 862. In short, we send a message to the server, and the server echos the exact same message back.

Usage

- Add the source file as `shell/xsh_echotest.c`.
- Modify `shell/shell.c` and `include/shell.h` to include the **echotest** command.
- Modify `shell/Makerules` to include `xsh_echotest.c` and then make XINU from the compile directory
- Boot XINU
- Run **netup** command from the shell
- Run **echoclient** from the shell with the arguments of the echoserver's IP address and the message to be sent in quotes, for example:

```
echoclient 192.168.6.102 "Hello XINU World!"
```

xsh_echotest.c

```
#include <stddef.h>
#include <stdio.h>
#include <device.h>
#include <ether.h>
#include <tcp.h>
#include <string.h>

#define MSG_MAX_LEN 64
#define ECHO_PORT 7

/**
 * Shell command (echotest) sends a message to an echo server per RFC 862.
 * It waits for a response, then prints out the reply from the echo server.
 * Expects args: echotest, echo server ip, Message to echo in quotes
 * @param nargs number of arguments in args array
 * @param args  array of arguments
 * @return non-zero value on error
 */
shellcmd xsh_echotest(int nargs, char *args[])
{
    ushort dev = 0;
    char buf[MSG_MAX_LEN + 1];
```

```
char *dest = args[1];

struct netaddr dst;
struct netaddr *localhost;
struct netif *interface;

int len;

/* Allocate a new TCP device */
if ((ushort)SYSERR == (dev = tcpAlloc()))
{
    fprintf(stderr, "Client: Failed to allocate a TCP device.");
    return SYSERR;
}

/* Look up local ip info */
interface = netLookup((ethertab[0].dev)->num);
if (NULL == interface)
{
    fprintf(stderr, "Client: No network interface found\r\n");
    return SYSERR;
}
localhost = &(interface->ip);

/* Change the destination to ipv4 */
if (SYSERR == dot2ipv4(dest, &dst))
{
    fprintf(stderr, "Client: Failed to convert ip address.");
    return SYSERR;
}

/* Open the TCP device with the destination and echo port*/
if (SYSERR == open(dev, localhost, &dst, NULL, ECHO_PORT, TCP_ACTIVE))
{
    fprintf(stderr, "Client: Could not open the TCP device\r\n");
    return SYSERR;
}

/* Send the message to the destination*/
memcpy(buf, args[2], MSG_MAX_LEN);

if(SYSERR == write(dev, buf, MSG_MAX_LEN))
{
    fprintf(stderr, "Client: Error writing packet to the network");
    close(dev);
    return SYSERR;
}

/* Read a response from the server */
if(SYSERR != (len = read(dev, buf, MSG_MAX_LEN)))
{
    /* Manual null termination needed in case of bad/malicious response  */
    buf[len] = '\0';
    printf("Client: Got response - %s\r\n", buf);
}

/* Close the device when done */
close(dev);
```

```
    return 0;
}
```

Resources

- Transmission Control Protocol - Wikipedia
- RFC793

3.8.6 UDP

XINU supports the **User Datagram Protocol** (**UDP**). The support can be found in the device/udp/ directory. Note that this is *not* in the network/ directory; this is because the UDP module is designed to provide **UDP devices** that can be controlled using the generic XINU device functions such as `open()`, `control()`, `read()`, `write()`, `close()`.

Debugging

The UDP module contains *Trace statements* for debugging. To enable, uncomment the following line in include/udp.h, and optionally change the device (such as TTY1) to which messages will be logged:

```
// #define TRACE_UDP  TTY1
```

Example (TFTP client)

See network/tftp/tftpGet.c. This supports a real protocol (TFTP GET), although there are some complications in the code.

Example (client + server)

About

This is a simple example of how to use the UDP networking features in XINU (version 2.0 and later).

Usage

- Add the both of the files to the shell directory as `xsh_udpclient.c` and `xsh_udpserver.c`.
- Modify `system/shell.c` and `include/shell.h` to include the udpclient and udpserver commands.

- Modify `shell/Makerules` to include `xsh_udpclient.c` and `xsh_udpserver.c`, then make XINU from the compile directory
- Boot two separate XINU consoles
- Run **netup** from the shell on both consoles
- Run **udpserver** from the shell on the first console
- Run **udpclient** from the shell on the second console with the arguments of the udpserver's ip and the message to be sent in quotes, for example:

```
udpclient 192.168.6.102 "Hello XINU World!"
```

xsh_udpclient.c

```
#include <stddef.h>
#include <stdio.h>
#include <device.h>
#include <ether.h>
#include <udp.h>
#include <string.h>

#define MSG_MAX_LEN 64
#define ECHO_PORT 9989


/**
* Shell command (udpclient) runs a client that sends an ASCII
* message over the network to a server using UDP.
* Expects arg0 to be echoclient, args1 to be the destination IP
  address, args2 to be the message in quotes
* @param nargs number of arguments in args array
* @param args array of arguments
* @return non-zero value on error
*/
shellcmd xsh_udpclient(int nargs, char *args[])
{
    ushort dev = 0;
    char buf[MSG_MAX_LEN];

    char *dest = args[1];

    struct netaddr dst;
    struct netaddr *localhost;
    struct netif *interface;


    /* Allocate a new UDP device */
    if ((ushort)SYSERR == (dev = udpAlloc()))
    {
        fprintf(stderr, "Client: Failed to allocate a UDP device.");
        return SYSERR;
    }

    /* Look up local ip info */
    interface = netLookup((ethertab[0].dev)->num);
    if (NULL == interface)
    {
```

```
        fprintf(stderr, "Client: No network interface found\r\n");
        return SYSERR;
    }
    localhost = &(interface->ip);

    /* Change the destination to ipv4 */
    if (SYSERR == dot2ipv4(dest, &dst))
    {
        fprintf(stderr, "Client: Failed to convert ip address.");
        return SYSERR;
    }

    /* Open the UDP device with the destination and echo port*/
    if (SYSERR == open(dev, localhost, &dst, NULL, ECHO_PORT))
    {
        fprintf(stderr, "Client: Could not open the UDP device\r\n");
        return SYSERR;
    }

    /* Send the message to the destination*/
    memcpy(buf, args[2], MSG_MAX_LEN);

    if(SYSERR == write(dev, buf, MSG_MAX_LEN))
    {
        close(dev);
        return SYSERR;
    }

    /* Closee the device when done */
    close(dev);

    return 0;
}
```

xsh_udpserver.c

```
#include <stddef.h>
#include <stdio.h>
#include <device.h>
#include <udp.h>
#include <stdlib.h>
#include <ether.h>
#include <string.h>

#define ECHO_PORT 9989

/**
* Shell command (udpserver) runs a UDP server that waits for an
* incoming message, and then prints it out. Does not expect any
* arguments.
* @param nargs number of arguments in args array
* @param args array of arguments
* @return non-zero value on error
*/
shellcmd xsh_echoserver(int nargs, char *args[])
{
```

```
ushort dev = 0;
int len = 0;

char buffer[UDP_MAX_DATALEN];

struct netaddr *localhost;

struct netif *interface;
struct udpPseudoHdr *pseudo;
struct udpPkt *udp;


/* Allocate a new UDP device */
if ((ushort)SYSERR == (dev = udpAlloc()))
{
    fprintf(stderr, "Server: Failed to allocate a UDP device.\r\n");
    return SYSERR;
}

/* Look up local ip info */
interface = netLookup((ethertab[0].dev)->num);

if (NULL == interface)
{
    fprintf(stderr, "Server: No network interface found\r\n");
    return SYSERR;
}


/* Open the UDP device using localhost and the echo port to listen to*/
localhost = &(interface->ip);

if (SYSERR == open(dev, localhost, NULL, ECHO_PORT, NULL))
{
    fprintf(stderr, "Server: Could not open the UDP device\r\n");
    return SYSERR;
}

/* Set the UDP device to passive mode */
if (SYSERR == control(dev, UDP_CTRL_SETFLAG, UDP_FLAG_PASSIVE, NULL))
{
    kprintf("Server: Could not set UDP device to passive mode\r\n");
    close(dev);
    return SYSERR;
}


/* Read lop, wait for a new request */
printf("Server: Waiting for message\r\n");

while (SYSERR != (len = read(dev, buffer, UDP_MAX_DATALEN)))
{
    pseudo = (struct udpPseudoHdr *)buffer;
    udp = (struct udpPkt *)(pseudo + 1);
    printf("Server: Received Message - %s\r\n", udp->data);
}

    close(dev);
```

```
    return 0;
}
```

Resources

- User Datagram Protocol - Wikipedia
- RFC768

3.8.7 DHCP

DHCP (**Dynamic Host Configuration Protocol**) support has been added to XINU as part of its *networking subsystem*. Currently, only IPv4 client support— that is, acquiring IPv4 address information— is supported. The code is located in network/dhcpc, and the API is declared in include/dhcpc.h.

In addition to basic IPv4 information (assigned IPv4 address, netmask, and gateway) the DHCP client returns the "bootfile" and "next-server" options if they are provided by the DHCP server. If specified, this information can be used to download the boot file using XINU's *TFTP client*.

Note: This page refers specifically to the DHCP client support built into XINU, which is completely separate from the DHCP support included in CFE, which is third-party firmware.

Resources

- Dynamic Host Configuration Protocol - Wikipedia
- RFC2131

3.8.8 TFTP

TFTP (**Trivial File Transfer Protocol**) support has been added to XINU as part of its *networking subsystem*. Currently, only client support has been implemented, and even then only TFTP Get requests are supported. (That is, downloading files is supported but uploading files is not.) The API is declared in include/tftp.h and includes tftpGet() and tftpGetIntoBuffer(). See the API documentation for more information.

Note that this page refers specifically to the TFTP client support built into XINU, which is completely separate from the TFTP support included in *CFE* on the various MIPS-based routers, which is third-party firmware.

include/tftp.h also includes several compile-time parameters and a *trace macro* that can be enabled for the TFTP code.

Resources

- Trivial File Transfer Protocol - Wikipedia
- RFC1350

3.9 USB

USB (Universal Serial Bus) is a standard for connecting devices to a computer system. It supports an immense range of devices, including (but not limited to) keyboards, mice, flash drives, microphones, and network adapters.

Although USB is ubiquitous in modern computer systems, even in some "embedded" devices, it is very challenging to implement software support for USB. This is primarily a result of the high complexity of USB, which arises from several factors, including support for virtually any arbitrary device, support for dynamic device attachment and detachment, backwards compatibility with multiple versions of the USB specification, and multiple supported speeds and transfer types. The USB 2.0 specification is 650 pages long, yet only covers a fraction of the information needed to implement, from scratch, a USB software stack and a driver controlling a specific USB device.

Due to the high complexity of USB, this article cannot fully explain USB, nor can it even fully explain Embedded Xinu's implementation of USB. Instead, it gives an overview of USB in the context of Embedded Xinu's implementation. For full details about USB, the reader will inevitably need to read the USB specification itself, as well as other relevant specifications and webpages. For full details specifically about Embedded Xinu's implementation, the reader will inevitably need to read the source code.

3.9.1 General USB Information

Bus Topology

Fundamentally, USB is just a way to connect devices to a computer system. A USB bus accomplishes this by arranging devices in a tree. Each node of the tree is a **USB device**. There are two fundamental types of USB devices: **hubs** and **functions**. USB hubs can have "child" devices in the tree, while functions cannot. Hubs can be "children" of other hubs, up to a depth of 7 levels.

The root node of the tree is the **root hub**, and every USB bus has one (although it may be faked by the Host Controller Driver, described later).

A USB hub provides a fixed number of attachment points for additional devices called **ports**. A USB port may be either completely internal or exposed to the "outside" as a place to plug in a USB cable. From the user's point of view there is certainly a difference between these two manifestations of a USB port, but from the software's point of view there is no difference. On a similar note, it is also possible that a single physical package, which a naive user might refer to as a "USB device", actually contains an integrated USB hub onto which one or more USB devices (as defined above) are attached. Such physical packages are referred to as **compound devices**. An example of a compound device is one of Apple's USB keyboards that provides a USB port to attach a mouse.

Since USB is a dynamic bus, USB devices can be attached or detached from the USB at any arbitrary time. Detaching a hub implies detaching all child devices.

For its part, Embedded Xinu's USB implementation fully supports the dynamic tree topology of a USB bus.

Devices

Due to the generality of USB a USB device that is not a hub can be virtually anything at all. This is made possible in part by a highly nested design:

- A USB device has one or more **configurations**.
- A configuration has one or more **interfaces**.
- An interface has one or more **alternate settings**.
- An alternate setting has one or more **endpoints**.

Every device, configuration, interface, and endpoint has a corresponding **descriptor** that can be read by the USB software to retrieve information about the described entity in a standard format.

Although this format allows for highly complex devices, most devices are relatively simple and have just one configuration. Furthermore, common devices only have one interface. In fact, as of this writing, Embedded Xinu's USB subsystem aims to support the common case only; it therefore always sets the device to its first listed configuration, then attempts to bind a device driver to the entire device rather than examining individual interfaces to see if they need separate "interface drivers".

Host Controllers

USB is a polled bus, so all transfers over the USB are initiated by the **host**. The term "host" in this context means the USB software as well as the USB Host Controller, which is the hardware responsible for actually sending and receiving data over the USB and maintaining the root hub. This is actually one of the trickier parts of USB. Since the USB specification itself does not standardize the exact division of tasks between software and hardware, it's often not clear who is responsible when the specification says "host".

The essential thing to know is that the place where the USB software directly meets the USB hardware is in the USB Host Controller Driver, which operates the USB Host Controller. Some USB Host Controllers present standard interfaces (such as UHCI, OHCI, or EHCI— all defined in specifications separate from the USB specification itself) to software. Others do not present a standard interface, but instead have vendor-provided documentation and/or a vendor-provided driver; an example of this is the *Synopsys DesignWare High Speed USB 2.0 On The Go Controller* used on the *Raspberry Pi*. Obviously, a standard interface is highly preferred when independently implementing a Host Controller Driver.

Transfers

To communicate with USB devices, the host sends and receives data over the USB using USB transfers. A USB transfer occurs to or from a particular endpoint on a particular device. Every endpoint is associated with a specific type of USB transfer, which can be one of the following:

- **Control** transfers. These are typically used for device configuration. There are two main unique features of these transfers. First, a special packet called SETUP is always sent over the USB before the actual data of the control transfer, and software needs to specify the contents of this packet. Second, every device has an endpoint over which control transfers in either direction can be made, and this endpoint is never explicitly listed in the endpoint descriptors.
- **Interrupt** transfers. These are used for time-bounded transmission of small quantities of data (e.g. data from a keyboard or mouse).

- **Bulk** transfers. These are used for reliable (with error detection) transmission of large quantities of data with no particular time guarantees (e.g. reading and writing data on mass storage devices).
- **Isochronous** transfers. These are used for regular transmission of data with no error detecting (e.g. video capture).

Embedded Xinu currently supports control, interrupt, and bulk transfers. Isochronous transfers have not yet been tested. Although currently functional, interrupt transfers may require some more work to guarantee, in all cases, the time-bounded transmission required by the USB specification.

Speeds

USB supports multiple transfer speeds:

- 1.5 Mbit/s (Low Speed) (USB 1+)
- 12 Mbit/s (Full Speed) (USB 1+)
- 480 Mbit/s (High Speed) (USB 2.0+)
- 5000 Mbit/s (Super Speed) (USB 3.0+)

Yes, Full Speed is in fact the second lowest speed. Well I think we all know that 12 Mbit/s ought to be enough for anyone. But anyway, due to the need to maintain backwards compatibility with legacy devices, the USB software (mainly the host controller driver) unfortunately needs to take into account transfer speeds. At minimum, it must be aware that transfers to or from devices attached at Low Speed or Full Speed are performed as a series of **split transactions**, which allow Low Speed or Full Speed transfers to occur without significantly slowing down the portion of the USB bus operating at a higher speed.

As of this writing, Embedded Xinu's USB subsystem supports USB 2.0, so it supports devices operating at Low Speed, Full Speed, or High Speed. USB 3.0 Super Speed is not supported.

3.9.2 Embedded Xinu's USB subsystem

Now that some general information about USB has been presented, it should be easier to understand the basic design of a USB software stack. The description that follows is certainly not the only way to organize the code, but it is the way that is used in most operating systems and makes the most sense based on how USB was designed. In terms of Embedded Xinu, perhaps the main question is why USB devices and/or the USB controller do not, by default, show up as device(s) in `devtab` like other Embedded Xinu devices. The reasons are that USB is a dynamic bus, so it cannot be described by a static table, and also because the highly nested structure of USB devices, as well as multiple supported transfer types, is too complicated for the simple "read() and write() from a device" paradigm.

Note: Specific USB device drivers can still provide device entries in `devtab` if needed. However, they must account for the fact that the physical devices are still hot-pluggable.

Note: Not all Embedded Xinu *platforms* support USB, either due to not having USB hardware available or not having an appropriate USB host controller driver implemented.

Components

- The **USB Host Controller Driver** is responsible for actually sending and receiving data over the USB by making use of the platform-dependent host controller hardware. The purpose of this driver is to isolate differences in USB host controllers from all other code dealing with USB. In Embedded Xinu, USB Host Controller Drivers must implement the interface declared in include/usb_hcdi.h. (However, as of this writing, there is only one

Host USB Controller Driver implemented and it controls the *Synopsys DesignWare High Speed USB 2.0 On The Go Controller* used on the *Raspberry Pi*.)

- The **USB Core Driver** is responsible for maintaining the USB device model, including the tree structure, and providing a framework in which USB device drivers can be written. It provides many convenience functions that simplify USB device driver development over using the Host Controller Driver directly; this can be viewed as an attempt to isolate the platform-dependent Host Controller Driver as much as possible. It also handles configuration that is common to all USB devices, such as setting a device configuration and address, and reading descriptors. In Embedded Xinu, the USB Core Driver can be found in device/usb/usbcore.c.
- **USB device drivers** are responsible for controlling specific USB devices. Since USB is a dynamic bus, USB device drivers are bound to actual USB devices at runtime with the help of USB Core Driver. A very important USB device driver that must always be implemented in any USB software stack is the **USB hub driver**, which is responsible for monitoring the status of a USB hub and reporting to the USB Core Driver when devices have been attached or detached. Embedded Xinu's USB hub driver can be found in device/usb/usbhub.c. Other USB device drivers can be found in device/; e.g. device/smsc9512/.

Note: More complete (and complicated) USB software stacks, such as Linux's, also support **USB interface drivers**, which are associated with USB interfaces rather than USB devices.

Enabling Embedded Xinu's USB Support

To include support for USB in a given build of Embedded Xinu, define `WITH_USB` in `xinu.conf` and add `usb` to the `DEVICES` variable in `platformVars`. Note that the USB hub driver will be included automatically as it is required for USB to support any devices whatsoever.

In addition, you need to ensure that an appropriate Host Controller Driver, which is platform-dependent code and is not located in this directory, has been written and is compiled into the kernel. For example, system/platforms/arm-rpi/usb_dwc_hcd.c is the Host Controller Driver that is used on the Raspberry Pi hardware.

Finally, you need to enable any actual USB devices you want to support by adding the corresponding device directories to the `DEVICES` variable in `platformVars`, then defining the appropriate static devices in `xinu.conf`. For example, on the Raspberry Pi, we enable the driver for the SMSC LAN9512 USB Ethernet Adapter, which is located in device/smsc9512, by adding `smsc9512` to `DEVICES` and defining the `ETH0` device in `xinu.conf`.

USB for embedded systems

For fully embedded systems where debugging facilities are not critical, unnecessary human-friendly functionality can be omitted from the USB core. See device/usb/usbdebug.c for more details.

USB-related shell commands

The **usbinfo** *shell command* prints out information about devices attached to the USB. See shell/xsh_usbinfo.c for more details, or run `usbinfo --help`.

How to write a USB device driver

You first of all must acquire any available documentation for the USB device. Note that many devices do not have their own documentation because they conform to one of the USB *class specifications*; in such cases the documentation is the class specification, even though these are typically fairly long and complicated.

For nonstandard devices with no documentation available, you will have to use whatever means are available to you for understanding the device protocol, such as source code for other operating systems. As a last resort, the software interface to a USB device can be reverse-engineered by snooping on USB traffic generated by binary drivers.

Either way, to write the driver you will need to understand the format and meaning of messages sent to and from the device, and which USB endpoints and transfer types they are associated with.

Examples:

- USB Human Interface Devices such as mice are required to have an IN interrupt endpoint which is used to report input data such as mouse coordinates, and certain metadata can be queried from the default control endpoint.
- USB networking devices, such as the *SMSC LAN9512*, provide a bulk IN endpoint for receiving networking packets and a bulk OUT endpoint for sending network packets.

On to the code itself: In Embedded Xinu, USB device drivers are implemented using the API provided by the USB Core Driver, which is declared in usb_core_driver.h. This API allows drivers to register themselves, bind themselves to USB devices that are detected by the core, and communicate with USB devices. It is documented fairly extensively in the source; also see device/smsc9512/ for an example of a USB device driver.

Note that Xinu's static device model is incompatible with USB's dynamic device model, which is something that needs to be worked around by the USB device drivers. For example, the driver might refuse to bind itself to more than a fixed number of USB devices, and it might block or return failure if code tries to open the static device before it has actually been bound to an actual USB device.

How to write a USB host controller driver

In Embedded Xinu, the USB Host Controller Driver is responsible for actually interacting with the hardware (the USB Host Controller) to send and receive data over the USB. Unfortunately, USB Host Controllers are not standardized by the USB specification itself, which is why this abstraction layer is needed. USB Host Controllers include those compliant with the UHCI, OHCI, or EHCI specifications, as well as nonstandard ones such as the *Synopsys DesignWare High Speed USB 2.0 On The Go Controller* used on the *Raspberry Pi*.

The very first step is to determine whether Xinu already supports the USB Host Controller for the hardware under consideration. If so, you can use that code, but some changes may be needed (e.g. the location of memory-mapped registers). Otherwise, read on....

The USB Host Controller Driver must implement the interface declared in include/usb_hcdi.h.

You first must acquire any documentation (if it exists) for the Host Controller. You also need to read relevant parts of the USB 2.0 Specification, mainly those that describe control, interrupt, and bulk transfers. Most of the 650 pages you do **not** need to read.

Next, in `hcd_start()`, you must write any code that is needed to prepare the Host Controller to be ready to use.

The next and essentially final step is to implement `hcd_submit_xfer_request()`, which is very difficult. You should initially focus on faking requests that are sent to the root hub. These will include various control transfers to and from the root hub's default endpoint as well as an interrupt transfer from the root hub's status change endpoint. Some root hub requests can be handled entirely in software; others will need to communicate with the Host Controller. Next, you must support control transfers to and from actual USB devices on the bus. Finally, you must support interrupt and bulk transfers. These must be asynchronous and interrupt-driven. Note that the hub driver uses interrupt transfers in order to detect port status changes; thus, it will be impossible to enumerate the entire USB until interrupt transfers have been implemented.

You can use the `usb_debug()` and `usb_dev_debug()` macros to print debugging messages. Enable them by changing the logging priorities in include/usb_util.h.

3.9.3 Further reading

- USB 2.0 Specification
- USB 3.1 Specification
- Embedded Xinu USB 2.0 subsystem. (device/usb)
- Embedded Xinu USB device drivers. (Example: device/smsc9512/)
- Embedded Xinu USB host controller drivers. (Example: system/platforms/arm-rpi/usb_dwc_hcd.c)

3.10 USB keyboard driver

Support for **USB (Universal Serial Bus) keyboards** has been added to *Embedded Xinu* via the *usbkbd* device driver, located in device/usbkbd/.

The *usbkbd* driver is a *USB device driver* and can only be built when Embedded Xinu's *USB* support has been enabled.

3.10.1 External interface

Like other Embedded Xinu device drivers such as the various UART drivers, the *usbkbd* driver provides one or more device table entries, such as `USBKBD0`, `USBKBD1`, etc. Characters can be read from these devices simply by using getc() or read() on these devices. These functions will block if the corresponding USB keyboard is detached or has yet to be attached.

3.10.2 Scope

The *usbkbd* driver only supports the keyboard boot protocol defined in the USB HID (Human Interface Device) specification. This protocol defines a fixed 8-byte report that the keyboard provides over its IN interrupt endpoint when a key is pressed or released. *usbkbd* does not parse the HID report descriptor and does not support any other Human Interface Devices, such as mice (or steering wheels, or data gloves...).

Since data is provided by *usbkbd* as 8-bit characters, there is limited support for special keys that do not correspond to printing characters, and currently most are simply ignored.

3.10.3 Implementation details

When sysinit() runs, `init()` is called on each device table entry, resulting in a call to usbKbdInit() for each keyboard device entry. As soon as one of these calls occurs, *usbkbd* registers itself with the *USB subsystem* as a USB device driver. usbKbdInit() does *not* wait for a keyboard to actually be attached before returning.

When a USB device is attached, usbKbdBindDevice() is called by the *USB subsystem*. If the device has a HID interface supporting the keyboard boot protocol (i.e. "is a USB keyboard"), a recurring USB transfer from the keyboard's IN interrupt endpoint is started. When each such transfer completes, usbKbdInterrupt() is called by the *USB subsystem*, and any new characters detected are placed in a buffer for later retrieval by reads from the keyboard device.

3.10.4 See also

- *USB*
- *How to write a USB device driver*
- *TTY driver*

3.10.5 References

- Universal Serial Bus (USB) Device Class Definition for Human Interface Devices (HID), Version 1.11
- Universal Serial Bus (USB) HID Usage Tables, Version 1.11

CHAPTER 4

MIPS ports (including Linksys routers)

4.1 Common Firmware Environment

4.1.1 About

The **Common Firmware Environment** (**CFE**) is the firmware developed by Broadcom for the BCM947xx SoC platform (among others). It is the first code that runs when the router boots and performs functions similar to Apple's Open Firmware:

- Initializes the system
- Sets up a basic environment in which code can run
- Optionally provides a command line interface non-standard usage
- Loads and executes a kernel image (expecting to be jettisoned shortly thereafter)

So, in normal operation, a user will not see CFE working at all; it will load the Linksys kernel and send it on its merry way without hesitation. For us, however, CFE is crucial, because it provides us with the ability to load an image over the network using TFTP.

We have access to two major documents covering CFE, the reference manual, and the functional specification. Much of the content in these two documents overlaps.

4.1.2 Getting into CFE

To get into CFE, it will be very helpful to enable "boot wait" from the Administration Tab under the router's Web GUI. This will cause the router to wait on startup for a signal to stop booting into the firmware and enter CFE.

Once you have that set up and you've *connected to the router*, just type "reboot" (assuming OpenWRT is installed, it may be different for other firmwares) to reboot the router. This can also be done by power-cycling the router. As it's booting up, send a continuous stream of Ctrl+C characters to cancel booting and you'll be entered right into CFE.

From there, you can prod around CFE's features or load your own kernel using the command line interface.

4.1.3 Command Line Interface

The CFE Command Line Interface (CLI) is a very simple "shell-like" command prompt. It has a few environmental variables and minimal functionality. However, it is complex enough power to load a boot image over the network and begin executing code. The User interface is described on page 19 of 145 in the CFE documentation.

To get the to the CLI, you can use either the power-on method or load OpenWRT and type reboot. The CFE boot screen looks like:

```
CFE version 1.0.37 for BCM947XX (32bit,SP,LE)
Build Date: Fri Sep 23 17:46:42 CST 2005 (root@localhost.localdomain)
Copyright (C) 2000,2001,2002,2003 Broadcom Corporation.

Initializing Arena
Initializing Devices.

No DPN
et0: Broadcom BCM47xx 10/100 Mbps Ethernet Controller 3.90.37.0
CPU type 0x29008: 200MHz
Total memory: 16384 KBytes

Total memory used by CFE:  0x80300000 - 0x803A39C0 (670144)
Initialized Data:          0x803398D0 - 0x8033BFE0 (10000)
BSS Area:                  0x8033BFE0 - 0x8033D9C0 (6624)
Local Heap:                0x8033D9C0 - 0x803A19C0 (409600)
Stack Area:                0x803A19C0 - 0x803A39C0 (8192)
Text (code) segment:       0x80300000 - 0x803398D0 (235728)
Boot area (physical):      0x003A4000 - 0x003E4000
Relocation Factor:         I:00000000 - D:00000000

Boot version: v3.7
The boot is CFE

mac_init(): Find mac [00:16:B6:28:7D:4F] in location 0
Nothing...

eou_key_init(): Find key pair in location 0
The eou device id is same
The eou public key is same
The eou private key is same
Device eth0:  hwaddr 00-16-B6-28-7D-4F, ipaddr 192.168.1.1, mask 255.255.255.0
        gateway not set, nameserver not set
Reading :: Failed.: Interrupted
CFE> ^C
CFE>
```

Of course, items like the hwaddr will be different from router to router.

Once you have a command prompt, you can type `help` and get a listing of commands available:

```
CFE> help
Available commands:

rndis               Broadcom USB RNDIS utility.
et                  Broadcom Ethernet utility.
modify              Modify flash data.
nvram               NVRAM utility.
reboot              Reboot.
flash               Update a flash memory device
memtest             Test memory.
f                   Fill contents of memory.
e                   Modify contents of memory.
d                   Dump memory.
u                   Disassemble instructions.
autoboot            Automatic system bootstrap.
batch               Load a batch file into memory and execute it
```

```
go                  Verify and boot OS image.
boot                Load an executable file into memory and execute it
load                Load an executable file into memory without executing it
save                Save a region of memory to a remote file via TFTP
ping                Ping a remote IP host.
arp                 Display or modify the ARP Table
ifconfig            Configure the Ethernet interface
show devices        Display information about the installed devices.
unsetenv            Delete an environment variable.
printenv            Display the environment variables
setenv              Set an environment variable.
help                Obtain help for CFE commands

For more information about a command, enter 'help command-name'
*** command status = 0
CFE>
```

A command status of 0 is always a good thing, other command statuses are errors.

The next two commands are very important to booting a custon kernel image: `ifconfig` and `boot`.

`ifconfig` is just the Linux counterpart, it will set up the specified interface. For our router, we have the switch portion of the router connected to a xinu server (which is simply a TFTP and DHCP server). From there we type `ifconfig -auto eth0` which will ask the xinu server for an IP address and set up the router.

```
CFE> ifconfig -auto eth0
Device eth0:  hwaddr 00-16-B6-28-7D-4F, ipaddr 192.168.5.2, mask 255.255.254.0
        gateway 192.168.5.220, nameserver 192.168.5.220, domain xinu.mu.edu
*** command status = 0
CFE>
```

We now have an IP address and can transfer our boot image.

For our purposes, we name our boot images after the unit on which it will load (supervoc is our demo router).

```
CFE> boot -elf 192.168.5.220:supervoc.boot
Loader:elf Filesys:tftp Dev:eth0 File:192.168.5.220:supervoc.boot Options:(null)
Loading: 0x80001000/3145 0x80001c49/23 Entry at 0x80001000
Closing network.
Starting program at 0x80001000
```

Let's walk through these lines:

```
boot -elf 192.168.5.220:supervoc.boot
```

This will begin booting the `supervoc.boot` kernel that is located at 192.168.5.220 (our xinu server and, no, name resolution does not work).

```
Loader:elf Filesys:tftp Dev:eth0 File:192.168.5.220:supervoc.boot Options:(null)
```

A fairly explanatory line stating the file type it is loading (`elf`), the file system to be used (`tftp`), the device which it is using to transfer the image (`eth0`), and where that image is from (`192.168.5.220:supervoc.boot`).

```
Loading: 0x80001000/3145 0x80001c49/23 Entry at 0x80001000
```

This is also a line of explanation. The first portion (`0x80001000/3145`) tells us the 'physical' address of where we begin loading our image and the size of the image (in bytes). Next is the address of the end of the image (`0x80001c49/23`) and (I believe) the amount of padding to make the image size base 16. The last part is the address which CFE will branch to upon completion of upload, this is the start of your kernel.

```
Closing network.
Starting program at 0x80001000
```

The closes the network and begins execution the code at address `0x8000100`. Any lines of text outputted after this are from your boot image (unless CFE throws an exception and shows a memory dump).

4.2 EJTAG

EJTAG is a MIPS-specific extension of IEEE 1149.1, the Joint Test Action Group. Allows interfacing with additional logic in SoC

- direct control of processor for step-by-step debugging
- access to busses and registers
  - aids in debugging
  - possible usage as additional peripheral data bus
  - direct writing to flash for firmware updates (and de-bricking)

4.2.1 Debugging

Attempting to use GNU debugger: http://www.gnu.org/software/gdb. GDB uses its own Remote Serial Protocol (RDB) to communicate to remote targets. This protocol could be used to communicate with the XINU backends through the current serial connection. Although, this would require additions to XINU: communication with the GDB host; altering of exception handler to allow GDB to take control of target processor.

The use of the EJTAG port on the WRT54-series routers gives the user hardware control of the processor, avoiding the need for strategically placed breakpoints and XINU interrupt subsystem modification. Additionally, requests by the debugger for specicfic data can be aquired directly from registers. The trick to this operation is software that can interpret commands from RDB into EJTAG signals to be sent through the host parallel port, and vice-versa. An implementation of this interpreter can be found at http://www.totalembedded.com/open_source/jtag/mips32_ejtag.php.

4.2.2 Specific Implementations

So far, development has focused exclusively on the WRT54GL. For anyone investigating the capabilities of the WRT54GL EJTAG system, note the instruction register size is a full 8 bits, not the 5 bits required by specification. Believing the 54GL CP0 Debug Program Counter register to be returning erroneous addresses, headers are being added to a 54G v.8, and a 350N v.1. For IDCODEs and implementation register values check *EJTAG ID Codes and Implementation Registers*.

4.2.3 Probes

Images are of three variant EJTAG connections. The first two buffered by active line drivers, the last passive. Xinu research is currently using an active probe similar to the OpenWRT "Wiggler" clone; although, the parallel port pinouts match the unbuffered cable diagram. Note that the unbuffered cable at the bottom of this page is only proven by xinu research functional in writing to the Test Access Port. It may not read data back from the target device. Additionally, rumor claims that the cable can be no longer than 6" (not 6'). This is partially substantiated by photographs "out there" of similar 6 inch cables used with a variety of devices.

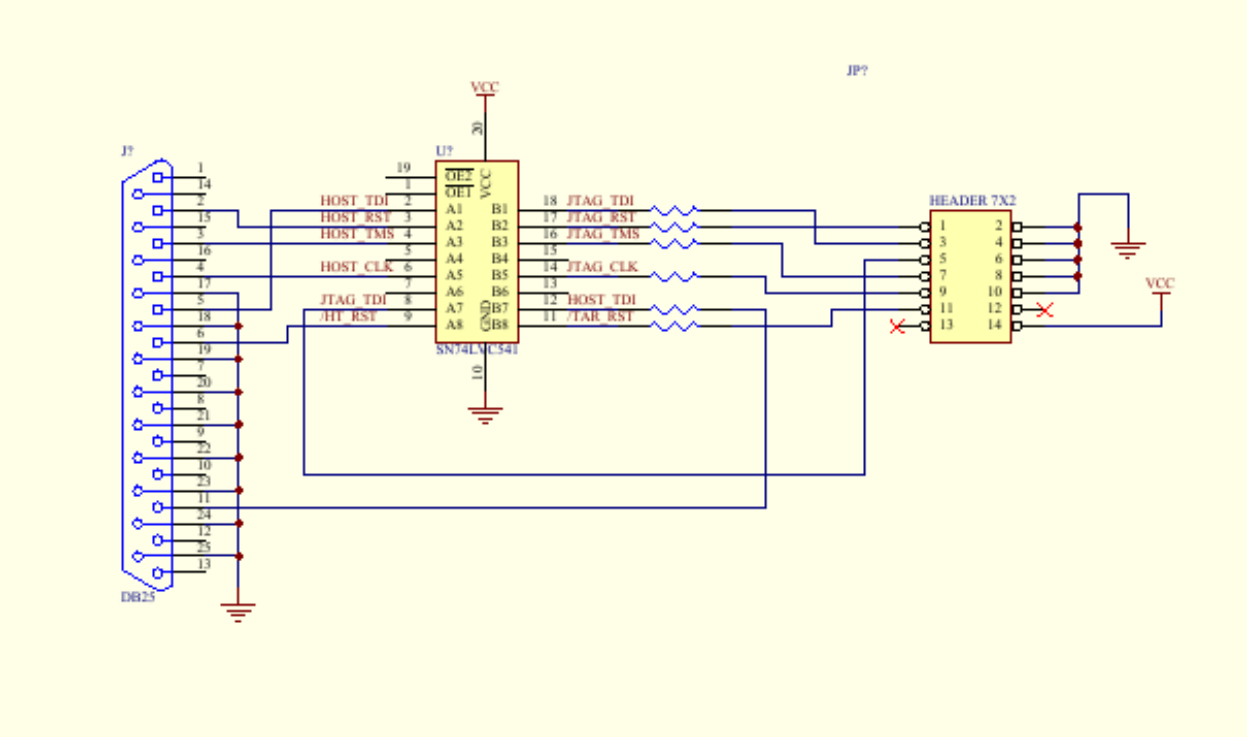


Figure 4.1: Total Embedded buffered cable

4.2.4 See also

- *EJTAG ID Codes and Implementation Registers*

4.3 EJTAG ID Codes and Implementation Registers

When an EJTAG system is reset, the data register is automatically filled with the result of an IDCODE instruction. This code usually includes the processor and the manufacturer, although it is not a standard. The important part of the IDCODE is using it to determine if your host hardware is communicating with your target. Whether or not the host speaks fluent jtag, if it can navigate to the data register and shift out the contents, one can see if the electrical connection is sound.

IDCODEs

WT54GLv1.1 : 0x0535217F

WRT54Gv8 : 0x1535417F

WRT350Nv1.0 : 0x0478517F

The implementation code instruction returns an indication of features on the particular platform. Below is the information from the MIPS EJTAG Specification, document #MD00047.

IMPCODEs

WT54GLv1.1 : 0x00800904

WRT54Gv8 : 0x00810904

WRT350Nv1.0 : 0x00810904

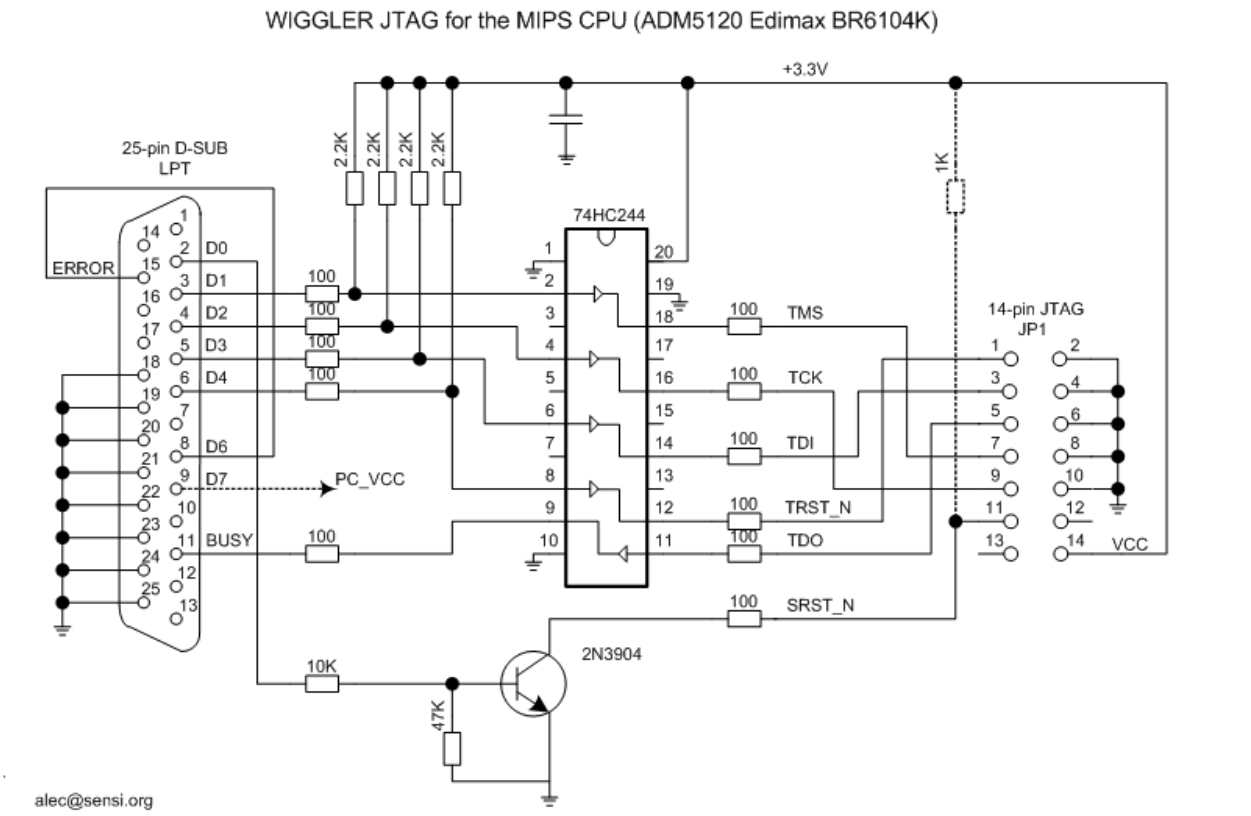


Figure 4.2: "wiggler" clone from OpenWRT

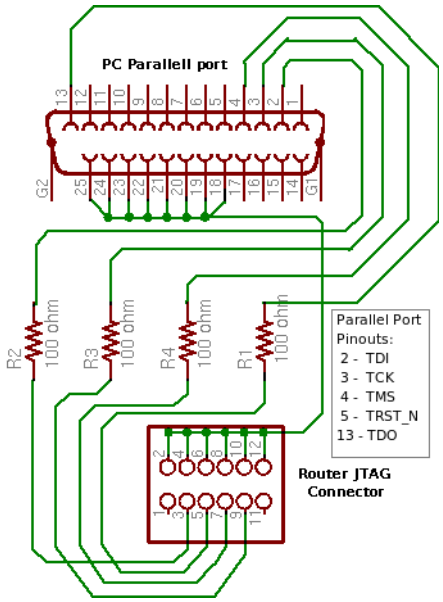


Figure 4.3: unbuffered cable from OpenWRT; used by de-brick utility

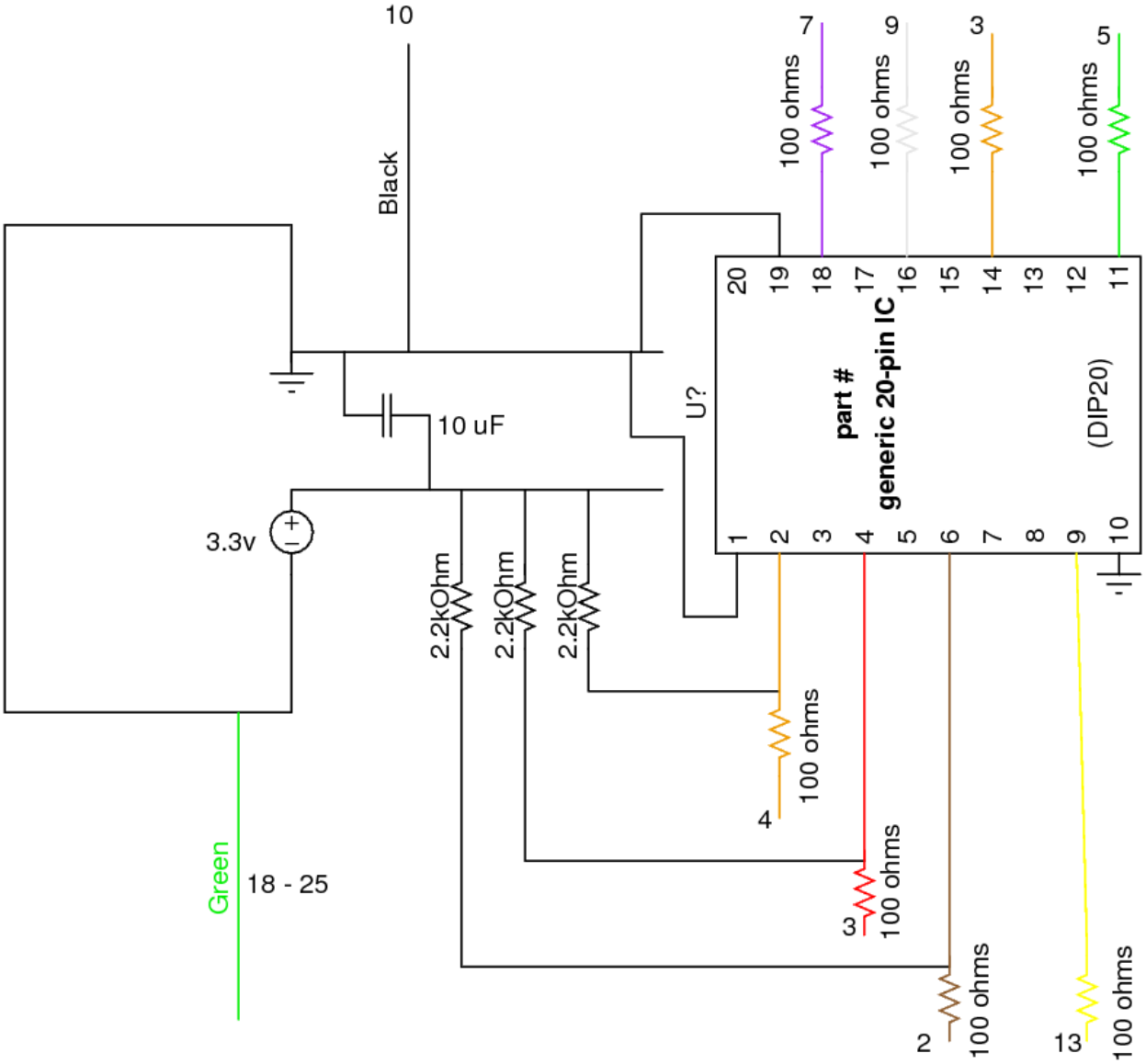


Figure 4.4: Our current buffer/wiggler setup

6.5.2 Implementation Register (TAP Instruction IMPCODE)

Compliance Level: Required with EJTAG TAP feature.

The Implementation register is a 32-bit read-only register that identifies features implemented in this EJTAG compliant processor, mainly those accessible from the TAP.

Figure 6-8 shows the format of the Implementation register; Table 6-4 describes the Implementation register fields.

Figure 6-8 Implementation Register Format

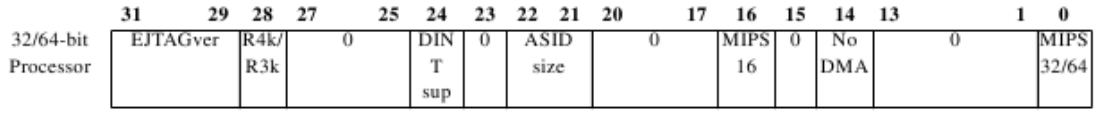


Table 6-4 Implementation Register Field Descriptions

Fields		Description	Read/ Write	Power-up State	Compliance
Name	**Bits**				
EJTAGver	31:29	Indicates the EJTAG version: **Encoding** / **Meaning** 0 – Version 1 and 2.0 1 – Version 2.5 2 – Version 2.6 3 – Version 3.1 3-7 – Reserved	R	Preset	Required
R4k/R3k	28	Indicates R4k or R3k privileged environment: **Encoding** / **Meaning** 0 – R4k privileged environment 1 – R3k privileged environment	R	Preset	Required
DINTsup	24	Indicates support for DINT signal from probe: **Encoding** / **Meaning** 0 – DINT signal from the probe is not supported by this processor 1 – Probe can use DINT signal to make debug interrupt on this processor	R	Preset	Required
ASIDsize	22:21	Indicates size of the ASID field: **Encoding** / **Meaning** 0 – No ASID in implementation 1 – 6-bit ASID 2 – 8-bit ASID 3 – Reserved	R	Preset	Required
MIPS16e	16	Indicates MIPS16e™ ASE support in the processor: **Encoding** / **Meaning** 0 – No MIPS16e support 1 – MIPS16e is supported	R	Preset	Required
NoDMA	14	Indicates no EJTAG DMA support: **Encoding** / **Meaning** 0 – Reserved 1 – No EJTAG DMA support			
		Indicates 32-bit or 64-bit processor:			

4.4 Exception and Interrupt Handling (MIPS)

On MIPS processors, *Embedded Xinu* tilizes a interrupt handling system which allows components to register custom interrupt handlers to the system at runtime or fall-back to the default trap handler.

MIPS processors will jump to and execute code beginning at `0x8000 0180` when an exception or interrupt occurs. Code for handling traps must occupy no more than `0x20` bytes at this location (eight instructions), therefore Embedded Xinu uses three instructions to jump to different code which will handle traps more robustly.

In order to handle exceptions (such as TLB misses) efficiently, Embedded Xinu uses an interrupt vector system to quickly read the exception code, load the registered exception handler, and jump to the handler. If any of these steps do not exist, the handler will fall-back to the default trap handler.

If an interrupt has occurred it is important to save the state of the processor and handle the interrupt gracefully so the system can continue running. Thus, if the interrupt handler was called by an interrupt and not an exception, the code will save the state of the processor and perform a similar lookup for interrupt handlers.

4.5 Flash driver

Embedded Xinu uses a multi-layered approach to dealing with *Flash memory* on platforms where it is available (including MIPS-based routers such as the *WRT54GL*). This allows the presentation of a simple and consistent interface to user programs, while handling the more complicated hardware interface underneath.

4.5.1 High level API

Like other drivers in Embedded Xinu, the Flash driver provides user level calls to `open()`, `close()`, `read()`, `write()`, and `control()`. In order to begin using a device the user must `open()` it, this initializes the logical layer and sets up structures for use. The complimentary `close()` function will clear those structures and write any cached data to the underlying Flash hardware.

`control()` provides several functions for getting information and performing operations on the driver. The control functions are presented below.

- `FLASH_BLOCK_SIZE` returns the size of logical blocks for the Flash device.
- `FLASH_N_BLOCKS` returns the number of block available on the Flash device.
- `FLASH_SYNC` forces a synchronization from cached data onto Flash memory, the two forms are:
  - `FLASH_BLOCK` synchronizes a specific erase block, and
  - `FLASH_LOGBLOCK` synchronizes a logical block of data.

`read()` and `write()`

The Flash device takes three slightly different parameters for `read()` and `write()` when compared to other devices in Embedded Xinu. Normal devices will take the device identifier, a buffer, and the size of the buffer. Since the Flash device uses fixed size logical blocks, it is assumed that the buffer will be the size of a single logical block. Therefore, the Flash driver API for `read()` and `write()` is:

```
read(int device_id, char *buffer, uint block_number);
write(int device_id, char *buffer, uint block_number);
```

4.5.2 Logical Layer

Normal block-oriented devices present a consistent view of data storage with each block being a small fixed size ranging from 512 bytes to 4,096 bytes. Flash memory does not act like normal block-oriented devices though. The underlying hardware is separated into erase block regions of which there can be four. Each erase block region can hold a number of erase blocks of a fixed size. These fixed sizes can be any size that is a power of two. For example, on the WRT54GL platform, Flash is separated into two erase block regions, one with 8 - 8 KB erase blocks and the other with 63 - 64 KB erase blocks.

To avoid the user level programmer from having to deal with this inconsistent view of erase blocks, the logical layer of the Flash driver splits all of Flash memory into uniformly sized logical blocks (at present this is 512 byte blocks). When a call to `read()` occurs, the logical layer will determine what erase block the logical block maps to, determine if the erase block has already been loaded into RAM and return a pointer to the cached data. Similarly, a call to `write()` will perform a mapping from logical to erase block and write the data to the cached memory. If too many erase blocks are stored in RAM, the logical layer will evict a block and if it has been modified since the read it will write it back to Flash memory.

4.5.3 Physical Layer

Once the logical to erase block mapping has occurred, the logical layer can pass the erase block stored in RAM to the physical layer to perform the low level hardware operations. At this layer, the software only deals in erase block units and uses manufacturer specific code. Currently, Embedded Xinu fully supports the Intel Standard Command Set (SCS) and the AMD/Samsung SCS is a work in progress.

Largely, the routines to handle the hardware follow similar concepts. When a non-read request is made to the physical layer the software steps through a series of operations to change an erase block from read-mode to program or erase mode. When this happens, the software is able to safely modify the data.

An interesting property of Flash memory is that certain devices allow program and erase operations to be suspended, so it may be possible to spin the physical layer off as a separate pre-emptible process. Unfortunately, while the Intel SCS supports suspend/resume operations the AMD/Samsung SCS does not, so this would lead to compatibility issues if implemented.

4.5.4 NVRAM

NVRAM settings are stored in Flash memory and take advantage of both the logical and physical layers of the Flash driver. When NVRAM is first initialized, the Flash driver determines what logical block the settings begin in and then begins reading and storing the settings into RAM. Each tuple is indexed into a hash table and allocated a piece of memory to store the data in. When a setting is changed, the original value is released from memory and the new value is added. If a value is requested, the driver will simply find the storage location and return the pointer to the data.

When the updated settings are committed to Flash, the NVRAM driver will discover the logical block to erase block mapping, create a complete erase block with the new settings, cause a write in the physical layer, and finally force a synchronization to commit the settings to Flash.

4.6 Flash memory

Note: This page appears to have been written with *WRT54GL* routers in mind and may or may not be applicable to other platforms.

Like other memory mapped hardware devices on the MIPS platform, **Flash memory** has an address range in KSEG1. This means that the memory is **unmapped** and **uncached**. An interesting, and important, piece of information is that

all 4 megabytes of Flash memory is mapped 1-1 into the address range between `0xBC00 0000` and `0xBC3F FFFF`. This allows for random read-access without using an interface to load the data a fixed amount of registers.

4.6.1 Data Locations

Stored on Flash memory are several important parts to make a backend work properly, some of these data points are listed below.

- `0xBC00 1000` has backup NVRAM settings. If the "proper" settings become corrupt, CFE will replace the proper settings with these.
- `0xBC00 1E00` holds the "true" MAC address of device. During CFE boot, this is the address that will be used. Once a full kernel has been loaded the MAC address may be different.
- `0xBC00 1F00` holds the current CFE boot version (should be "v3.7" for *WRT54GLs*).
- `0xBC00 2000` is the beginning of CFE code.
- `0xBC03 F400` is a unique device ID (should match the NVRAM setting for `eou_device_id`).
- `0xBC03 F408` is a unique private key for device (should match the NVRAM setting for `eou_private_key`).
- `0xBC03 F508` is a unique public key for device (should match the NVRAM setting for `eou_public_key`).
- `0xBC04 0000` is the beginning of the operating system kernel (*Embedded Xinu* or some Linux variant). Typically, this will be a gzipped version of the raw kernel code prefixed with a *TRX header*.
- `0xBC3F 8000` is the location of proper *NVRAM settings*.

This is not a comprehensive list of memory locations within Flash memory, but a guide of where some values may be stored when trying to interface with a new system.

4.6.2 Writing Flash

Writing data to Flash memory is not simply a matter of writing data to the memory address. For the WRT54GL backends the common NOR type of Flash memory is used. As with all Flash memories there are certain properties that must be followed when storing data.

An important property of NOR based Flash memory is that each bit on Flash can only be changed from a `1` to a `0` and not the other way around. So if a byte has the pattern `1001 1101` only the high bits can be written. This presents an interesting challenge for efficient file system structures. Once a bit has been set to `0` and the operating system wishes to reset the bit to `1` a special erase command must be sent to the device. Because of this Flash memory is broken down into several distinct segments called *erase blocks*. These erase blocks can vary in size between Flash memory chips and even within the same chip. After sending the command to erase an erase block, the entire erase block will be set to `1`s, allowing any data to be written. The specific method of erasing and writing data depends on the manufacturer of the underlying hardware. In general it is a matter of writing a sequence of values to a certain location to prepare the device, then writing the new data to the correct position. These operations are more detailed on the *Flash driver* page under *physical layer*.

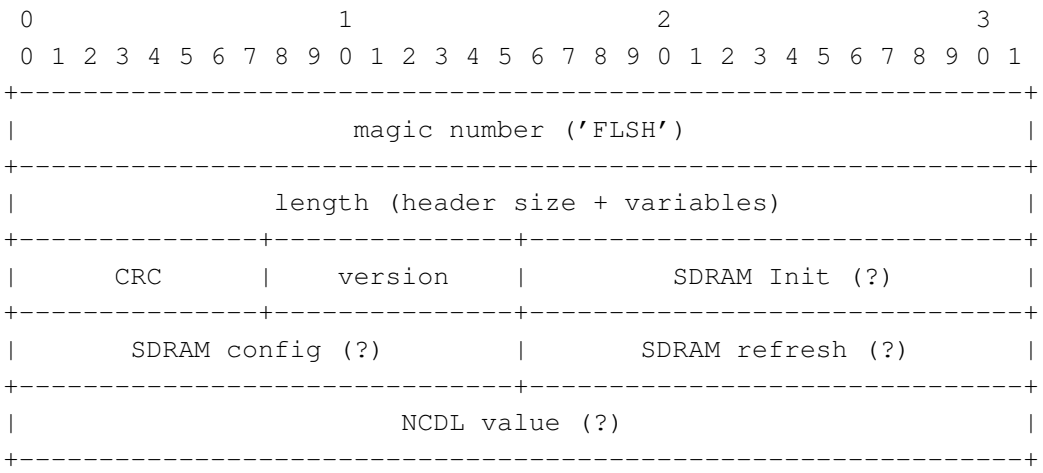
4.6.3 Common Flash Interface

Luckily for software authors, the manufacturers of Flash memory have developed a standard for discovering information about a Flash device, called the Common Flash Interface (CFI). By implementing a CFI query routine, the operating system can discover what command set the chip implements (Intel, AMD, and Mitsubishi all have a standard command set and extended command set). Other information that can be queried is voltages, timeouts for writing and erasing, access mode (word or byte), device size (as 2^n), and information about up-to four erase block regions.

The information about each erase block region will consist of the size of an erase block in the region and the number of equally sized erase blocks that exist in the regions.

4.6.4 NVRAM

While technically a misnomer, NVRAM (non-volatile random access memory) refers specifically to the platform settings stored across power cycles of the device. These settings will always begin 8 pages (32 kilobytes) away from the end of Flash memory. In the case of the WRT54GL, this means NVRAM settings are stored beginning at `0xBC3F 8000`. At this point there is a 20 byte header which is laid out as follows:



Several of the values are not used by Embedded Xinu as the values represent something that is not fully understood (all the SDRAM values and the NCDL value).

Immediately after the header begins the NVRAM settings as NULL delimited `name=value` tuples stored as plain text. It is possible that after the final tuple the settings are NULL character padded to the nearest 4 byte word.

4.7 General purpose input and output

Note: This page appears to have been written with *WRT54GL* routers in mind and may not be applicable to other platforms.

General Purpose Input and Output (**GPIO**) is a simple method of communication. Currently the shell implements the **led** and **gpiostat** commands to use these ports.

4.7.1 Port Assignments

Pin	Assignment
GPIO 0	WLAN LED
GPIO 1	Power LED
GPIO 2	Cisco LED White
GPIO 3	Cisco LED Orange
GPIO 4	Cisco Button
GPIO 5	*Unknown*
GPIO 6	Reset Button
GPIO 7	DMZ LED

4.7.2 Registers

There are four control and status registers, each which is 2 bytes.

- Input (0xb8000060) - If a GPIO pin is set for output, its input bit is automatically set to 0.
- Output (0xb8000064) - If a GPIO pin is set for input, its output bit is automatically set to 0.
- Enable (0xb8000068) - Determines if a GPIO pin is used for input or output. A bit value of 0 is input and 1 is output.
- Control (0xb800006c) - Usage is currently unknown.

4.7.3 LEDs

Research Notes:

- An LED is enabled by setting its enable bit to 1.
- When an LED is enabled, its input bit becomes 0.
- Once an LED is enabled, if its output bit is 0, the LED is on and if its output bit is 1, the LED is off.

4.7.4 Resources

- SD Card Reader Driver
- Adding an MMC/SD Card

4.8 Backing up your router

Note: This page appears to have been written with *WRT54GL* routers in mind and may or may not be applicable to other platforms.

When experimenting with kernels, you may find yourself corrupting the router and having to recover from a known good state. It is a good idea to make a copy of the CFE when it is in its original factory configuration for if and when. Here are a few different methods depending on your resources:

4.8.1 dd-wrt

If you are running a relatively recent version of dd-wrt, you can download the CFE from the web interface.

Location: `http://ROUTER_IP/backup/cfe.bin>`

4.8.2 CFE

To backup the CFE from within the CFE itself you need an active *serial console* and a live network connection to a *TFTP server*. On the TFTP server, create a file for the backup image. It must be world writable. If you do not pre-create the file for the TFTP client, the backup may fail. We name and label our routers to keep them straight. Consider naming the backup image after each router's hostname if you have many of them.

Example:

```
user@xinuserver:tftpboot$ touch routername.cfe
user@xinuserver:tftpboot$ chmod a+w routername.cfe
```

Access the *CFE* using the *usual method*.

If necessary, configure the network interface and check the connection to your TFTP server (192.168.6.10 in this example):

```
CFE> ifconfig eth0 -auto
Device eth0:  hwaddr 00-1E-E5-86-02-7A, ipaddr 192.168.6.122, mask 255.255.255.0
        gateway 192.168.6.50, nameserver 134.48.7.10, domain xinu.mu.edu
*** command status = 0
CFE> ping 192.168.6.10
192.168.6.10 (192.168.6.10) is alive
192.168.6.10 (192.168.6.10): 1 packets sent, 1 received
*** command status = 0
```

Save the CFE region to the file you created on the TFTP server:

```
CFE> save 192.168.6.10:routername.cfe BC000000 40000
262144 bytes written to 192.168.6.10:routername.cfe
*** command status = 0
```

Note: You can also save the entire flash image (CFE+Kernel+NVRAM) by passing 400000 as the length instead of 40000. This isn't really necessary, but you might find it referenced elsewhere. If you have to *recover* via JTAG it will take a LONG time to restore the entire flash image. It is much more efficient to load just the CFE, then upload the kernel via TFTP and use a factory reset to restore NVRAM.

4.8.3 JTAG

For this method to work, we assume you have a working *EJTAG* interface to your router. For details, check out our *Recovering a router* page.

Use the `-probeonly` option to figure out what options TJTAG needs for your particular setup.

Backup the CFE with TJTAG:

```
user@host:tjtag$ ./tjtag -backup:cfe /wiggler /noemw /noreset
```

TJTAG will create a CFE.BIN file with some sort of timestamp identifier appended to the filename. Rename and store somewhere safe.

4.9 Connecting to a modified router

4.9.1 Summary

This will explain how to connect to the serial ports on a modified Linksys WRT54G using serial communication software. In our tutorial we will use Picocom for our serial communication software because it is free and easy to get with a front end or server running Linux.

4.9.2 Before Starting

Expose a serial port on the router

You must have successfully modified a Linksys WRT54G to expose at least its first serial port in such a way that you can connect it to another machine with serial communications software. If you have not done so yet, please see *Modifying the Linksys hardware*.

Acquire serial communication software

There is a freely available software package for serial communication on almost every major platform. Picocom is one such piece of software that is easy to obtain on a machine running Linux. To get Picocom installed on your front end simply open a terminal and type ‘‘ yum install picocom ‘‘ (or use your system’s package install command if it does not support the ‘‘ yum ‘‘ command). **NOTE:** you may need *root* access to your front end machine in order to install packages. We installed Picocom on a front end machine running Fedora 9 and got the following output:

```
[root@argolis ~]# yum install picocom
Loaded plugins: refresh-packagekit
Setting up Install Process
Parsing package install arguments
Resolving Dependencies
--> Running transaction check
---> Package picocom.i386 0:1.4-4.fc9 set to be updated
--> Finished Dependency Resolution

Dependencies Resolved

================================================================================
 Package                 Arch       Version          Repository        Size
================================================================================
Installing:
 picocom                 i386       1.4-4.fc9        fedora             29 k

Transaction Summary
================================================================================
Install      1 Package(s)
Update       0 Package(s)
Remove       0 Package(s)

Total download size: 29 k
Is this ok [y/N]: y
Downloading Packages:
(1/1): picocom-1.4-4.fc9.i386.rpm                          |  29 kB     00:00
Running rpm_check_debug
Running Transaction Test
Finished Transaction Test
```

```
Transaction Test Succeeded
Running Transaction
  Installing: picocom                      ########################## [1/1]

Installed: picocom.i386 0:1.4-4.fc9
Complete!
[root@argolis ~]#
```

Alternatively, if you are building multiple backends to be made available as a pool, our suite of XINU Console Tools includes a basic serial console utility called **tty-connect**. However it is recommended that you do **not** use the XINU Console Tools's **tty-connect** utility for directly connecting a single back end router to a front end machine because this utility does not allow the user to send a `ctrl-C` command over the serial connection, which is necessary in the upcoming steps in order to properly communicate with your router.

4.9.3 Steps to Connect to the Router

Task One: Connect Serial (& Optionally Network) Cable(s)

Ensure that the connection is going from UART0 (the first serial port–if you followed our instructions on *modifying the router* it will be the **DB9 Female** serial port on the left) as this is where the console will be running. If you are connecting a standard PC serial port (a DTE) to your router, use a straight serial cable. Other arrangements may require a *Null Modem*; check your transmit/receive line polarities to be sure.

Also, because the goal is to upload custom code to the router, it would be a good idea to connect the router to your network by wiring it up via one of the numbered LAN ports on the back of the router (NOT the Internet/WAN port). This is not necessary to simply connect and communicate with the router, but it is necessary if you want to try and boot the router running your own custom code (which is the point of this Xinu lab after all).

Task Two: Configure your Serial Communication Software

The connection used by the router's serial port is fairly standard: 115200bps, with 8 data bits, no parity bit, and 1 stop bit, or 8N1. Set your software to connect using these settings.

If you are following our tutorial and using Picocom as your serial connection software, the command to open Picocom with these settings is `` picocom -b 115200 /dev/ttyS0 `` (where `` /dev/ttyS0 `` is the name of your front end's serial communication device hooked up to the router). By default the other necessary settings are already set on picocom; it's default connection uses 8 data bits, no parity bits, and 1 stop bit. If you use picicom to set up a connection you should get output like the following:

```
[root@argolis ~]# picocom -b 115200 /dev/ttyS0
picocom v1.4

port is        : /dev/ttyS0
flowcontrol    : none
baudrate is    : 115200
parity is      : none
databits are   : 8
escape is      : C-a
noinit is      : no
noreset is     : no
nolock is      : no
send_cmd is    : ascii_xfr -s -v -l10
receive_cmd is : rz -vv

Terminal ready
```

Task Three: Power up the Router

Yes, that means plug it in.

With serial communications software listening, you should see something like the following output:

```
CFE version 1.0.37 for BCM947XX (32bit,SP,LE)
Build Date: Mon Nov 14 18:06:25 CST 2005 (root@localhost.localdomain)
Copyright (C) 2000,2001,2002,2003 Broadcom Corporation.

Initializing Arena
Initializing Devices.

No DPN
et0: Broadcom BCM47xx 10/100 Mbps Ethernet Controller 3.90.37.0
CPU type 0x29008: 200MHz
Total memory: 16384 KBytes

Total memory used by CFE:  0x80300000 - 0x803A39C0 (670144)
Initialized Data:          0x803398D0 - 0x8033BFE0 (10000)
BSS Area:                  0x8033BFE0 - 0x8033D9C0 (6624)
Local Heap:                0x8033D9C0 - 0x803A19C0 (409600)
Stack Area:                0x803A19C0 - 0x803A39C0 (8192)
Text (code) segment:       0x80300000 - 0x803398D0 (235728)
Boot area (physical):      0x003A4000 - 0x003E4000
Relocation Factor:         I:00000000 - D:00000000

Boot version: v3.7
The boot is CFE

mac_init(): Find mac [00:18:39:6F:78:15] in location 0
Nothing...

eou_key_init(): Find key pair in location 0
The eou device id is same
The eou public key is same
The eou private key is same
Device eth0:  hwaddr 00-18-39-6F-78-15, ipaddr 192.168.1.1, mask 255.255.255.0
        gateway not set, nameserver not set
Loader:raw Filesys:raw Dev:flash0.os File: Options:(null)
Loading: ..... 1601536 bytes read
Entry at 0x80001000
Closing network.
Starting program at 0x80001000
CPU revision is: 00029008
Primary instruction cache 16kb, linesize 16 bytes (2 ways)
Primary data cache 8kb, linesize 16 bytes (2 ways)
Linux version 2.4.20 (root@localhost.localdomain) (gcc version 3.2.3 with Broadcom modifications)
...
(snip)
...
Hit enter to continue...
```

Pressing enter will give you a root shell:

```
BusyBox v0.60.0 (2005.11.14-09:45+0000) Built-in shell (msh)
Enter 'help' for a list of built-in commands.

#
```

Task Four: Access the Common Firmware Environment CLI

If you reboot the router while holding CTRL+C on the serial console, you will get a CFE prompt:

```
CFE version 1.0.37 for BCM947XX (32bit,SP,LE)
Build Date: Mon Nov 14 18:06:25 CST 2005 (root@localhost.localdomain)
Copyright (C) 2000,2001,2002,2003 Broadcom Corporation.

Initializing Arena
Initializing Devices.

No DPN
et0: Broadcom BCM47xx 10/100 Mbps Ethernet Controller 3.90.37.0
CPU type 0x29008: 200MHz
Total memory: 16384 KBytes

Total memory used by CFE:  0x80300000 - 0x803A39C0 (670144)
Initialized Data:          0x803398D0 - 0x8033BFE0 (10000)
BSS Area:                  0x8033BFE0 - 0x8033D9C0 (6624)
Local Heap:                0x8033D9C0 - 0x803A19C0 (409600)
Stack Area:                0x803A19C0 - 0x803A39C0 (8192)
Text (code) segment:       0x80300000 - 0x803398D0 (235728)
Boot area (physical):      0x003A4000 - 0x003E4000
Relocation Factor:         I:00000000 - D:00000000

Boot version: v3.7
The boot is CFE

mac_init(): Find mac [00:18:39:6F:78:15] in location 0
Nothing...

eou_key_init(): Find key pair in location 0
The eou device id is same
The eou public key is same
The eou private key is same
Device eth0:  hwaddr 00-18-39-6F-78-15, ipaddr 192.168.1.1, mask 255.255.255.0
        gateway not set, nameserver not set
Automatic startup canceled via Ctrl-C
CFE> ^C
CFE> ^C
CFE>
```

See the CFE page for more information about using this prompt.

4.9.4 What to do next?

Now that you have successfully modified and connected to your router, you are ready to *Build* and *Deploy* XINU.

4.9.5 Acknowledgements

This work is supported in part by NSF grant DUE-CCLI-0737476.

4.10 Installing OpenWRT

4.10.1 What is OpenWRT?

OpenWRT is essentially a Linux distribution for embedded systems, specifically routers. It has an incredibly modular structure which allows it to build easily for dozens of different devices and makes package selection easy. It also makes browsing around its source relatively difficult. When you first download a copy of "White Russian", the stable branch of OpenWRT, you don't have a Linux kernel, or even a toolchain, but you have its unique build system, which is everything you need to build a firmware image. As far as we can tell the build process follows these steps:

- Download the correct toolchain
- Build the toolchain
- Download a linux kernel
- Download selected packages
- Use the toolchain to build the kernel / packages
- Smush everything together into several flavors of executable (depending on file system)
- Also create versions with proper Linksys headers so that they can be uploaded though the web interface as "legit" firmware upgrades

So though the precious bounty is not in the original download, once you complete the build process, the build system leaves the linux source behind in the **build_mipsel** directory, and the toolchain is left waiting to be swiped as well. Although we recommend building your own *cross compiler* which can be more finely tuned.

The *Embedded Xinu* project has used OpenWRT's linux source as a reference in our work on implementing XINU for MIPS.

4.10.2 Installing OpenWRT

This is a quick overview of the very easy process of installing the OpenWRT open source firmware into a LinkSys WRT54GL. Several much more detailed sources of documentation exist on this [1] [2], but we include bare essentials here for simplicity's sake and also because the bulk of OpenWRT does not interest us–it only provides us with a working open-source implementation of an embedded operating system on the router.

OpenWRT provides a mature environment for exploring your router hardware, but is not required to run XINU.

Before Starting

Get the latest OpenWRT binary from http://downloads.openwrt.org/whiterussian/newest/bin/. The correct file is `openwrt-wrt54g-squashfs.bin`

Steps to Install OpenWRT

1. Connect to the LinkSys web interface by visiting its address (default 192.168.1.1) in a web browser.
2. Upload the OpenWRT file as a "firmware update".
3. Watch as your router magically[#magic]_ transforms into an OpenWRT-running box.

[1] http://wiki.openwrt.org/OpenWrtDocs/Installing
[2] http://wiki.openwrt.org/InstallingWrt54gl

What to do next?

First it is a good idea to play around with the OpenWRT installation and get a feel for its web interface. You can also login via ssh to the router and poke around its directory structure.

The next big step towards a custom operating system on the router is covered in the next HOWTO in which we will *modify the Linksys hardware*.

4.10.3 Related Links

- http://www.openwrt.org - OpenWRT home page
- http://wiki.openwrt.org/OpenWrtDocs/Hardware/Linksys/WRT54GL - information on WRT54GL router

4.10.4 Notes

4.11 Modifying the ASUS hardware

4.11.1 Summary

The purpose of this walk through is to explain how to add hardware to the ASUS wl-330gE router to take advantage of the serial port on the router and use it to communicate with the serial console for *Embedded Xinu*. This communication is important for interacting with the *Common Firmware Environment*'s, or *CFE*, command line interface which is necessary to run *Embedded Xinu* on the router.

4.11.2 Before Starting

NOTE: The following lists all the *necessary* parts. However, the following tutorial describes assembling the transceiver on one of our custom transceiver boards. One could assemble the parts of the entire transceiver properly without the board, but with more difficulty. Our transceiver board design is freely available for public use.

- Transceiver schematic is in postscript format, suitable for XCircuit.
- Transceiver PCB layout is in PCB format.
- Transceiver fabrication tarball contains Gerber photoplotter and CNC drill files suitable for professional fabrication. (No warranty express or implied, obviously.)

Parts List

Quantity	Part Name	Details	Part / Model Number	Price
1	ASUS [[wl-330gE]] Router	802.11b/g wireless access point	http://usa.asus.com/	~$40.00
1	IDC socket connector	4 pin header	Jameco	
1	IDC socket connector	5 pin header	Jameco	
1	IDC shrouded double header	0.1", 10 conductor	Jameco 67811CM	$0.33
1	ADM202 Transceiver Chip	Serial Transceiver ADM202EAN	Jameco 1800464	$1.60
2	Capacitor 220 nF	Tantalum,.22uF,35V,10%	Jameco 33507	$0.18
3	Capacitor 100 nF	Tantalum,.1uF,35V,10%	Jameco 33488	$0.22
1	DB9 Female	22AWG,SOLDER CUP	Jameco 15771CM	$0.59

(We provide this parts list as a data point; we offer no guarantees about current prices, and it is not our intent to endorse any particular vendor.)

Tools List

- Soldering Iron
- Dremel tool (for cutting holes in plastic case)
- Continuity Tester (Multimeter, or some other way of checking for proper connections)
- Voltmeter (Multimeter will work for this, too)

4.11.3 Steps to Modify the Hardware

Task One: Open the Router

Using a screwdriver, remove the two nails located underneath the router and gently remove the top of the router from the bottom, revealing the PCB.

DO NOTE: This is where the warranty on the router is voided!

Task Two: Attach the Serial Header

The PCB is easily removable at this state from the router. Located in the center of the PCB is the Broadcom BCM5354 chip. Above the chip are four holes that are aligned vertically. The four holes represent the input and output for the serial interface, along with the 3.3 volt power and ground sources for the serial port.

For easier connectivity, we can use a 4-pin header on the board to easily attach and detach a 4 connection cable. Use a soldering iron to solder the 4-pin header onto the board.

Task Three: Create space for access to serial port on the router

Using a dremel or other power tool, carefully cut out a rectangular shaped hole on the faceplate of the router. The hole should be cut above the words “Portable” and it should be 3 mm wide and 1 cm in height, or enough to see the serial port through the hole. This will be used for a 4-wired cable to attach the router to the transceiver board, detailed in step seven.

Task Four: Creating the ADM202 Transceiver Circuit Board

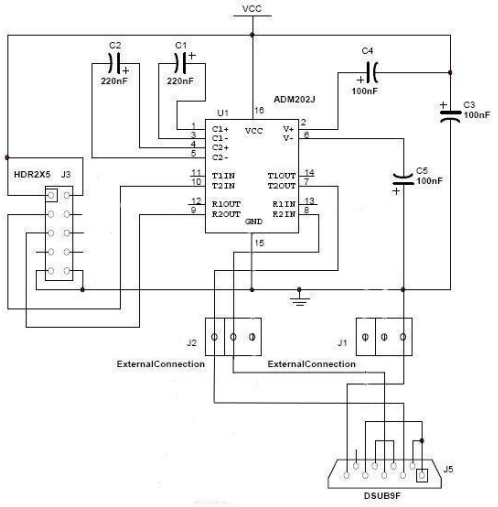


Figure 4.5: Schematic showing the connections between the components of the ADM202 transceiver circuit board and between the board and the DB9 serial port.

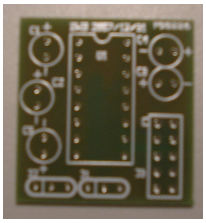


Figure 4.6: Blank transceiver board before adding components.

A transceiver circuit is needed to convert the 3.3 volt serial signals from the router to conventional RS-232 serial voltages. To do this, we need a small square of "perf board", or other circuit prototyping techniques. A soldering iron needs to be used to solder the components onto the board.

Solder the shrouded double header, the socket, and the capacitors onto the board. The direction of the pins matter due to their polarity.

Once the components have been placed on the board, use a continuity tester to check the connection between the header soldered into the router's board and the socket on the transceiver board. Now the ADM202 chip can be inserted onto the board. Next, wires need to be soldered onto the bottom of the transceiver board. Since this router only has one transceiver board, only three of the holes need wires. Under the J2 label, solder wires into the two left most holes. Under the J1 label, which is under the chip, solder a wire on the right most hole.

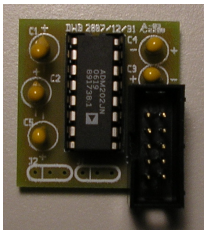


Figure 4.7: Transceiver board with all components in place except ribbon cables.

Task Five: Attach Transceiver Board to the Router

The easiest way to accomplish this is to use an 4-wire audio cable between the router's serial header and the shrouded double header on the transceiver board. Using the 4-pin header on the router, connect the four wires from the audio cable into the 4-pin header. On the transceiver board, follow the diagram to match the corresponding cables on the shrouded double header, but using a 5-pin serial header to easily attack to the shrouded double header.

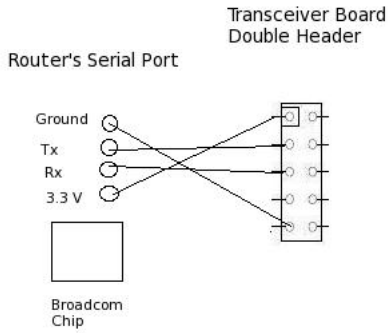


Figure 4.8: Schematic showing the connections between the components of the ADM202 transceiver circuit board and between the board and the DB9 serial port.

Now you can use a continuity tester to make sure that all the connections are good and that no wires or solder cups are touching. The router should be placed back it its case, and the box keeping all the components together should separate the router from the transceiver board. It will be very bad if the circuit board and the transceiver board were to touch.

Task Seven: Creating a box case for the component

The ASUS router is small, but because of this, there is no space for the DB9 female serial port, the adaptor, the relay, and the transceiver board. Because of this, a box is needed to enclose all of these components together. The box should have holes cut out for the DB9 female serial port, the power adapter and the Ethernet port. Also, a small barrier needs to be placed between the transceiver board and the relay so they do not meet. The PCB can be safely placed inside the ASUS router case.

Task Six: Attach Transceiver Board to DB9 Serial Ports

Since the router is very small, it will not have space to place the DB9 Serial Port. Therefore, a small container needs to be created to encase all of the components. This will be discussed in step seven. Take the three wires from the transceiver board and attach them to the DB9 female according to the diagram. Make sure that the solder cups 1, 4, and 6 are connected to each other and solder cups 7 and 8 are connected to each other in the DB9 Female serial port. Notice that in the case of the DB9 Female the T1OUT pin of the ADM202 transceiver chip needs to be connected to solder cup 2, the R1IN pin of the ADM202 transceiver chip needs to be connected to solder cup 5.

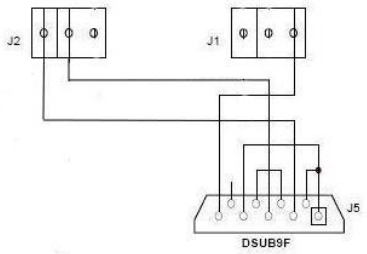


Figure 4.9: Diagram demonstrating proper wiring between the transceiver board and the DB9 serial port.

4.11.4 What to do next?

Connect UART0 (the DB9 Female serial port) to a computer and follow the next HOWTO on using a PC to *connect to a modified router*.

4.11.5 References

This work is supported in part by NSF grant DUE-CCLI-0737476.

4.12 Modifying the Linksys hardware

4.12.1 Summary

This will walk through adding hardware to a Linksys *WRT54GL* wireless router that will take advantage of existing connections on the PCB for two UART connections, which will be exposed as DB9 serial port connectors mounted to the faceplate of the router. These connections can be used to communicate with the serial console for *Embedded Xinu* and also to interact with the *Common Firmware Environment*'s command line interface. Gaining direct access to *CFE* is a key step towards being able to run *Embedded Xinu* on the router.

4.12.2 Before Starting

NOTE: The following lists all the *necessary* parts. However, the following tutorial describes assembling the transceiver on one of our custom transceiver boards. One could assemble the parts of the entire transceiver properly without the board, but with more difficulty. Our transceiver board design is freely available for public use.

- Transceiver schematic is in postscript format, suitable for XCircuit.
- Transceiver PCB layout is in PCB format.
- Transceiver fabrication tarball contains Gerber photoplotter and CNC drill files suitable for professional fabrication. (No warranty express or implied, obviously.)

Parts List

Quantity	Part Name	Details	Part / Model Number	Price
1	Linksys *WRT54GL* Router	802.11b/g wireless broadband router	Linksys WRT54GL	~$65.00
1	Ribbon cable	28 AWG, 10 conductor, 25'	Jameco 643508CM	$4.99
2	IDC socket connector	0.1", 10 conductor	Jameco 32491CM	$0.25
2	IDC shrouded double header	0.1", 10 conductor	Jameco 67811CM	$0.33
1	ADM202 Transceiver Chip	Serial Transceiver ADM202EAN	Jameco 1800464	$1.60
2	Capacitor 220 nF	Tantalum,.22uF,35V,10%	Jameco 33507	$0.18
3	Capacitor 100 nF	Tantalum,.1uF,35V,10%	Jameco 33488	$0.22
1	DB9 Female	22AWG,SOLDER CUP	Jameco 15771CM	$0.59
1	DB9 Male	22AWG,SOLDER CUP	Jameco 15747CM	$0.59

(We provide this parts list as a data point; we offer no guarantees about current prices, and it is not our intent to endorse any particular vendor.)

Tools List

- Soldering Iron
- Dremel tool (for cutting holes in plastic case)
- Continuity Tester (Multimeter, or some other way of checking for proper connections)
- Voltmeter (Multimeter will work for this, too)

4.12.3 Steps to Modify the Hardware

Task One: Open the Router

Figure 4.10: It's really very easy.

There are no screws or tools needed to open the router, just pop open the front with your thumbs as shown in the picture. Some nice illustrated opening instructions can be found for a more detailed explanation of this step.

DO NOTE: This is where the warranty on the router is voided!

Task Two: Attach the Serial Header

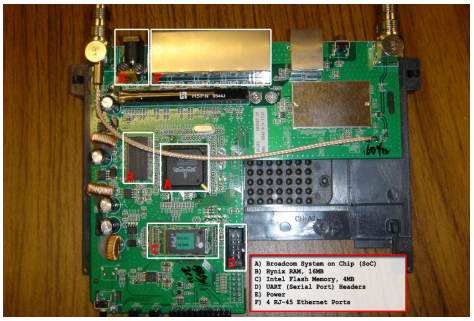


Figure 4.11: An overhead view to get your bearings. The serial header is (D) here.

First you need to unscrew the two screws keeping the router's board attached to the case. Once the PCB has been removed from the case, locate the serial header holes provided by Linksys. This would be a grid of 10 holes (5x2) located on the bottom-right corner of the board when the antennae stubs are on top (see the top-down photo for clarification). These ten holes hold all of the input and output for the two serial interfaces–UART0, and UART1–on the device.

Now, we could just solder wires right onto these holes, but a by placing a nice 10-pin header on the board we can easily attach and detach a 10 connection cable. Here you will use your **soldering iron** to solder the **IDC shrouded double header** onto the board. Make sure to note where the 1 pin is on the board (marked with a square around the hole instead of a circle) and where the 1 pin is located on the header (on ours it was marked with a triangle). Make sure that these two line up when soldering the header into the board.

Task Three: Create the ADM202 Transceiver Circuit Board

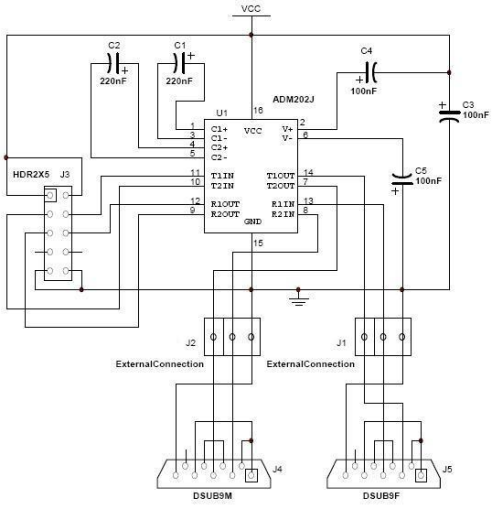


Figure 4.13: Schematic showing the connections between the components of the ADM202 transceiver circuit board and between the board and the DB9 serial ports.

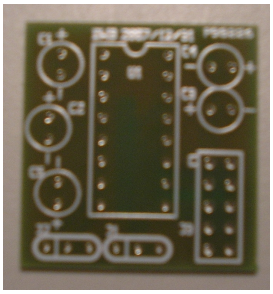


Figure 4.14: Blank transceiver board before adding components.

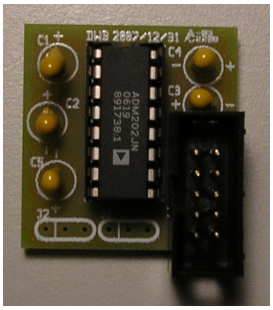


Figure 4.15: Transceiver board with all components in place except ribbon cables.

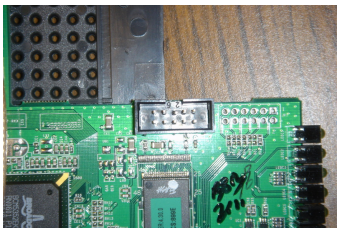


Figure 4.12: A closer look at our attached serial header.

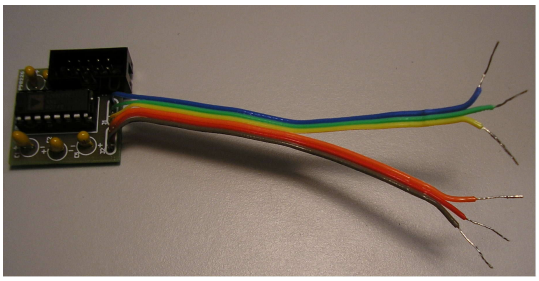


Figure 4.16: Complete transceiver board with all components in place.

The next step is to build the transceiver circuit, which converts the 3.3 volt serial signals from the router to conventional RS-232 serial voltages. The circuit includes only a handful of components, so it can be assembled using a small square of "perf board", or a variety of other inexpensive circuit prototyping techniques. We use a custom-made printed circuit board to simplify assembly, as shown here. (Link to page with PCB specs, and directions.) Again, you'll need your **soldering iron** to secure the different pieces in the transceiver board.

Using the diagram on the left, solder the **shrouded double header**, the **socket**, and the **capacitors** into the board in the appropriate places. **NOTE:** the positions of the components on the physical board are not represented in the diagram, but the silkscreen on the board indicates placement and orientation. **FURTHER NOTE:** each component has a proper polarity or pin marking – direction matters!

The pictures to the right show the transceiver board in various stages of completion. The top one shows the blank board on which the other components will be added. The bottom one shows the **shrouded double header**, the **socket**, and the **capacitors** soldered in place. It also shows the actual ADM202 chip inserted into the socket, however, before inserting the chip it is a good idea to test what you've completed so far.

Use a **continuity tester** to check the connection between the header soldered into the router's board and the socket on your transceiver board. The next step we recommend for testing your work is to plug in the router and use a **voltmeter** to check that the *ground* and *power* pins on the socket (pins 15 and 16) are registering at 3.3 volts. Now, actually insert the ADM202 chip into the socket and power up the router again, making sure that the lights turn on and nothing shorts out.

The next step is to get six wires from a chopped up piece of the ribbon cable (or any six spare wires) and solder them into place in the six holes (two sets of three) at the bottom of the transceiver board. The resulting completed transceiver board should look something like the picture below the diagram.

Task Four: Attach Tranceiver Board to the Router

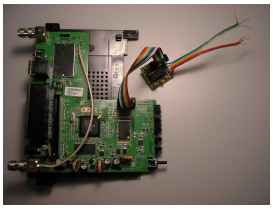


Figure 4.17: Transceiver board attached via ribbon cable to the serial header soldered into the router's board.

First take a piece of ribbon cable and attach each end to one of your IDC socket connectors. Notice the marker on the connector that signifies where pin 1 of the header will connect to. Make sure that the same side of the ribbon cable is attached to the marked side of both connectors. In other words make sure that the same wire will line up with pin 1 on both headers when the connectors are eventually attached to the headers. The next step is to actually plug in the connectors to the headers. Attach one connector to the header we soldered into the router's board and the other connector to the header we soldered into the transceiver board. The result should look something like the picture to the left. Now is a good time to reattach the router's board to its case by screwing the two screws into place and then closing up both black pieces of the back part of the router's case.

Task Five: Attach Transceiver Board to DB9 Serial Ports

Before soldering the wires from the transceiver board to the serial ports, it is a good idea to drill two holes in the front of the router's casing to use for the serial ports and also two small holes on each side of the bigger ones to use for screws or bolts to keep the **DB9 Serial Ports** in place. The three pictures to the right show how to take off the front sticker and what the case should look like after you've drilled two holes in the front for the serial ports. It is also a good idea to cut the sticker and place the left part back on to cover up the remaining holes in the casing.

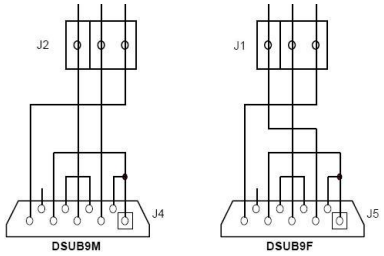


Figure 4.18: Diagram of wiring to connect the two DB9 serial ports to the transceiver board.

Next, feed the six wires coming from the transceiver board through the two holes you just drilled. Make sure that the three wires soldered into the holes marked **J1** on the transceiver board go through the hole on the left of the front of the router and the three wires soldered into the holes marked **J2** on the transceiver board go through the hole on the right of the front of the router.

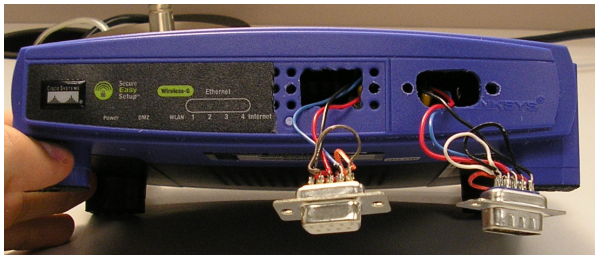
Following the diagram to the left, solder some spare wires or chopped pieces of ribbon cable into the two DB9 serial ports. Notice that solder cups 1, 4, and 6 are connected to each other and solder cups 7 and 8 are connected to each other on both the **DB9 Female** and **DB9 Male** serial ports. Then, again following the diagram, solder in the wires coming from **J1** into the appropriate solder cups of the **DB9 Female** and the wires coming from **J2** into the appropriate solder cups of the **DB9 Male**.

Notice that in the case of the **DB9 Female** the *T1OUT* pin of the ADM202 transceiver chip needs to be connected to solder cup 2, the *R1IN* pin of the ADM202 transceiver chip needs to be connected to solder cup 3, and the *ground* needs to be connected to solder cup 5.

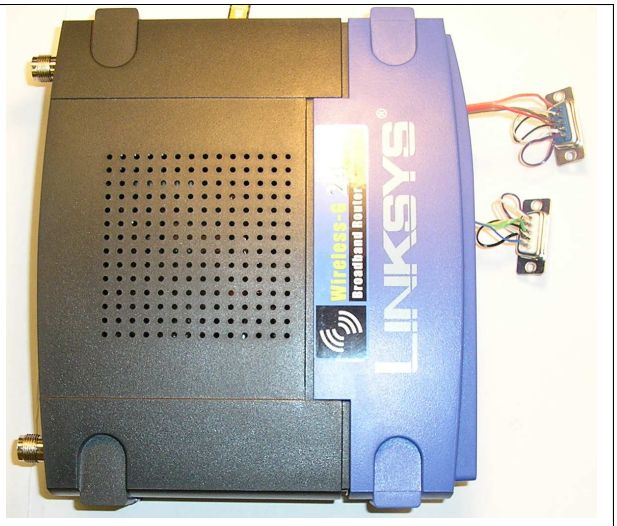
Also, notice that in the case of the **DB9 Male** the *R2IN* pin of the ADM202 transceiver chip needs to be connected to solder cup 2, the *T2OUT* pin of the ADM202 transceiver chip needs to be connected to solder cup 3, and the *ground* needs to be connected to solder cup 5.

Feeding the wires through the holes and connecting the serial ports in this way ensures that the router's primary serial device will be connected to the **DB9 Female** serial port and will be located on the left side while the router's secondary serial device will be connected to the **DB9 Male** serial port and will be located on the right side of the front of the router.

After all the soldering is done it is a good idea to use a **continuity tester** to make sure that all the connections are good and no wires or solder cups may be accidentally touching. Your result should look something like the pictures below. Now is a good time to tape the transceiver board down to the front of the case. It would be extremely bad for the transceiver board to rub up against the router's circuit board when it was plugged in.



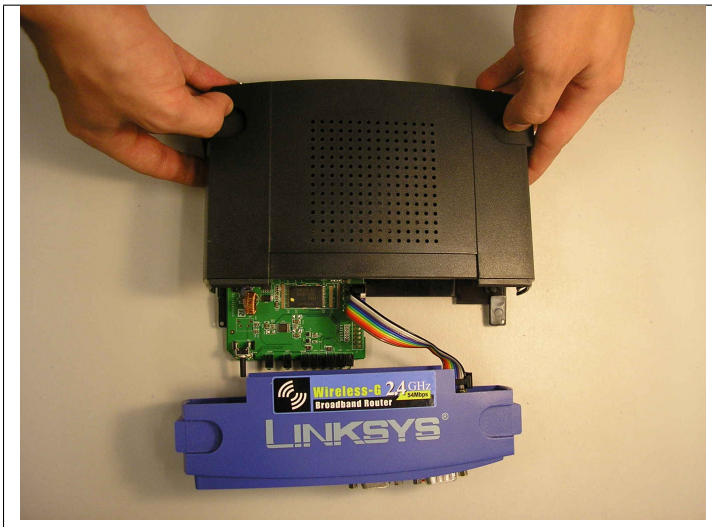
Front view of what the router will look like after the DB9 serial ports are correctly soldered into place, but before they have been screwed and secured into the router's case.



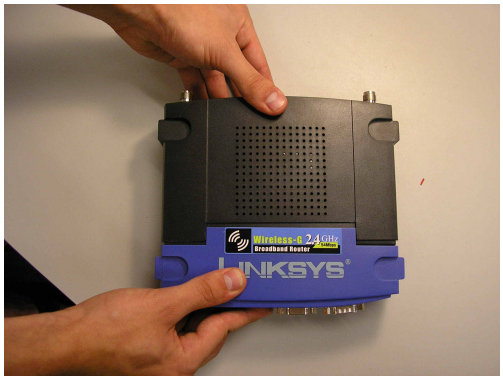
Overhead picture of what the router will look like after the DB9 serial ports are correctly soldered into place, but before they have been screwed and secured into the router's case.

Task Six: Close the Router

This final task is best described in photos:



Now that everything is connected we can re-assemble it. First you put on the back/top half. Keyed ribbon cable is plugged in to serial port header on circuit board.



Next you can carefully install the front half (making sure not to break any of the wires we have).

Task Seven: Rejoice

4.12.4 What to do next?

Connect UART0 (the DB9 Female serial port) to a computer and follow the next HOWTO on using a PC to *connect to a modified router*.

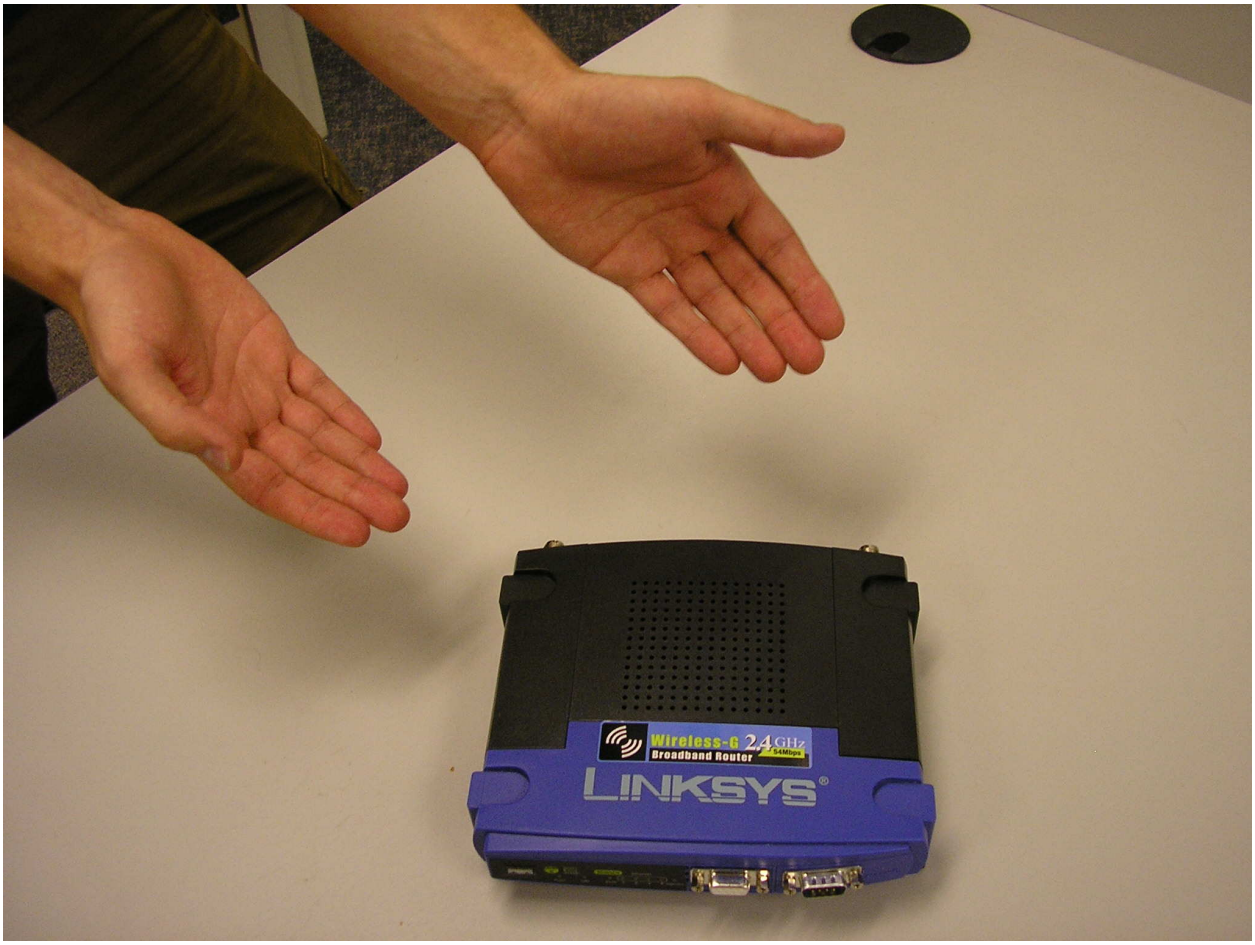


Figure 4.19: Now you have a WRT54GL with two serial ports installed and ready to run your own operating system.

4.12.5 Acknowledgements

This work is supported in part by NSF grant DUE-CCLI-0737476.

4.13 Recovering a router

So you've created yourself an expensive paperweight...

Not to worry! If you aren't breaking things, then chances are you aren't making hardcore progress. This page serves as a knowledge pool for methods to revive routers that are corrupted or otherwise considered non-functional. The information below is mostly specific to the WRT54GL as it is our most popular and well understood platform at this time. The process is somewhat similar for other models/platforms; however, some of the utilities are limited to specific platforms and commands vary slightly between bootloaders (ex. U-Boot vs CFE).

Sometimes the router won't boot because of a corrupted NVRAM variable and a simple factory reset will resolve the problem. Chances are if you've sought out this page you are in much deeper and probably need a more serious TFTP or *JTAG* recovery. We'll start with the simple solutions and work our way to the more intense recovery methods.

4.13.1 Before You Begin

If you haven't already, *backup your router's configuration*. Hopefully you did this earlier so you can restore to a "known good" working state. If you didn't, it is still a good idea to do that now; it can always get worse. You'll also want to grab yourself a copy of some reliable firmware. The default firmware that shipped with your router is a good place to start (generally available from the manufacturer's website). Otherwise, a stable release of your favorite embedded Linux distribution is a good alternative.

4.13.2 Factory Reset

Don't get your hopes up for this one, but sometimes Occam's razor applies to router recovery. To do a factory reset, hold down the reset switch for about 10 seconds while the unit is powered on, then unplug it. Let it rest for a little while then power it back up. If this isn't working for you, try the dd-wrt 30/30/30 reset method.

There's another option if you have access to a serial console, but your router isn't necessarily readily accessible (say locked in a rack somewhere with a pool of backends). Access the CFE as you normally would. Then, issue the command `CFE> nvram erase` and then reboot. Some models do not properly reinitialize their NVRAM variables automatically, so be careful with this method. The WRT54GL does recover them conveniently from a separate stored location in flash.

If you haven't caught on by now, these methods erase any custom settings that were stored in NVRAM. Don't forget to re-configure and commit your network settings, if applicable.

4.13.3 Serial Console

Now is a good time to check that your serial console is up and running. If you don't see any text coming across the serial link, then you should double check your transceiver is working properly. Swap with a working one or at least try the one in question on another working router, if you have one available. If you can access the web interface (assuming the OS in flash has one) at either the default IP address or the one you configured, then your flash image is probably fine–fix your serial console. It is important that you are confident your serial console if functional; henceforth we'll be looking for output on the serial port as a metric for whether each recovery method is successful or not.

If you can see text and access the CFE but your router won't boot, try re-flashing the firmware with TFTP.

If you are confident the serial interface hardware is working properly but your router appears dead, then proceed to the next section.

4.13.4 JTAG

In a nutshell, JTAG is an external interface that allows external control of an SoC and its memory. You can read more about this on our EJTAG page. JTAG allows us to recover routers that are completely unresponsive (aka debricking). Before continuing, you'll need a JTAG cable (active or passive will do) and a header soldered to the JTAG connector on your router. See the references below for some suggestions on this bit.

Software

For WRT54GL recovery, the popular programs are the original HairyDairyMaid utility and a port called TJTAG. If you purchase a commercial cable, it may come with a hardware specific recovery tool. This guide focuses on TJTAG. Download a copy of the source (linked below) and compile as usual.

If you built your own cable, chances are it uses a legacy printer style parallel port interface. You'll need adequate permissions to use this device in order to run the JTAG software. In *nix style systems usually means the user you execute TJTAG as must be a member of the `lp` group.

The result of the `groups` command should look something like this before you continue:

```
user@host:~$ groups
user lp dialout
```

Membership of the `dialout` group isn't strictly necessary; however, you will need this as well if you want to use a local serial console.

Establish a Connection

Now we must verify that TJTAG can properly connect to the JTAG interface on the router. Connect the JTAG cable to both your PC and the router but leave the power disconnected. On most routers you will be fighting the watchdog timer so it is a good idea to type out whatever command you want to execute (without hitting `enter`), then provide power, and finally quickly hit `enter` as soon as the router LEDs light up.

Active vs Passive

If you built the active buffered cable you need to add the `/wiggler` option to all of your TJTAG commands. The passive unbuffered cable does not require this option and you should leave it off when using this type of cable. If you anticipate needing to revive routers often, an active cable is surely worth the additional investment in time and parts so you aren't restricted to working within 6 inches of your parallel port. Otherwise, the unbuffered cable works great provided you can manage the logistics of the restricted cable length.

TJTAG Options

The next trick is to find the magical combination of optional TJTAG parameters which makes your router happy. Even within a single make/model this seems to vary greatly–most likely because of various flash chip manufacturers. For starters, we'll use the `-probeonly` option to guess and check which options will work before modifying the contents of flash. Usually something like

```
user@host:tjtag$ ./tjtag -probeonly /wiggler /noemw /noreset
```

will do the trick. If you are not getting the desired output (see below), try experimenting with the DMA, break, and reset switches. Once you've mastered the combinatorics game, you can move onto read/write operations.

Successful Output

When you've got the right combinations of parameters, you should see an output like this:

```
============================================
 EJTAG Debrick Utility v3.0.1 Tornado-MOD
============================================

Probing bus ... Done

Instruction Length set to 8

CPU Chip ID: 00000101001101010010000101111111 (0535217F)
*** Found a Broadcom BCM5352 Rev 1 CPU chip ***

    - EJTAG IMPCODE ....... : 00000000100000000000100100000100 (00800904)
    - EJTAG Version ....... : 1 or 2.0
    - EJTAG DMA Support ... : Yes
    - EJTAG Implementation flags: R4k MIPS32

Issuing Processor / Peripheral Reset ... Skipped
Enabling Memory Writes ... Skipped
Halting Processor ... <Processor Entered Debug Mode!> ... Done
Clearing Watchdog ... Done

Probing Flash at (Flash Window: 0x1fc00000) ...
Done

Flash Vendor ID: 00000000000000000000000011101100 (000000EC)
Flash Device ID: 00000000000000000010001010100010 (000022A2)
*** Found a K8D3216UBC  2Mx16 BotB     (4MB) Flash Chip ***

    - Flash Chip Window Start .... : 1fc00000
    - Flash Chip Window Length ... : 00400000
    - Selected Area Start ........ : 00000000
    - Selected Area Length ....... : 00000000



 *** REQUESTED OPERATION IS COMPLETE ***
```

The last line is important. Don't move on until you get this response.

Troubleshooting

If you see something like this:

```
============================================
 EJTAG Debrick Utility v3.0.1 Tornado-MOD
============================================

Probing bus ... Done

Instruction Length set to 8
```

```
CPU Chip ID: 00000101001101010010000101111111 (0535217F)
*** Found a Broadcom BCM5352 Rev 1 CPU chip ***

    - EJTAG IMPCODE ....... : 00000000100000000000100100000100 (00800904)
    - EJTAG Version ....... : 1 or 2.0
    - EJTAG DMA Support ... : Yes
    - EJTAG Implementation flags: R4k MIPS32

Issuing Processor / Peripheral Reset ... Done
```

You probably don't have the correct combination of options for your router. Play with the different switches available before attempting to read/write from flash.

If you see something like this:

```
=============================================
 EJTAG Debrick Utility v3.0.1 Tornado-MOD
=============================================

Probing bus ... Done

Instruction Length set to 5

CPU Chip ID: 11111111111111111111111111111111 (FFFFFFFF)
*** Unknown or NO CPU Chip ID Detected ***

*** Possible Causes:
    1) Device is not Connected.
    2) Device is not Powered On.
    3) Improper JTAG Cable.
    4) Unrecognized CPU Chip ID.
```

Aside from what the output mentions already check that

- the header is soldered properly
- tjtag has permission to use the parallel port
- you didn't forget the `/wiggler` switch (active cable only).

General Advice for Read/Write Operations

In the next few steps you'll attempt to correct some issues in flash memory that might prevent the router from booting correctly. Ideally when you deal with flash, it is best not to interrupt the process before it finishes on its own. That is why it is important to get the TJTAG options correct with the `-probeonly` option. If an operation hangs while attempting to read/write, don't panic. It is probably in your best interests not to buy any lottery tickets tonight, but most likely all is not lost. Be patient–be sure you've given it ample time to complete. If it doesn't seem to be making any progress then you probably need to reset the router. Various sources on the Internet have different opinions on the best way to reset. Nevertheless, we've found that disconnecting the power first and then canceling the operation (via CTRL+C) works the best. Lastly, try the operation again (double check your parameters).

Erase NVRAM

Step 1. As before, it's a good idea to ensure NVRAM has been wiped out and isn't harboring corrupt variables. Use the same TJTAG options that got you a successful completion when trying to probe the device.

Example:

```
user@host:tjtag$ ./tjtag -erase:nvram /wiggler /noemw /noreset
```

When the device reboots, it should reinitialize the correct NVRAM settings from the backup location within the CFE. If you now have a serial console, success, you're good to go. Don't forget to reconfigure any custom NVRAM settings. If that didn't work, read on.

Erase the Kernel

Step 2. For whatever reason, it is possible for a corrupted kernel to prevent the bootloader from producing any output. Again, use the same options you figured out during the `-probeonly` phase.

Example:

```
user@host:tjtag$ ./tjtag -erase:kernel /wiggler /noemw /noreset
```

After rebooting your router, you should get console output that indicates the CFE was upset to find there's no kernel to load from flash. This is normal; you did just erase this region of flash (hopefully). Now you can proceed to flashing a new kernel or maybe you just want to *load an elf image* over the network.

Still got a blank serial console? Read on.

CFE Recovery

Step 3. Your last ditch effort is to replace the bootloader. If your CFE is corrupted then there's no hope of booting. Luckily, we can flash new one using TJTAG. The CFE contains a few settings unique to each router. If you made a backup of your CFE before things went South, you can use that to restore the router to working order. If you don't have a backup, you can borrow a copy from another identical router. In the latter case you must customize the CFE binary a bit before using it on a different router. In the event you don't have access to a working router of the same make and model, try searching around on the Internet for a pristine CFE. There have been a few "CFE collection" projects out there; you might get lucky.

Transplant Another Router's CFE

If you have the original CFE for this exact router, skip ahead to the next section. Otherwise, start by cloning the CFE of your good router using *the usual methods*.

There are a few CFE variables unique to each router. For the WRT54GL, see our *flash memory* page for specific locations. There should be a unique identifier and a pair of cryptography keys as well as the device MAC addresses. We're primarily concerned with the MAC address of the first physical Ethernet interface, but feel free to update the others as well. For the WRT54GL, 0x1E00 contains the MAC address used by the CFE at boot time. While you can override this setting later for your kernel in your local network configuration or NVRAM, you can't fool the bootloader (well you can, but not persistently). Especially, if you are running a pseudo-static DHCP configuration for a pool of backends, you'll get lots of network conflicts during the boot process unless this is set correctly. For the WRT54GL, this MAC address should match the one on the bottom sticker. Other routers have various schemes/offsets for what the address should be relative to the one printed on the case depending on how many physical interfaces the unit has and how the manufacturer chose to allocate the addresses. If you are feeling ambitious, you can update the default NVRAM settings in the CFE backup location so they are correct when you do a factory reset. Alternatively, these can always be corrected later using the NVRAM utilities.

To edit the CFE, fire up your favorite hex editor and tweak each location as necessary. We happen to like `shed`, which has a nice `nano` like interface. Note that with `shed` your changes are affecting the file directly as you make them. There is no "quit without saving" option. It is always a good idea to make a copy of the CFE.BIN file you are planning to edit so you can revert to the original without having to grab it off the good router again.

Example:

```
offset    asc hex dec oct bin
00001DFE:     00  000 000 00000000
00001DFF:     00  000 000 00000000
00001E00:  C  43  067 103 01000011
00001E01:  0  30  048 060 00110000
00001E02:  :  3A  058 072 00111010
00001E03:  F  46  070 106 01000110
00001E04:  F  46  070 106 01000110
00001E05:  :  3A  058 072 00111010
00001E06:  E  45  069 105 01000101
00001E07:  E  45  069 105 01000101
00001E08:  :  3A  058 072 00111010
00001E09:  C  43  067 103 01000011
00001E0A:  0  30  048 060 00110000
00001E0B:  :  3A  058 072 00111010
00001E0C:  F  46  070 106 01000110
00001E0D:  F  46  070 106 01000110
00001E0E:  :  3A  058 072 00111010
00001E0F:  E  45  069 105 01000101
00001E10:  E  45  069 105 01000101
00001E11:     00  000 000 00000000
00001E12:     FF  255 377 11111111
00001E13:     FF  255 377 11111111
00001E14:     FF  255 377 11111111
                                                          1E00/40000 (hex)
SPACE|E edit  S|W|F search  J jump to   T dec/hex   D dump     1|2|4 cursor
X       exit  R|N   repeat  B bin edit  A ext. asc  P preview  `     endian
```

You should now have a CFE.BIN file with the correct MAC address(es) ready for flashing! Proceed to the instructions below as if you had a correct backup all along.

Using the Same Router's Backup

Copy your CFE binary to a file called CFE.BIN in the same directory as the TJTAG executable. You don't have a choice for what file TJTAG reads in. When you are ready to write it to the router, once again make sure you know which TJTAG switches keep your particular router happy.

Example:

```
user@host:tjtag$ ./tjtag -flash:cfe /wiggler /noemw /noreset
```

Now, go get a cup of coffee or take a power nap. Bit-banging a few hundred kilobytes with a parallel interface can take awhile. You should see exactly what TJTAG is writing to flash whirring by as well as the percentage written slowly increasing. Sometimes the watchdog timer doesn't disable correctly and you have to try this a few times before it will keep going. If it going to fail usually this happens within the first few seconds.

A fresh CFE should fix most stubborn routers that aren't physically damaged, but we make no guarantees. Your mileage may vary. Hopefully you have your serial console back and you can proceed to restoring a new kernel. If your router is still unresponsive, unfortunately we have no more advice for you. It is probably time to invest in a new one.

4.13.5 External References

- OpenWrt JTAG Reference (includes various DIY cable designs and links to commercial products)
- OpenWrt Utilities (HairyDairyMaid Download)
- TJTAG Download

- TIAO Wiki Debrick Guide
- Shed (Simple Hex Editor)

4.14 Memory

Memory on MIPS-based processors is broken into several segments, consuming the entire 32-address space. These segments are arranged as follows:

- User Segment (USEG), 2 GB **mapped** and **cached**, addresses `0x0000 0000` through `0x7FFF FFFF`
- Kernel Segment 0 (KSEG0), 512 MB **unmapped** and **cached**, addresses `0x8000 0000` through `0x9FFF FFFF`
- Kernel Segment 1 (KSEG1), 512 MB **unmapped** and **uncached**, addresses `0xA000 0000` through `0xBFFF FFFF`
- Kernel Segment 2 (KSEG2), 1 GB **mapped** and **cached**, addresses `0xC000 0000` through `0xFFFF FFFF`

Note that the *WRT54GL* only has 16 MB of main memory, so a 1-1 mapping is not be available above `0x..FF FFFF`.

4.14.1 User Segment

The user segment of memory, or USEG, is the range of memory addresses from `0x0000 0000` through `0x7FFF FFFF`. This memory is both mapped and cached, meaning that any attempt to access memory within this range will result in the hardware consulting the memory manager prior to access. **Note** that any attempted access in this range must with the CPU privilege level set to user mode (i.e. $Status(KSU) = 2$) or the processor must be in the exception state with the error level bit set (i.e. $Status(EXL) = 1$). In the latter case, all mappings turn into 1-1, so directly accessing these address is not recommended.

Under normal operation, when an address in this memory range is accessed, the processor will query the memory management unit is consulted for a mapping. In turn this will ask the translation lookaside buffer (TLB), and if no mapping is found cause a TLB load or store exception. When this exception occurs, the operating system is consulted and should write the correct mapping to the TLB and return from the exception handler.

It should be noted that when a TLB exception occurs in the USEG range of addresses, a special "fast" exception handler is consulted instead of the normal exception handler. This fast handler is at most 32 instructions long and begins at `0x8000 0000`.

User Segment under Xinu

Embedded Xinu has basic *memory management* as of the 2.0 release. During initialization, the kernel allocates some amount of memory (defined in `xinu.conf` as `UHEAP_SIZE`) to act as the user memory heap. Once this memory is initialized, calls to `malloc` and `free` will use the user heap for memory allocation and automatically insert mappings into the system page table. All mappings are 1-1 since there is no backing store for a virtual memory subsystem, though it would be possible to provide each thread with a private address space this requires lots of memory overhead.

Exception code to handle TLB faults is in the tlbMissHandler() function and simply performs a lookup of the faulting address in the system page table, checks to see if it is valid and in the correct address space, and inserts the mapping in the TLB hardware.

4.14.2 Kernel Segments

While the first part of memory is dedicated to the user segment, the remainder is the kernel segment. Unlike the user segment, the kernel segment is sub-divided into three segments with different memory access properties. **Note** that these properties can be very important if you are dealing with device drivers and/or hardware that uses direct memory access (DMA) because there may be caching considerations.

In brief:

- KSEG0 uses **unmapped** and **cached** memory accesses,
- KSEG1 uses **unmapped** and **uncached** memory accesses, and
- KSEG2 uses **mapped** and **cached** memory accesses.

Kernel Segment 0

The first kernel segment, or KSEG0, is the range of memory addresses from `0x8000 0000` through `0x9FFF FFFF`. This memory is **unmapped** and **cached**, meaning that when the processor attempts to access an address in this range it will not consult the memory manager for a mapping, but will store and modifications in the on-chip memory cache. **Note** that when allocating memory for a device driver that will be using DMA, the caching effects could lead to major headaches. If memory is being given to a hardware backend it should be mapped into the range of KSEG1.

On many MIPS processors the first page (4096 bytes) of KSEG0 is considered to be reserved system space where small amounts of specialized code can be loaded for fast execution. Typically, this memory is used for exception handling and the following sections are reserved for the following:

- `0x8000 0000` (32 instructions) is for the TLB exception handler,
- `0x8000 0080` (32 instructions) is for the 64-bit TLB exception handler, and
- `0x8000 0180` (32 instructions) is for the generic exception handler.

Other reserved portions of this memory page remain unknown.

After the reserved system page, the operating system is free to use memory however it sees fit.

KSEG0 under Xinu

Embedded Xinu uses KSEG0 extensively for kernel operations. As the *WRT54GL* uses a 32-bit MIPS processor, Embedded Xinu loads a quick TLB handler into memory at `0x8000 0000` and a generic exception handler at `0x8000 0180`, both of these are limited to 32 instructions and jump to higher level C code when needed. It is important to note that Embedded Xinu also makes use of reserved memory starting at `0x8000 0200` to store an array of exception handler entry points (32-bit function pointers for 32 possible exceptions) and `0x8000 0280` to store an array of interrupt handler entry points (32-bit function pointers for 8 possible interrupts).

Xinu loads the kernel entry point beginning at `0x8000 1000`, and upon booting begins execution at that address. Within Embedded Xinu, the memory segments are in the following order (as defined by `ld.script`): text, read-only data, data, and block started by symbol (BSS, uninitialized data). The kernel allocates a small kernel stack after the BSS segment and finally initializes a dynamic memory heap for the remaining physical memory addresses.

The *kernel memory allocator* will allocate memory from the kernel heap as requested. Since Embedded Xinu uses a single page table, all kernel addresses will be mapped read-only in all address spaces, giving a user thread the ability to read from but not write to kernel memory.

Kernel Segment 1

The second kernel segment, or KSEG1, is the range of memory addresses from `0xA000 0000` through `0xBFFF FFFF`. This memory **unmapped** and **uncached**, meaning that when the processor attempts to access an address in this range it will not consult the memory manager for a mapping and it *will* bypass the on-chip memory cache for memory loads and stores.

By skipping the hardware cache, KSEG1 will see slower memory accesses because it must get data directly from the RAM. Because of this, it is not typical to use KSEG1 for normal kernel operations, rather this segment is useful for accessing memory that is mapped to some other hardware device on the platform. These mappings will either be pre-existing, so they are out-of-range of physical memory addresses, or they will be dynamically allocated memory that will be shared between the operating system and some hardware device.

KSEG1 under Xinu

Embedded Xinu uses several hardware devices that are mapped out-of-range of physical memory and some hardware devices that use dynamically allocated memory for sharing. Some devices on the *WRT54GL* that are beyond the range of physical memory are:

- Broadcom I/O controller registers at `0xB800 0000`,
- UART registers at `0xB800 0300` and `0xB800 0400`,
- Broadcom Ethernet 47xx registers at `0xB800 1000`,
- Broadcom Wireless LAN controller registers at `0xB800 5000`,
- Broadcom 47xx RoboSwitch registers at `0xB800 6000`, and
- *Flash memory* (4 MB) read mapped beginning at `0xBC00 0000`.

Certain drivers (such as the Ethernet driver), also take advantage of shared memory between the operating system and the hardware. This requires the use of dynamically allocated kernel memory (originating in KSEG0), that has been mapped to KSEG1 address range. This is not problematic because both KSEG0 and KSEG1 use a 1-1 memory mapping. With the Ethernet driver of Embedded Xinu, the shared memory that is in KSEG1 hold the DMA descriptor rings and the Ethernet packet buffers to store the packets in.

Kernel Segment 2

The third kernel segment, or KSEG2, is the range of memory addresses from `0xC000 0000` through `0xFFFF FFFF`. This memory is both **mapped** and **cached**, meaning that the processor will consult the memory manager for a mapping and store memory modifications in the on-chip cache.

Like the user segment of memory any attempt to access memory in KSEG2 will result in the processor querying the memory manager and the TLB to find a mapping. If a mapping does not exist the processor will generate a TLB load or store exception and the operating system must fill the TLB entry. Unlike USEG, a TLB exception will not jump to the "fast" handler and instead follow the normal path for exception handling through the generic exception mechanism.

This memory segment could be useful to create the appearance of page aligned data to the underlying hardware or operating system if needed.

KSEG2 under Xinu

Embedded Xinu does not make use of any KSEG2 memory yet. However, to take advantage of the Context register of MIPS processors when a TLB exception occurs, it is possible that a mapping of the system page table to KSEG2 might exist in future versions.

4.14.3 References

- Sweetman, Dominic. *See MIPS Run*. San Francisco: Morgan Kaufmann Publishers, 2007.

4.15 Mips console

```
#!/usr/bin/expect -f


set ip 192.168.1.2

proc powercycle {} {
        send -null 1
        expect "(command-mode)"
        send -- "p"
        #expect "powered on"

        expect {
                "CFE> " { }
                -re ".*\r\n"    { send "\003"
                                  exp_continue }
                }
}


set timeout -1
if {$argc > 1} {
  puts "$argc, $argv"
  puts "usage: mips-console [backend]"
  exit
}

if {$argc == 1} {
  set backend $argv
  set spawned [spawn xinu-console -c mips $argv]
} else {
  set backend null
  set spawned [spawn xinu-console -c mips]
}
expect {
        "error: connection not available"
                { send_user "error: connection not available\r\n"
                  exit }
        -re "connection '(.*)', class '(.*)', host '(.*)'\r\n"
                { set backend $expect_out(1,string)
                  set class   $expect_out(2,string)
                  set host    $expect_out(3,string)
                # send_user "connection $backend, class $class, host $host\r\n"
                }
}
sleep 1
send -null 1
expect "(command-mode) "
send -- "d"
expect "file: "
send -- "xinu.boot\r"
```

```
expect {
        "download complete\r\n"
                { }
        "No such file or directory"
                { send_user "No such file: xinu.boot\r\n"
                  exit }
}
sleep 1
send -- "\r"
set boot 1
expect {
        -timeout 1 "CFE> " {set boot 0}
}
if {1==$boot} powercycle
send -- "ifconfig -auto eth0\r"
expect "CFE> "
send -- "boot -elf $ip:$backend"
send -- ".boot\r"
expect -- "Starting program"
interact
```

4.16 mipsel-qemu

Embedded Xinu has been ported to the MIPSel (little-endian MIPS) virtual environment provided by QEMU. This provides an easy way to run a basic Embedded Xinu environment on a RISC architecture without devoting "real" hardware.

4.16.1 Building

Compile Embedded Xinu with `PLATFORM=mipsel-qemu`. Note that this requires a *cross compiler* targeting little-endian MIPS ("mipsel"). This will produce the file `xinu.boot` in the `compile/` directory.

4.16.2 Running

```
$ qemu-system-mipsel -M mips -m 16M -kernel xinu.boot -nographic
```

4.16.3 Notes

The `mipsel-qemu` platform does not yet support networking.

4.17 Processor

Coprocessor 0 contains a wealth of information which is required of any MIPS CPU. Registers of note are processor identification (register 15) and two configuration registers (register 16, select 0 and select 1). Below is what has been gleaned from the processor on the WRT54GL and the WRT54G (differences will be noted).

4.17.1 Processor Identification

This register will contain information about what company manufactured the CPU, what options are installed, the implementation of the processor and the revision of the processor.

```
0x00029008 (WRT54GL)
0x00029029 (WRT54G)
```

The identification is split into 4 8-byte chunks in the following order (starting with bit 31): manufacturer options, manufacturer identification, processor implementation, and revision. For both the WRT54GL and the WRT454G there are no manufacturer options. A manufacturer identification of 0x02 is reserved for broadcom processors. Of most importance is the processor implementation, which for both units is 0x90, which makes the processor a MIPS4KEc (MIPS32 R2 compliant). The last field, revision, is the only difference and should be unimportant for XINU.

4.17.2 Configuration

Configuration for MIPS processors is stored on coprocessor 0, and contains important information about what the processor supports, how memory works, and what is implemented on the processor. Configuration is always in register 16, but it is possible to access different data by selecting what configuartion data we are looking for (select 0 for CONFIG1, select 1 for CONFIG2).

Config, select 0

Both the WRT54GL and WRT54G contain the same value for config registers `0x80000083`. The significant information is listed below:

- bit 31 - (1) CP0_CONFIG1 exisits
- bit 15 - (0) Little Endian
- bit 14:13 - (0) MIPS 32 standard
- bit 12:10 - (0) Revision 1
- bit 9:7 - (1) MIPS 32/64 Compliant TLB
- bit 3 - (0) I-cache is not indexed or tagged with virtual addresses
- bit 2:0 - (3) kseg0 coherency algorithm (cacheable)

Config, select 1

The second configuration register on the MIPS processor reports slightly different data between the WRT54GL and the WRT54G. Data from the WRT54GL will be introduced first.

`0x3ed94c82 (WRT54GL)`

- bit 30:25 - (31) 2^5 entries in TLB (31+1)
- bit 24:22 - (3) I-cache number of index positions 64*2^3 = 512-bytes
- bit 21:19 - (3) I-cache line size 2*2^3 = 16-bytes
- bit 18:16 - (1) I-cache associativity (A+1) = 2-way set associative
- bit 15:13 - (2) D-cache number of index positions 64*2^2 = 256-bytes

- bit 12:10 - (3) D-cache line size 2*2^3 = 16-bytes
- bit 9:7 - (1) D-cache associativity (A+1) = 2-way set associative
- bit 6 - (0) no CP2
- bit 5 - (0) no MDMX ASE implementation
- bit 4 - (0) no performance counter
- bit 3 - (0) no watchpoint register
- bit 2 - (0) no MIPS16e instruction set available
- bit 1 - (1) EJTAG debug unit IS available
- bit 0 - (0) no floating point unit attached

This gives the following data: I-cache has 512 sets/way, 16 bytes/line, and is 2-way set-associative (16 KByte I-cache) and D-cache has 256 sets/way, 16 bytes/line, and is 2-way set-associative (8 KByte D-cache).

`0x3e9b6c86 (WRT54G)`

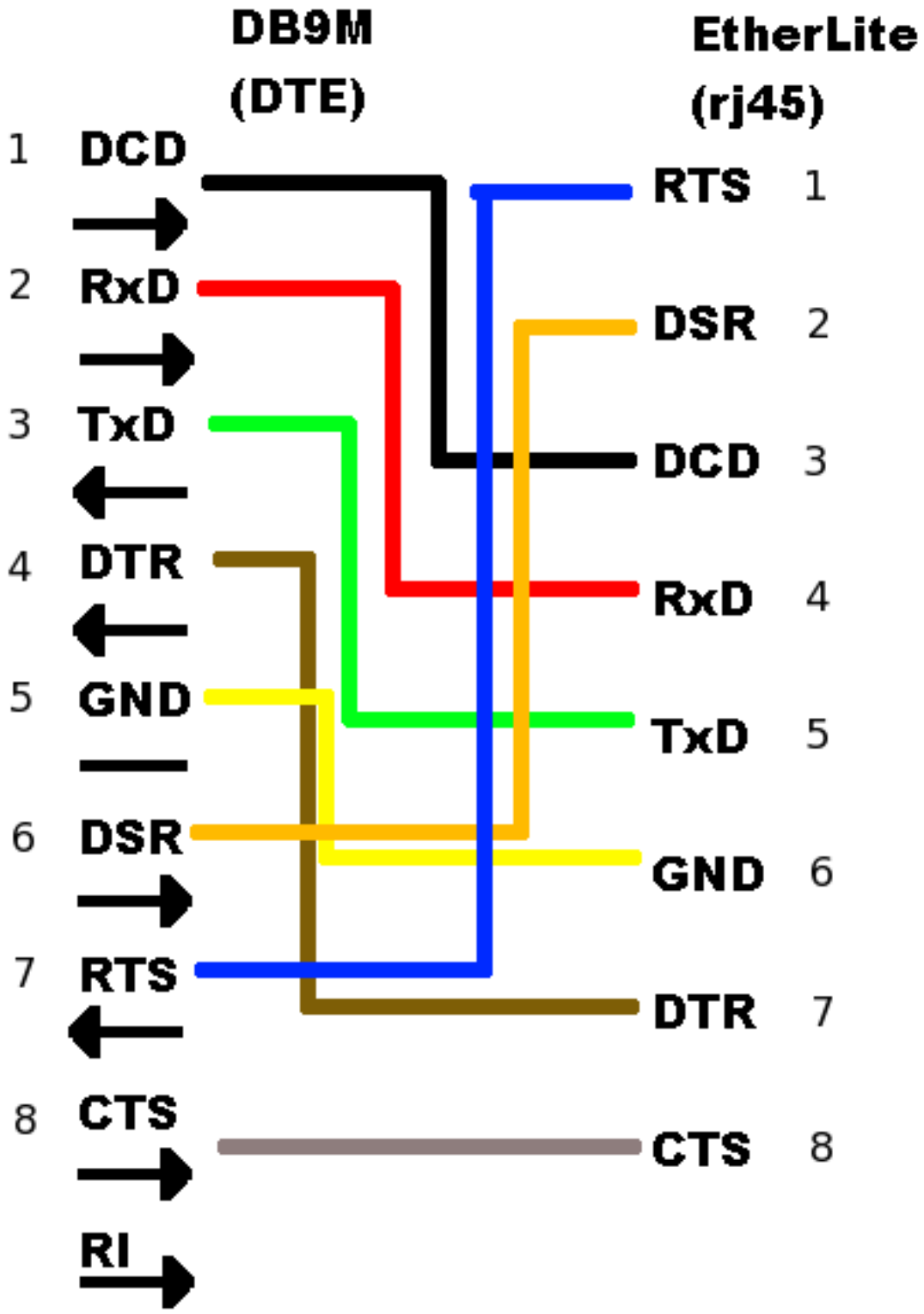
- bit 30:25 - (31) 2^5 entries in TLB (31+1, same as WRT54GL)
- bit 24:22 - (2) I-cache number of index positions 64*2^2 = 256-bytes
- bit 21:19 - (3) I-cache line size 2*2^3 = 16-bytes
- bit 18:16 - (3) I-cache associativity (A+1) = 2-way set associative
- bit 15:13 - (3) D-cache number of index positions 64*2^3 = 512-bytes
- bit 12:10 - (3) D-cache line size 2*2^3 = 16-bytes
- bit 9:7 - (1) D-cache associativity (A+1) = 2-way set associative
- bit 6 - (0) no CP2
- bit 5 - (0) no MDMX ASE implementation
- bit 4 - (0) no performance counter
- bit 3 - (0) no watchpoint register
- bit 2 - (1) MIPS16e instruction set IS available
- bit 1 - (1) EJTAG debug unit IS available
- bit 0 - (0) no floating point unit attached

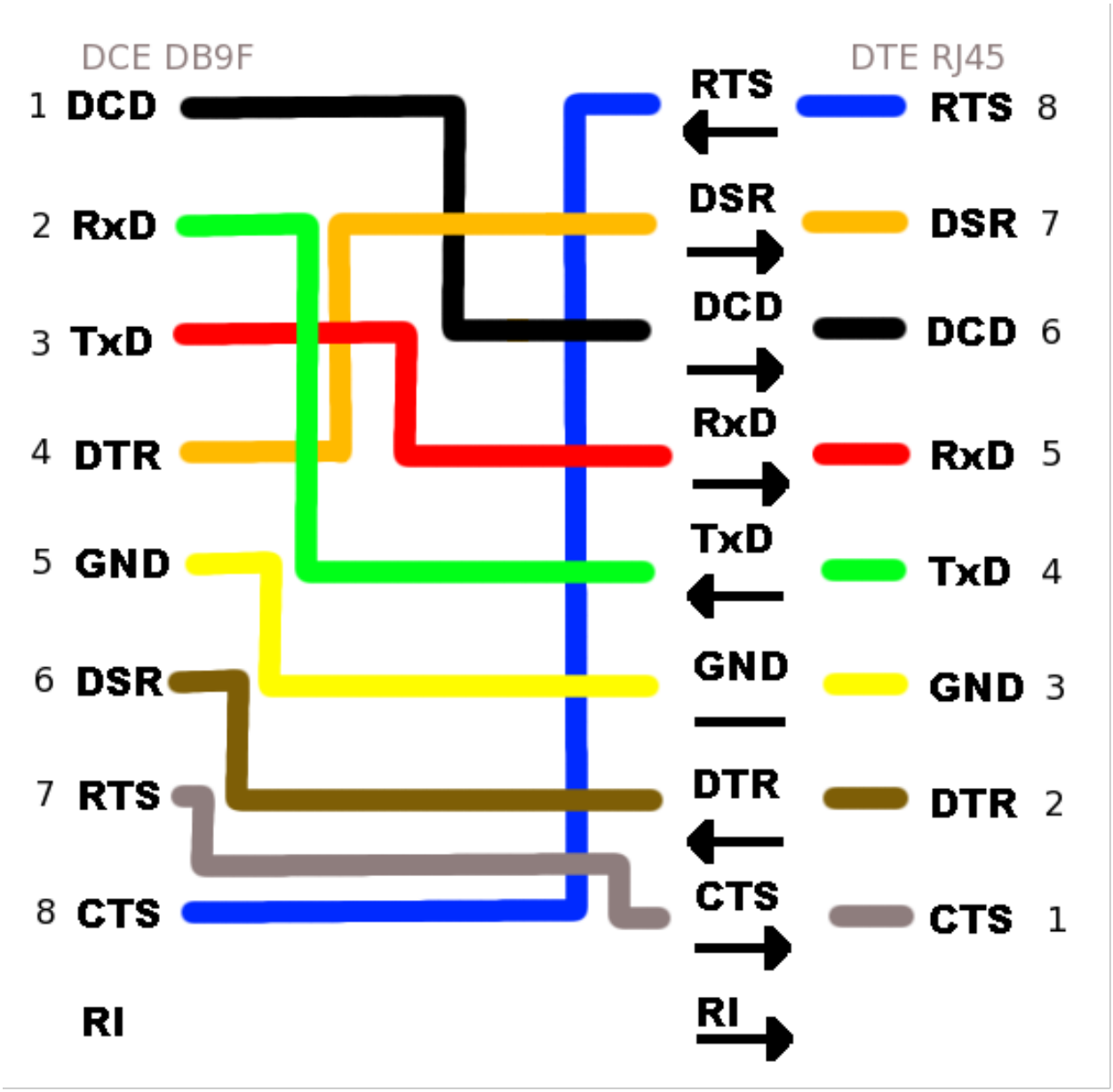
Again, giving the following data (which does differ from the WRT54GL): I-cache has 256 sets/way, 16 bytes/line, and is 2-way set-associative (8 KByte I-cache) and D-cache has 512 sets/way, 16 bytes/line, and is 2-way set-associative (16 KByte D-cache)

4.18 Serial adapter diagrams

4.18.1 RJ45/DB9 adapters

Below are diagrams for RJ45 to DB9 adapters allowing connection between an *Etherlite serial bay and XINU backends </teaching/HOWTO-Build-Backend-Pool>* in a pool. The first diagram is for UART 0 (DTE). The second diagram is for the platform-dependent UART 1 (DCE).


DB9M
(DTE)
EtherLite
(rj45)
1 DCD
2 RxD
3 TxD
4 DTR
5 GND
6 DSR
7 RTS
8 CTS
RI
RTS 1
DSR 2
DCD 3
RxD 4
TxD 5
GND 6
DTR 7
CTS 8

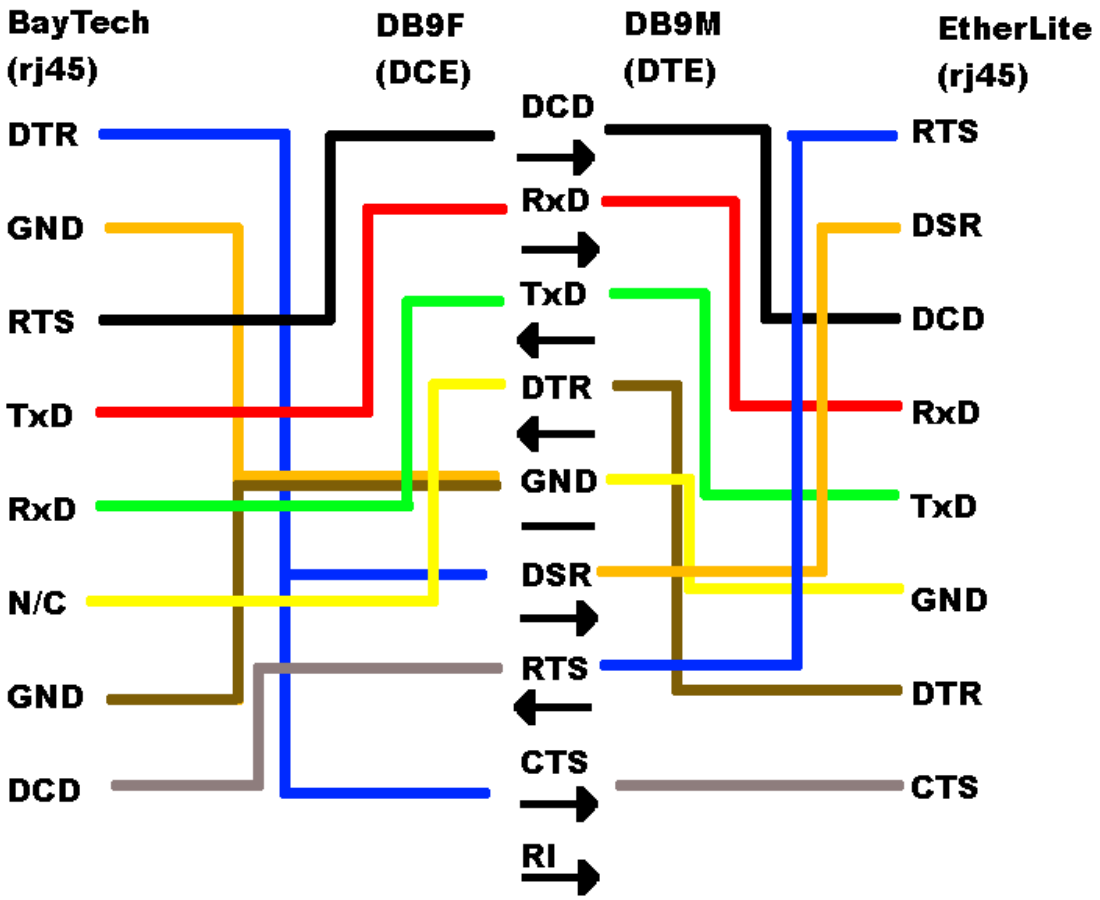


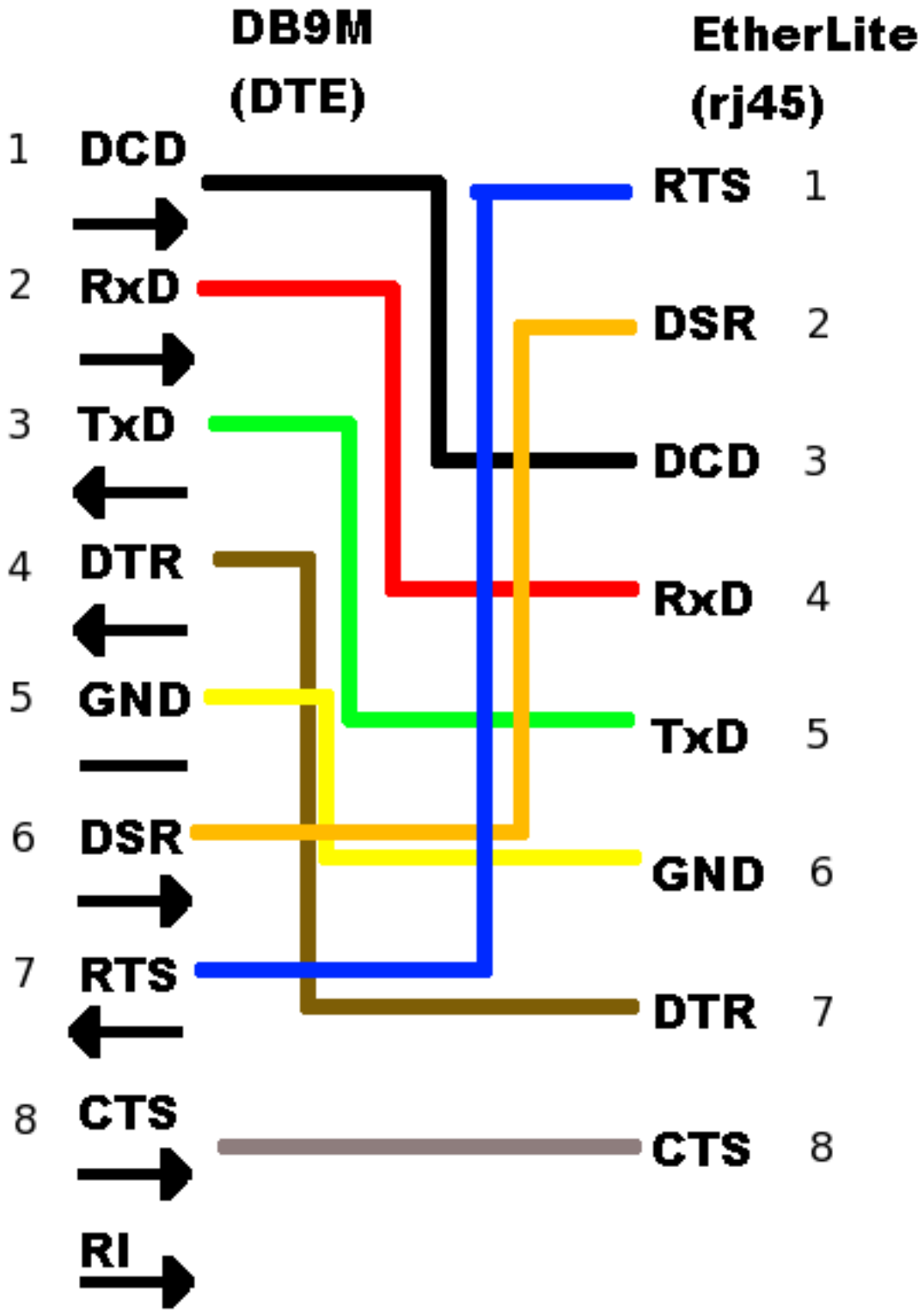
4.18.2 Null Modem

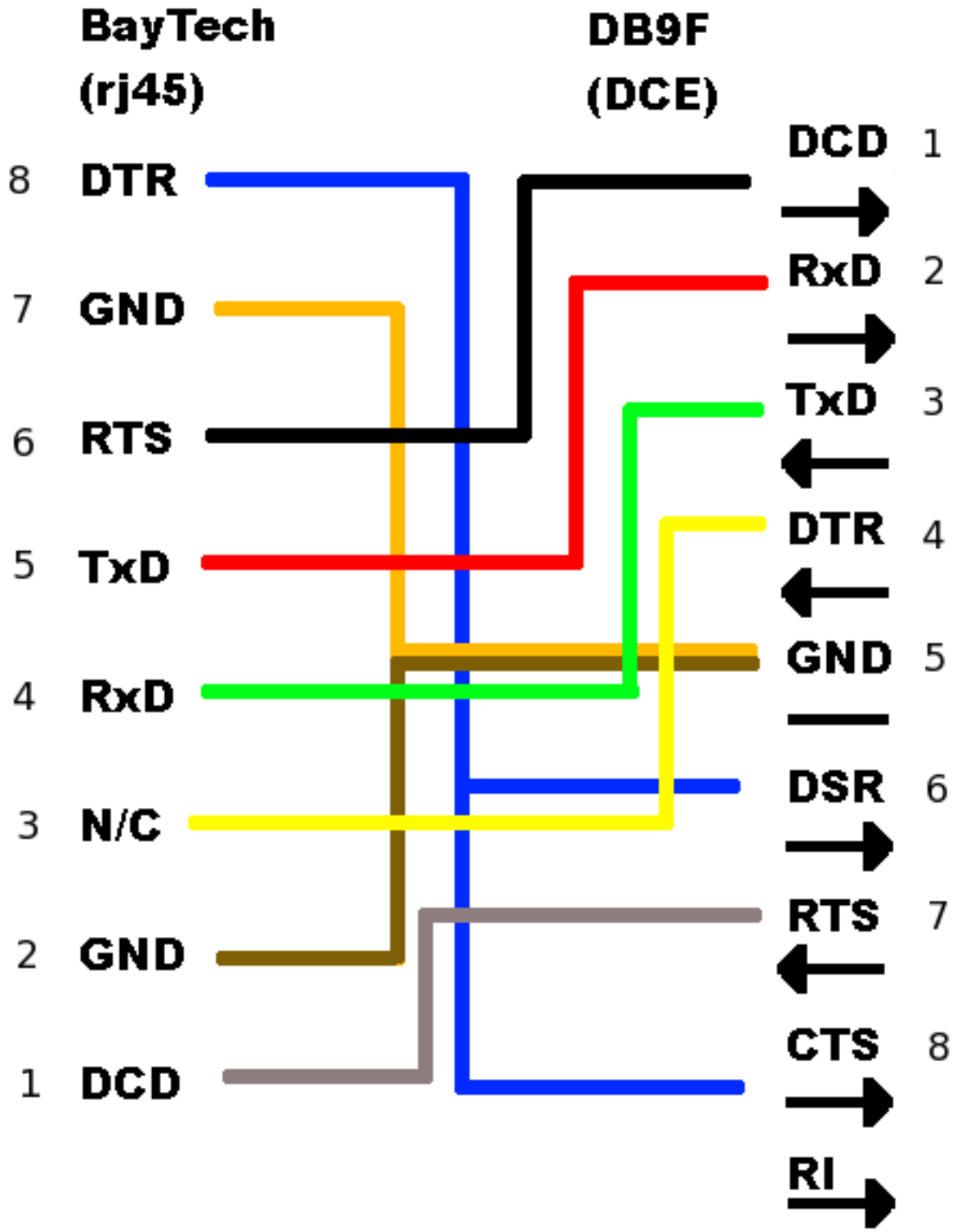
The null modem adapter is required to make connections between available UART 1 ports on two machines. The above UART 1 diagram functions as a null modem when connecting directly to other backends, as well as to the EtherLite serial bay.

4.18.3 EtherLite to Baytech

The third diagram represents a connection between the between a Baytech serial-controlled power strip and the EtherLite terminal annex. The final two diagrams are the Baytech/Etherlite diagram broken into two parts, representing the mating of two individual RJ45/DB9 adapters.


BayTech
(rj45)
DB9F
(DCE)
DB9M
(DTE)
EtherLite
(rj45)
DTR
GND
RTS
TxD
RxD
N/C
GND
DCD
DCD
RxD
TxD
DTR
GND
DSR
RTS
CTS
RI
RTS
DSR
DCD
RxD
TxD
GND
DTR
CTS


DB9M
(DTE)
EtherLite
(rj45)
1 DCD
2 RxD
3 TxD
4 DTR
5 GND
6 DSR
7 RTS
8 CTS
RI
RTS 1
DSR 2
DCD 3
RxD 4
TxD 5
GND 6
DTR 7
CTS 8


BayTech
(rj45)
DB9F
(DCE)
8 DTR
7 GND
6 RTS
5 TxD
4 RxD
3 N/C
2 GND
1 DCD
DCD 1
RxD 2
TxD 3
DTR 4
GND 5
DSR 6
RTS 7
CTS 8
RI

4.19 Startup

4.19.1 CFE Jettison

CFE begins executing code at 0x80001000. It passes a firmware handler, firmware entry point, and an entry point seal. The firmware entry point handler points to an address in the middle of the heap space (confirmed once to point to 0x803029FC, which may or may not be a deterministic address).

4.19.2 Cache Flush

The L1 instruction and data caches are intialized and flushed.

4.20 Switch driver

4.20.1 Ethernet Port Numbering

On the back of a Linksys WRT54GL router, the Ethernet ports appear in this order:

WAN	1	2	3	4

Internally, the Ethernet ports are indexed in this order:

4	3	2	1	0

4.20.2 CFE and OpenWRT VLAN Configuration

In order to use the Linksys WRT54GL routers for complex routing purposes, both CFE and the operating system burned into Flash must be modified to separate the four LAN ports into their own network interfaces.

By default, the four LAN ports (0-3) are part of the same VLAN in CFE. (Port 5 is internal to the CPU.)

```
CFE> nvram get vlan0ports
3 2 1 0 5*
*** command status = 0
```

This needs to be changed so that only one LAN port is in the VLAN. Select an appropriate port number based on the diagram above. The port that remains in the VLAN should be the one connected to the Xinu server.

```
CFE> nvram set vlan0ports="0 5*"
*** command status = 0
CFE> nvram commit
*** command status = 0
```

The network configuration on OpenWRT must also be changed.

```
root@OpenWrt:/# vi /etc/config/network
```

The file will originally contain this section.

```
#### VLAN configuration
config switch eth0
        option vlan0    "0 1 2 3 5*"
        option vlan1    "4 5"
```

It should be changed to look like this where the port in vlan0 is the one connected to the Xinu server.

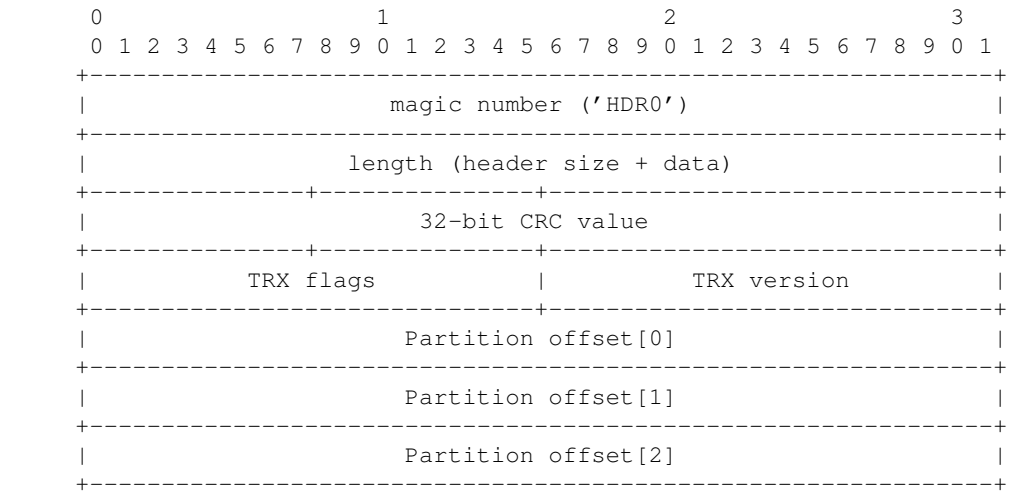
```
#### VLAN configuration
config switch eth0
        option vlan0    "0 5*"
        option vlan1    "4 5"
```

4.21 TRX header

TRX is the format used to store kernel images in *Flash memory* for CFE based (and possibly others) routers. Unfortunately, not much is known about the format or what limitations and rules exist. Currently, *Embedded Xinu* uses a simple utility from the OpenWRT repository to build TRX images. However, the quality of our TRX images seems to vary between revisions of the operating system. We do not yet know why. Possible reasons include:

- alignment problems,
- compression/extraction problems,
- incorrectly configuration at startup (differences between TFTP booting and booting from Flash), or a
- combination of above and some unknown problem.

What we do know is the format of the 28 byte TRX header, it is as follows:



After the TRX header, the data section begins.

4.21.1 Code Pattern

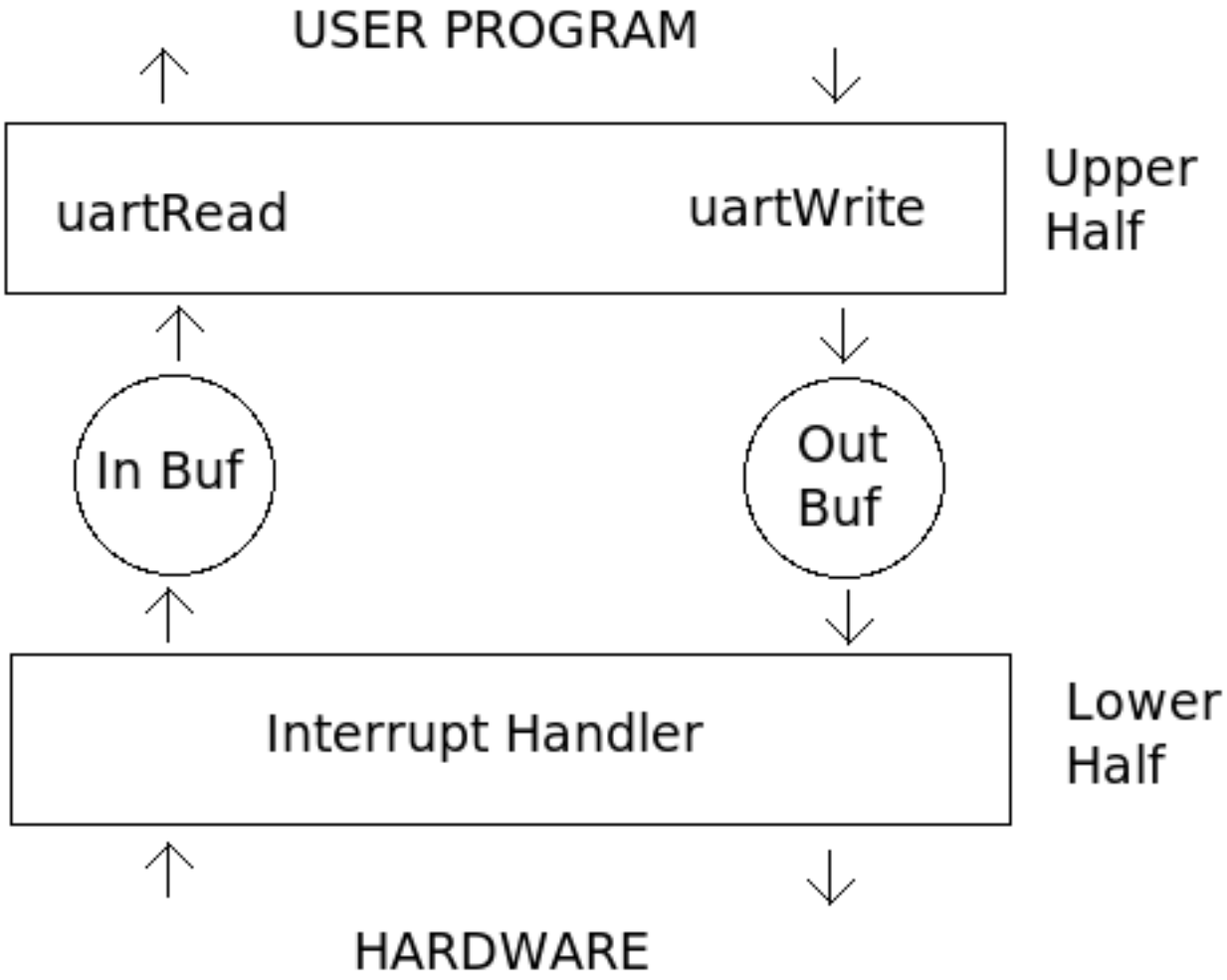
It is common to see an additional 32 byte header prepended to the TRX image as a way to tag certain firmware images specific to a particular hardware platform. The first 4 bytes correspond to an ASCII "Code Pattern" that makes this

identification. For example, the WRT54G series routers (including the WRT54GL) contain the characters `W54G` as the first field in this additional header. Some methods of writing to flash, such as the Linksys Web GUI and TFTP, check for this pattern before actually writing the firmware. The flash process will error out when attempting to flash a router without the correct code pattern using these methods. When the code pattern header is present, filenames traditionally have the `.bin` extension instead of `.trx`.

Our TRX image creation process for Xinu uses the addpattern utility from OpenWRT to add the correct pattern to our TRX file. This utility also supports additional fields in the code pattern header: dates, versions, board ID, and flags.

4.22 UART driver

Note: This page appears to have been written with *WRT54GL* routers in mind and may or may not be applicable to other platforms.



The UART driver is a char-oriented driver designed to work with a National Semiconductor 16550 UART. The driver is responsible for receiving and sending bytes of data asynchronously.

The UART driver is divided into two sections: an upper half and a lower half. The two halves communicate via semaphores and buffers. The lower half is interrupt driven and interacts with the physical hardware. The upper half of the driver interacts with user programs. It does not interact directly with the hardware nor does it spinlock while waiting for the hardware to be ready. The upper half waits on semaphores which are signaled by the lower half to

indicate bytes of data or free space are avaialable in the appropriate buffer.

4.22.1 Physical UART

The XINU backends have been equipped with serial ports that are representative of the National Semiconductor 16550 UART. Documentation on the 16550 UART can be found at http://www.national.com/ds.cgi/NS/NS16C552.pdf.

4.22.2 Initialization

Intialize defines the starting values for all members of the control block: statistical counts are zeroed, buffers are defined, and semaphores are allocated. Also part of the initialization process is setting values in the control and status registers:

- Line control is set to 8 bit, no parity, 1 stop.
- Receiver FIFO full, transmitt buffer empty, and receiver line status interrupts are enabled.
- Hardware FIFOs are enabled.
- Divisor Latch bits (high and low)
  - The divisor can be calculated by using the formula:

$$divisor = \frac{baud\_base + \frac{baud\_rate}{2}}{baud\_rate}.$$

Where `baud_rate` is the speed you wish to connect at (typically 115,200) and

$$baud\_base = \frac{clockrate}{16}.$$

The clockrate should be measured in hertz and may not be equivalent to the clockspeed. (The WRT54GL, for example, has a hard-coded clockrate of 20,000,000 or 20MHz, while the WRT54G has a clockrate of about 25MHz.)

4.22.3 Upper Half (Read and Write)

Read is part of the upper half of the driver that fills a user supplied buffer with bytes from the input buffer filled by the lower half of the driver. If the input buffer is empty, read waits for the lower half to signal on the input semaphore and indicate bytes are avaiable in the input buffer.

Write is part of the upper half of the driver and places bytes from a user supplied buffer into the output buffer read by the lower half of the driver. If there is no free space in the output buffer, write waits for the lower half to signal on the output semaphore and indicate free space is available in the output buffer.

4.22.4 Lower Half (Interrupt Handler)

The interrupt handler is the lower half of the driver. The 16550 UART sends an interrupt (if enabled) when the transmitter FIFO is empty or the receiver FIFO has reached its available bytes tigger level. Three different types of interrupts are handled by the lower half:

- Line or modem status: The interrupt is merely noted in the UART's statistical counts.
- Receiver hardware FIFO trigger level: The driver moves bytes from the UART's receive hardware FIFO into the input buffer. Received bytes are read from the UART until the Data Ready bit in the Line Status Register is no longer set. The input semaphore is signaled to let the upper half know bytes of data are in the input buffer.
- Transmitter hardware FIFO empty: The lower half fills the UART's transmit hardware FIFO from the output buffer. The interrupt handler fills the transmit hardware FIFO until the FIFO is full or the output buffer is empty. The output semaphore is signaled to let the upper half know bytes of space are available in the output buffer.

4.22.5 Control

The control functions are used to set, clear, and get the input and output flags for the UART driver. Non-blocking flags indicate the upper half read and write functions should perform as much of the requested read or write length as possible, but should not block to wait for the lower half to fill or empty the input or output buffers. When the echo input flag is set, the UART outputs every byte as it is received in addition to placing the byte in the input buffer.

Loopback

`UART_ENABLE_LOOPBACK` and `UART_DISABLE_LOOPBACK` control functions enable and disable hardware loopback. Be aware that loopback is precarious and must be used carefully. It is recommended that you turn off interrupts prior to enabling loopback and after disabling loopback to avoid interleaving output while in loopback mode.

Prior to enabling and disabling hardware loopback, the control function ensures the transmitter is completely empty and has completed all previous transmission. When in loopback mode the hardware does not throw interrupts, so the control functions call the UART interrupt handler explicitly.

4.22.6 See also

- *TTY driver*

4.23 WRT54GL

This page lists details about the Linksys WRT54GL device.

4.23.1 Hardware Info

As reported by OpenWRT

- **eth0**: Broadcom 47xx 10/100BaseT Ethernet
- **eth1**: Broadcom BCM4320 802.11 Wireless Controller 3.90.37.0

4.23.2 See also

- WRT54G

CHAPTER 5

ARM ports (including Raspberry Pi)

5.1 Interrupt Handling (ARM)

This page provides an overview of how Embedded Xinu performs interrupt handling on ARM architectures. This page only concerns ARM-specific details; in particular it must be understood that the actual meaning prescribed to interrupts is determined using a board-specific mechanism, such as the *BCM2835 Interrupt Controller* on the *Raspberry Pi*. Furthermore, note that the ARM architecture and its exception/interrupt handling mechanisms are well documented by ARM Ltd., especially in various versions of the ARM Architecture Reference Manual. This page is only intended to give an overview of relevant details in the context of Embedded Xinu.

5.1.1 IRQs and FIQs

Overview

ARM processors define two types of "interrupts":

- **IRQs** (Interrupt Requests). These are the "normal" type of interrupt.
- **FIQs** (Fast Interrupt Requests). These are an feature that software can optionally use to increase the speed and/or priority of interrupts from a specific source. For simplicity, Embedded Xinu does **not** use FIQs. However, FIQs could be useful for those looking to design real-time and embedded software on top of or instead of the base Embedded Xinu kernel.

Both IRQs and FIQs are examples of **exceptions** supported by the ARM. Beware that the term "IRQ" is often used generically, whereas here it specifically refers to the ARM-architecture IRQ exception.

Receiving an IRQ or FIQ

When the ARM receives an IRQ, it will enter a special **IRQ mode** and, by default, begin execution at physical memory address `0x18`. Similarly, when the ARM receives a FIQ, it will enter a special **FIQ mode** and, by default, begin execution at physical memory address `0x1C`. Before enabling IRQs or FIQs, software is expected to copy ARM instructions to the appropriate address. In the case of IRQs, there is only room for one ARM instruction, so it needs to be a branch instruction to a place where the full handler is stored. In Embedded Xinu, these special "glue" instructions, or **exception vectors**, are set in loader/platforms/arm-rpi/start.S. The "full" IRQ handler is located in system/arch/arm/irq_handler.S.

Banked registers

In IRQ mode and FIQ modes, some registers are **banked**, meaning that their contents are dependent on the current processor mode. The advantage of such registers is that their original values do not need to be explicitly saved by the interrupt handling code. FIQ mode banks more registers than IRQ mode, but both IRQ mode and FIQ mode bank the stack pointer (sp), which essentially means that each mode can use its own stack. However, for simplicity and consistency with other CPU architectures, Embedded Xinu does **not** use this capability. Instead, the interrupt handling code immediately switches the processor from IRQ mode to "System" mode, which is the mode in which Embedded Xinu normally operates the ARM CPU. This means that the interrupt handling code uses the stack of the currently executing thread, so perhaps the main disadvantage of this approach is that it increases the stack size required by each thread.

5.1.2 Managing interrupts

The ARM responds to IRQs and FIQs if and only if bits 7 and 6, respectively, of the Current Program Status Register (`cpsr`) are 0. By default (after reset) these bits are both 1, so software must initially set them to 0 to enable IRQs and FIQs. Similarly, software can set them to 1 if it needs to disable IRQs and FIQs. However, software does not necessarily need to explicitly manipulate these bits because an alternate instruction named `cps` (Change Program State) is available that can handle changing these bits, as well as changing processor modes.

Below we explain the `enable()`, `disable()`, and `restore()` functions used by Embedded Xinu to manage interrupts. These are all implemented in the ARM assembly language file system/arch/arm/intutils.S.

`enable()`

`enable()` allows the processor to receive IRQ exceptions:

```
enable:
        cpsie i
        mov pc, lr
```

`enable()` executes the `cpsie` ("Change Program State Interrupt Enable") instruction to enable IRQs. (Recall that FIQs are not used by Embedded Xinu.) It then overwrites the program counter (`pc`) with the link register (`lr`) to return from the function. Note that since the second instruction is merely overhead of a function call, `enable()` could instead be efficiently implemented as an inline function containing inline assembly.

`disable()`

`disable()` blocks IRQ exceptions and returns a value that can be passed to `restore()` to restore the previous state. The previous state may be either IRQs disabled or IRQs enabled. Note that an IRQ exception received during a region of code where interrupts are `disable()`-d is not lost; instead, it remains pending until IRQs are re-enabled.

```
disable:
        mrs r0, cpsr
        cpsid i
        mov pc, lr
```

`disable()` copies the `cpsr` (Current Program Status Register) into `r0`, which as per the ARM calling convention [1] is the return value of the function. Therefore, the `cpsr` is treated as the value that can be passed to `restore()` to restore the previous interrupt state. The code then executes the `cpsid` (Change Program State Interrupt Disable) instruction to actually disable the IRQ exception.

`restore()`

`restore()` restores the IRQ exceptions disabled/enabled state to the state before a previous call to `disable()`.

```
restore:
        msr cpsr_c, r0
        mov pc, lr
```

As per the ARM calling convention [1], the argument to `restore()` (the previous state value— in the code this is often stored in a variable named `im`, for "interrupt mask") is passed in `r0`. `r0` is then copied to the `cpsr` (Current Program Status Register), which is the opposite of what `disable()` does. `restore()` then overwrites the program counter with the link register to return from the function. Note that since the second instruction is merely overhead of a function call, `restore()` could instead be efficiently implemented as an inline function containing inline assembly.

5.1.3 Further reading

As mentioned in the introduction, this page deals with ARM-architecture details only and therefore does not provide a full explanation of interrupt handling on any specific platform, which typically requires the use of some interrupt controller to actually assign meaning to IRQ exceptions.

- The interrupt controller on the *Raspberry Pi* is the *BCM2835 Interrupt Controller*.

5.1.4 Notes

5.2 Preemptive multitasking (ARM)

This page documents how Embedded Xinu implements *preemptive multitasking* on ARM architecture platforms that it has been ported to, such as the *Raspberry Pi*.

5.2.1 Thread context

The format and size of the *thread context* used for ARM ports of Embedded Xinu rests on two factors: the registers available on the ARM architecture, and the standard ARM calling convention [2].

- ARM processors have 16 "general-purpose" registers numbered `r0` - `r15`, as well as the Current Program Status Register (`cpsr`). However, despite being considered "general-purpose" registers, `r13` - `r15` actually have special purposes; namely, `r13` is used as the stack pointer (`sp`), `r14` is used as the link register (`lr`), and `r15` is used as the program counter (`pc`).

[1] http://infocenter.arm.com/help/topic/com.arm.doc.ihi0042e/IHI0042E_aapcs.pdf
[2] http://infocenter.arm.com/help/topic/com.arm.doc.ihi0042e/IHI0042E_aapcs.pdf

- The standard ARM calling convention specifies which registers are callee-save (`r4 - r11`, `r13 - r14`) and which are caller-save (`r0 - r3`, `r11`), as well as how arguments are passed to procedures (up to four arguments in `r0 - r3`; additional arguments spill onto stack).

The thread context we chose is 15 words long and is the following:

Offset	Register	Notes
`0x00`	`r0`	First thread argument, caller-save
`0x04`	`r1`	Second thread argument, caller-save
`0x08`	`r2`	Third thread argument, caller-save
`0x0C`	`r3`	Fourth thread argument, caller-save
`0x10`	`r4`	Callee-save
`0x14`	`r5`	Callee-save
`0x18`	`r6`	Callee-save
`0x1C`	`r7`	Callee-save
`0x20`	`r8`	Callee-save
`0x24`	`r9`	Callee-save
`0x28`	`r10`	Callee-save
`0x2C`	`r11`	Callee-save
`0x30`	`cpsr`	Current program status register
`0x34`	`lr`	Link register
`0x38`	`pc`	Program counter

The ARM version of `ctxsw()` is implemented in system/arch/arm/ctxsw.S and contains a detailed explanation that will not be replicated here.

5.2.2 Preemption

The means of generating a timer interrupt for *preemption* is not standard to the ARM architecture; instead, software must make use of a board-specific or chip-specific device such as the *BCM2835 System Timer*.

5.2.3 Notes

5.3 arm-qemu

Embedded Xinu has been ported to an ARM virtual environment provided by QEMU. Specifically, the supported emulation environment consists of an ARM1176 CPU combined with the peripherals of the ARM Versatile Platform Baseboard. These peripherals consist of two ARM Dual Timer Module (SP804), a PrimeCell Vectored Interrupt Controller (VIC) (PL011), four PrimeCell UARTs (PL011), and other devices. Similar to the *mipsel-qemu* port, the *arm-qemu* port of Embedded Xinu provides an easy way to run a basic Embedded Xinu environment on a RISC architecture without devoting "real" hardware.

5.3.1 Building

Compile Embedded Xinu with `PLATFORM=arm-qemu`. Note that this requires a *cross compiler* targeting ARM. This will produce the file `xinu.boot` in the `compile/` directory.

5.3.2 Running

```
$ qemu-system-arm -M versatilepb -cpu arm1176 -m 128M -nographic -kernel xinu.boot
```

Note the `-cpu arm1176` option. This requires QEMU v1.0 (released December 2011) or later.

5.3.3 Notes

The `arm-qemu` platform does not yet support networking.

5.4 Raspberry Pi port

5.4.1 BCM2835

The **BCM2835** is a SoC (System-on-a-chip) designed by Broadcom. It is used on the *Raspberry Pi*, where it is easily visible as the black chip in the center of the board. The chip contains many of the components of a traditional computer, such as a CPU, memory, and a GPU.

The BCM2835 is actually not specific to the *Raspberry Pi* and is used in at least one other consumer device (the Roku 2) [3].

See also

- *Raspberry Pi*
- *BCM2835 System Timer*
- *BCM2835 Interrupt Controller*
- *BCM2835 memory barriers*
- *Synopsys DesignWare High Speed USB 2.0 On The Go Controller*

Notes

External links

- BCM2835 ARM Peripherals (datasheet by Broadcom)

5.4.2 BCM2835 Interrupt Controller

The **BCM2835 Interrupt Controller** is a memory-mapped peripheral available on the *BCM2835* used in the *Raspberry Pi*. It allows software to enable or disable specific IRQs (interrupt requests). Each IRQ usually corresponds to some sort of device available on the chip.

Hardware Details

It is important to understand that on the BCM2835, some IRQs are shared between the ARM CPU and VideoCore GPU. This interrupt controller controls **both** these shared IRQs as well as a few ARM-specific IRQs, and the layout of the registers reflects this separation. Some of the shared IRQs are already enabled by the GPU and therefore should not be enabled. However, this interrupt controller is only used by the ARM to control which interrupts actually get routed to the ARM; the GPU most likely has its own interrupt controller.

[3] http://www.electronicproducts.com/Roku_2_XS_3100R_Streaming_Media_Adapter-whatsinside_text-120.aspx

The BCM2835 Interrupt Controller is a memory-mapped peripheral available at physical memory address 0x2000B000. The following table describes the registers, each of which is 32 bits. **Note that the offsets start at 0x200, not 0. We do this for consistency with Broadcom's documentation. To be completely clear, IRQ_basic_pending is located at physical memory address 0x2000B200.**

Table 5.1: BCM2835 Interrupt Controller registers

Offset	Name	Description
+0x200	IRQ_basic_pending	Bitmask of pending ARM-specific IRQs, as well as additional bits (not currently used by Embedded Xinu) to accelerate interrupt handling.
+0x204	IRQ_pending_1	Bitmask of pending shared IRQs 0-31
+0x208	IRQ_pending_2	Bitmask of pending shared IRQs 32-63
+0x20C	FIQ_control	TODO
+0x210	Enable_IRQs_1	Write 1 to the corresponding bit(s) to enable one or more shared IRQs in the range 0-31
+0x214	Enable_IRQs_2	Write 1 to the corresponding bit(s) to enable one or more shared IRQs in the range 32-63
+0x218	Enable_Basic_IRQs	Write 1 to the corresponding bit(s) to enable one or more ARM-specific IRQs
+0x21C	Disable_IRQs_1	Write 1 to the corresponding bit(s) to disable one or more shared IRQs in the range 0-31
+0x220	Disable_IRQs_2	Write 1 to the corresponding bit(s) to disable one or more shared IRQs in the range 32-63
+0x224	Disable_Basic_IRQs	Write 1 to the corresponding bit(s) to disable one or more ARM-specific IRQs

For this interrupt controller to actually be of any use, the mapping of IRQs to devices must be known. The following table is an **incomplete** list that documents the IRQs we have tested in our work with Embedded Xinu. The full list can be found declared in a Linux header Below we use the numbering scheme used by both Embedded Xinu and Linux, where the shared IRQs are numbered 0-63, and ARM-specific IRQs are numbered starting at 64.

Table 5.2: Incomplete list of BCM2835 IRQs

IRQ	Device	Notes
0	System Timer Compare Register 0	Do **not** enable this IRQ; it's already used by the GPU.
1	System Timer Compare Register 1	See *BCM2835 System Timer*
2	System Timer Compare Register 2	Do **not** enable this IRQ; it's already used by the GPU.
3	System Timer Compare Register 3	See *BCM2835 System Timer*
9	USB Controller	This is the *only* USB IRQ because all communication with USB devices happens through the USB Controller. See *Synopsys DesignWare High Speed USB 2.0 On The Go Controller*.
55	PCM Audio	
62	SD Host Controller	

Notes:

- Software cannot "clear" interrupts using the interrupt controller. Instead, interrupts must be cleared in a device-specific way.
- Although some shared interrupts appear in the IRQ_Basic_Pending register as well as in the IRQ_Pending_1 or IRQ_Pending_2 registers, they cannot be enabled or disabled in Enable_Basic_IRQs or Disable_Basic_IRQs.

Use in Embedded Xinu

Embedded Xinu (that, is *XinuPi*) uses the BCM2835 Interrupt Controller to implement `enable_irq()` and `disable_irq()`. The code is in system/platforms/arm-rpi/dispatch.c. These functions simply are passed the number of the IRQ to enable or disable. Shared IRQs are numbered 0-63, while ARM-specific IRQs (currently not actually used) are numbered starting at 64. Also in this file you will find `dispatch()`, which is called from the assembly language IRQ handler in system/arch/arm/irq_handler.S to handle an interrupt. The purpose of `dispatch()` is to figure out which number IRQs are actually pending, then call the registered interrupt handler for each.

External Links

- BCM2835 ARM Peripherals datasheet by Broadcom The interrupt controller is documented in Section 7 (p. 109-118). Compared to some of the Raspberry Pi hardware, this is one of the better documented components. Beware, though, that Broadcom's docs don't mention some of the important IRQ numbers, such as 0-3 (System Timer) and 9 (USB Controller).

5.4.3 BCM2835 memory barriers

As documented on page 7 of the *BCM2835 ARM Peripherals* document [4], ARM code executing on the *BCM2835* in the *Raspberry Pi* should:

- execute a memory write barrier before the first write to a peripheral
- execute a memory read barrier after the last read to a peripheral

As of this writing, in Embedded Xinu both types of memory barrier are implemented by the same memory_barrier() function, which executes a **data memory barrier**, which is an operation that ensures that all explicit memory accesses occurring previously in program order are globally observed before any explicit memory accesses occurring subsequently in program order. This should be sufficient to prevent problems with memory access reordering on the BCM2835.

`memory_barrier()` is already called before and after interrupt dispatch, but any other code that attempts to access peripherals outside of the interrupt handler, or access multiple peripherals within the some interrupt handler, must make its own call to `memory_barrier()`. This does not need to occur before and after every access to the peripheral, only after a series of accesses to a *single peripheral*.

Despite the above, we have not encountered any observable difference when no memory barriers are used, so their true necessity on the BCM2835 is unclear.

Notes

5.4.4 BCM2835 System Timer

The **BCM2835 System Timer** is a memory-mapped peripheral available on the *BCM2835* used in the *Raspberry Pi*. It features a 64-bit free-running counter that runs at 1 MHz and four separate "output compare registers" that can be

[4] http://www.raspberrypi.org/wp-content/uploads/2012/02/BCM2835-ARM-Peripherals.pdf

used to schedule interrupts. However, two output compare registers are already used by the VideoCore GPU, leaving only two available for the ARM CPU to use.

Hardware details

The interface to the BCM2835 System Timer is a set of 32-bit memory-mapped registers beginning at physical address `0x20003000`.

Table 5.3: BCM2835 System Timer registers

Offset	Name	Description
+0x00	CS	System Timer Control and Status
+0x04	CLO	System Timer Counter Lower 32 bits
+0x08	CHI	System Timer Counter Upper 32 bits
+0x0C	C0	System Timer Compare 0; corresponds to IRQ line 0.
+0x10	C1	System Timer Compare 1; corresponds to IRQ line 1.
+0x14	C2	System Timer Compare 2; corresponds to IRQ line 2.
+0x18	C3	System Timer Compare 3; corresponds to IRQ line 3.

`CLO` and `CHI` form a 64-bit free-running counter, which increases by itself at a rate of 1 MHz, that software can read to get the current number of timer ticks. There are, however, two caveats:

- Appropriate *memory barriers* should be inserted to guarantee that read data is not re-ordered with that from a different peripheral.
- Reading `CLO` can be done in a single 32-bit access. However, we are not currently aware of a way to read `CLO` and `CHI` together atomically. To work around this when the full 64-bit time is desired, software can read `CHI`, then `CLO`, then read `CHI` and retry if `CHI` changed.

To schedule an interrupt using the System Timer, software can write the value of `CLO` at which an interrupt will be generated into one of the System Timer Compare registers. However, the CPU actually only use `C1` and `C3`, since `C0` and `C2` are used by the GPU. Also, to actually receive the scheduled interrupt, the software must have previously enabled the corresponding IRQ line using the *BCM2835 Interrupt Controller*. To clear the interrupt, software must write 1 to the bit in `CS` that has the index the same as that of the System Timer Compare register. That is, to clear an interrupt set in `C1`, software must write `0x20` to `CS`, and to clear an interrupt set in `C3`, software must write `0x80` to `CS`.

Use in Embedded Xinu

In the *Raspberry Pi* port of Embedded Xinu, or *XinuPi*, the BCM2835 System Timer is used to implement *preemptive multitasking* and keep the system time. The code can be found in system/platforms/arm-rpi/timer.c and is fairly simple, as it only needs to implement `clkcount()` and `clkupdate()`.

5.4.5 Raspberry Pi

The **Raspberry Pi** is an inexpensive credit-card sized computer designed for educational use. This page provides information about the Raspberry Pi in the context of those looking to run *XinuPi* on it. Readers unfamiliar with the Raspberry Pi are advised to also see other sources such as the Raspberry Pi foundation's website.

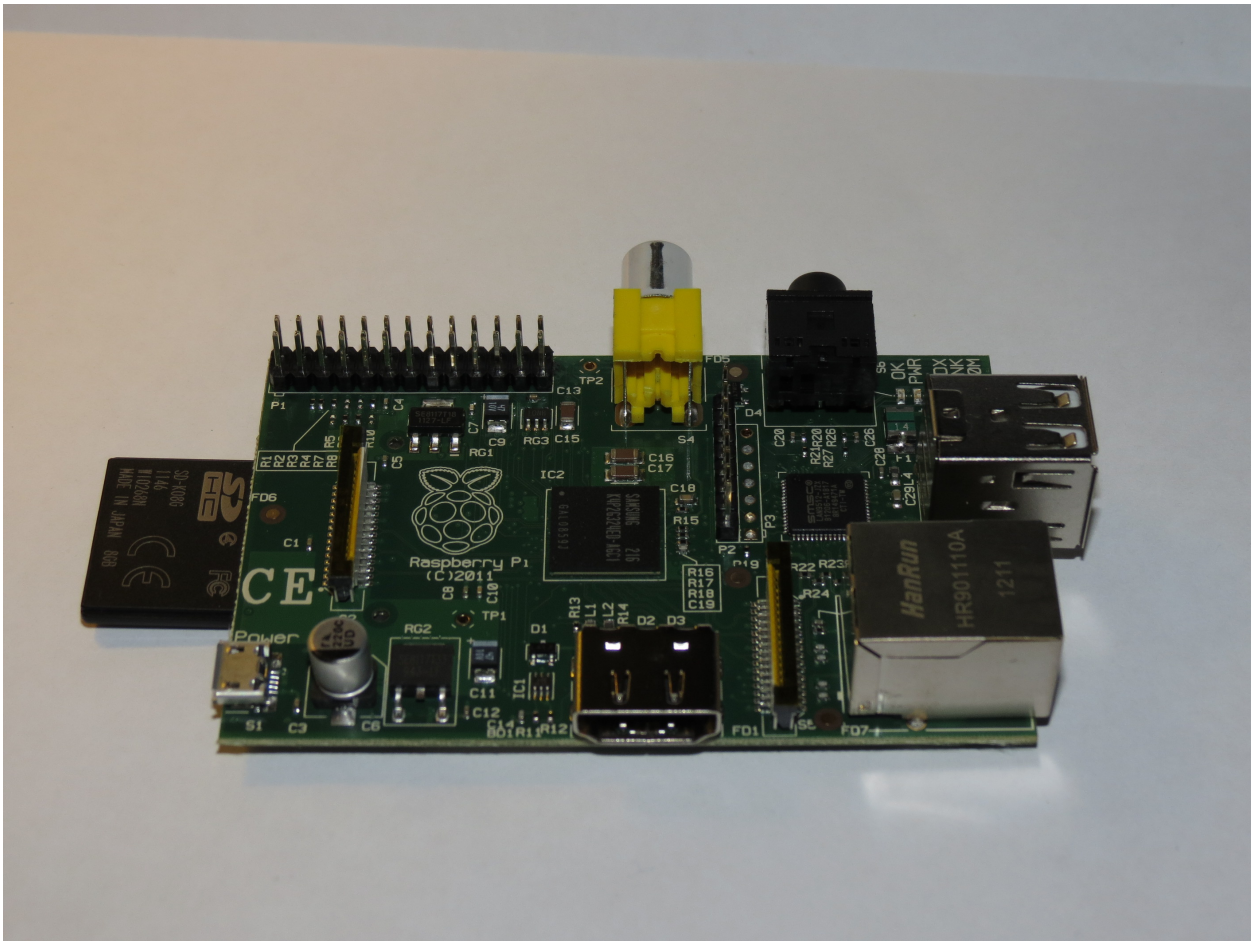


Figure 5.1: A freshly unpacked Raspberry Pi with additional SDHC card.

Acquiring the hardware

Model A vs. Model B

The Raspberry Pi Model A costs $25, whereas the Raspberry Pi Model B costs $35. We generally recommend the Model B because it includes an Ethernet port and 2 USB ports, as opposed to the Model A which merely has 1 USB port. Also, currently the Model B has more memory (512 MiB) than the Model A (256 MiB), but since XinuPi is very lightweight and only uses a small amount of the available memory, the difference in memory is mostly irrelevant.

Hardware accessories

One way the cost of the Raspberry Pi was kept down was increasing modularity. A consequence of this is that a Raspberry Pi board by itself is useless until at least two additional components have been added:

- SD card. To boot, the Raspberry Pi requires an appropriately formatted SD card containing certain boot files as well as the operating system or kernel to run. Note: as of this writing, XinuPi has no SD card driver; therefore, when running XinuPi the SD card is only used for booting. Useful tip: Since the SD card can easily be removed, it is trivial to have different SD cards and swap them out when needed. This trick can be used to easily use the same Raspberry Pis for different purposes.
- Power source. The Raspberry Pi requires 700 mA at 5V, delivered either through the microUSB port or through the GPIO pins. For the microUSB port, most cell phone chargers should work. For the GPIO pins, a useful trick is that a USB to TTL Serial converter, such as this one, can double as a power source as well as a serial connection to the Raspberry Pi over which the console runs. We have primarily used the latter method while developing XinuPi.

Other useful hardware and accessories include the following:

- Serial cable for text input/output to/from the Raspberry Pi, such as this one. This is very important for XinuPi because this is its primary way to interact with a human. Furthermore, as noted above, such a serial cable can double as a power source. However, eventually a keyboard-and-monitor setup will be supported as well, providing an alternative to a serial cable when human interaction with the system is desired.
- Monitor or TV to display graphics output from the Raspberry Pi. While important for Linux, this is less important for XinuPi, which is primarily intended to produce text output over a serial connection as described above. However, XinuPi does support a framebuffer console and a turtle graphics application for those interested.
- USB devices can be plugged in and recognized, but the device driver support for specific devices is extremely limited at this point. Support for USB keyboards as an input method is in development.
- Ethernet cable to take advantage of the networking support.
- Case to enclose the Raspberry Pi in. This protects the board and adds aesthetic value; otherwise it has no purpose.

Booting the Raspberry Pi

The Raspberry Pi can only boot from its SD card, not from any external devices, and it requires several files in order to do so. Several boot files, which are not distributed with XinuPi, must be placed in the root directory of a FAT-formatted partition of the SD card.

The following binary blobs (created by Broadcom, but freely distributable, at least when using them on Raspberry Pis) must exist:

- `bootcode.bin` is a first-stage bootloader. Download link.
- `loader.bin` is a second-stage bootloader. Apparently, this file is no longer required.

- `start.elf` is the GPU firmware. Download link.

The following text files are optional:

- `config.txt` is parsed by the GPU firmware and is used to set various hardware parameters. XinuPi runs fine with the default parameters, so `config.txt` need not exist.
- `cmdline.txt` is used to pass a command line to the Linux kernel. This file need not exist for the XinuPi kernel, which does not take command line parameters.

Finally, the actual kernel:

- `kernel.img` must exist and is loaded as raw data at physical memory address `0x8000` by the GPU firmware. The ARM begins execution at the very first instruction in this loaded image. `kernel.img` can be a XinuPi kernel (rename `xinu.boot` to `kernel.img`), a Linux kernel, or other bare-metal code such as the *raspbootin* bootloader. *raspbootin* has been helpful in developing XinuPi; see its documentation for more information.

There are a couple ways you can actually achieve the final result of a properly set up SD card:

- Follow the installation instructions for a Linux distribution supported on the Raspberry Pi, such as Raspbian or Arch Linux ARM. This will leave the appropriate boot files. To switch to XinuPi, simply replace `kernel.img` on the FAT partition with `xinu.boot`. (Perhaps rename `kernel.img` to `linux.img` to save a backup first.)
- Manually partition the SD card and create a FAT filesystem, then copy the boot files to the filesystem. The binary blobs can be downloaded using the links provided above.

5.4.6 Interrupt handling (Raspberry Pi)

Interrupt handling on the *Raspberry Pi* is concerned with all software and hardware used to configure and process interrupts. An example of an interrupt that can be enabled on the *Raspberry Pi* is that from the *BCM2835 System Timer*, which is used in *XinuPi* to implement *preemptive multitasking*. Interrupt handling on the *Raspberry Pi* consists of two complementary parts:

- *Interrupt Handling (ARM)*
- *BCM2835 Interrupt Controller*

5.4.7 SMSC LAN9512

This page describes Embedded Xinu's (or *XinuPi*'s) driver for the SMSC LAN9512 USB Ethernet Adapter, which is the Ethernet adapter integrated into the *Raspberry Pi* Model B.

Driver overview

The driver is implemented in device/smsc9512/.

Since the SMSC LAN9512 is a USB device, *USB* support must be enabled to use it.

Other operating systems name the equivalent driver smsc95xx or similar because SMSC apparently makes several very similar devices that differ only in these last two digits. However as of this writing, this driver has only been tested with the SMSC LAN9512.

Actually, the SMSC LAN9512 is an integrated USB hub *and* Ethernet adapter. The Ethernet adapter itself appears on the USB as a separate device attached to this hub. And in fact, the USB ports you can plug stuff into on the Raspberry Pi model B are other ports attached to this hub. Fortunately, this detail is handled by the USB subsystem, which will automatically use the hub driver for the hub and this driver for the actual Ethernet adapter device.

Device model

This driver was written for the Raspberry Pi Model B, where the SMSC LAN9512 is permanently attached to the board. For this reason and for compatibility with the rest of Xinu, this driver conforms to Xinu's static device model. It therefore cannot be expected to work (yet) to physically plug an external SMSC LAN9512 into a USB port on the board, or to enable this driver on a system that does not in fact have an integrated SMSC LAN9512. But this could be implemented if needed, since Xinu's USB subsystem already supports dynamic attachment and detachment of devices.

MAC address generation

To have a predetermined MAC address, a given SMSC LAN9512 must be attached to an EEPROM that contains the MAC address. But on the Raspberry Pi Model B, this EEPROM is not present; therefore, this driver must assign a MAC address itself. We do this by generating a MAC address from the board's serial number. This guarantees that a given Raspberry Pi will always have the same MAC address and that two Raspberry Pis are extremely unlikely to be assigned the same MAC address.

Sending and receiving packets

Packets are sent and received by calling `etherWrite()` and `etherRead()` just like in Xinu's other Ethernet drivers. The rest of this section therefore describes driver-internal details.

As seems to be fairly standard for USB Ethernet adapters, networking packets are sent and received over the USB using USB bulk transfers to/from the USB Ethernet adapter device. These transfers contain, more or less, some device-specific data followed by the raw packet data. See the code for details.

The specific details of how USB bulk transfers operate are internal to the *USB subsystem*.

Hardware documentation

As far as we know, there exists no "Programmers Reference Manual" or similar for this device. Therefore, to write this driver we had to glean the necessary hardware details from the driver that SMSC contributed to Linux. In the file device/smsc9512/smsc9512.h we have attempted to document some of the registers we use in our driver, since the corresponding definitions in the Linux driver contain no documentation.

Unimplemented features

- Support for other potentially compatible SMSC LAN95xx devices
- Dynamically attaching/detaching the device
- Reading from attached EEPROM
- VLANs
- TCP/IP checksum offload
- Suspend
- Wake-on-LAN
- Various PHY features

5.4.8 Synopsys DesignWare High Speed USB 2.0 On The Go Controller

The **Synopsys DesignWare High-Speed USB 2.0 On-The-Go Controller** is the USB controller used on the *Raspberry Pi*. This hardware is notorious for having no official documentation available to end users [5] and for having an extremely complicated, poorly written Linux driver. According to Greg Kroah-Hartman, the maintainer of Linux's USB subsystem [6]:

> " ... it's just a really bad USB controller chip, combined with a sad way to hook it up to the processor, combined with with a truly horrible driver make for the fact that USB works at all on this board a total miracle." [7]

This page attempts to explain this hardware in the context of the USB Host Controller Driver we wrote for it as part of the project to port Embedded Xinu to the Raspberry Pi. Unfortunately, it is not intended to *fully* document the hardware, since Embedded Xinu's driver is a relatively simple, stripped-down driver that does not support many features of the Linux driver.

Overview of Embedded Xinu's driver

As mentioned, there is no documentation available for this USB Controller; therefore, it obviously was difficult to implement a driver for it. Since there was no other option, we had to gleam the relevant hardware details from other drivers, mainly the Linux driver [8], but also other drivers written for the controller, such as the CSUD driver [9] and the Plan 9 driver [10]. Our code, however, is a new implementation that is intended to be simple and well-documented, and appropriate (to the extent possible for USB and for this hardware) to include in a simple educational operating system.

Embedded Xinu's driver supports control, interrupt, and bulk transfers. As a Host Controller Driver, it implements the interface declared in include/usb_hcdi.h. For simplicity, Embedded Xinu's driver **does not** support some features of the Linux driver, including but not limited to the following:

- Device mode. The "On-The-Go" portion of the hardware's name means it supports the On-The-Go protocol, which is an extension to the main USB specification that allows the USB hardware to operate in either "host" or "device" mode. However, in our driver we are only concerned with host mode.
- Isochronous transfers
- Support for instantiations of the silicon other than the one used on the Raspberry Pi
- Advanced transaction scheduling that takes into account special properties of periodic transfers
- Various module parameters to configure the driver
- Power management, including suspend and hibernation
- Slave or Descriptor DMA modes

More details

More details about the device and the registers may eventually be added here. For now, see the source code (system/platforms/arm-rpi/usb_dwc_hcd.c and system/platforms/arm-rpi/usb_dwc_regs.h), which is intended to be easy to read and well documented. There is obviously a limit to how "easy to read" it can be, though, since USB itself is very complicated.

[5] http://www.raspberrypi.org/phpBB3/viewtopic.php?f=72&t=27695
[6] http://lxr.linux.no/linux/MAINTAINERS
[7] http://lists.infradead.org/pipermail/linux-rpi-kernel/2012-September/000214.html
[8] https://github.com/raspberrypi/linux/tree/rpi-3.6.y/drivers/usb/host/dwc_otg
[9] https://github.com/Chadderz121/csud
[10] http://plan9.bell-labs.com/sources/plan9/sys/src/9/bcm/usbdwc.c

Notes

5.4.9 XinuPi

XinuPi is the port of Embedded Xinu to the *Raspberry Pi*. XinuPi provides a simple, lightweight operating system for the Raspberry Pi that contains several orders of magnitude fewer lines of code than the Linux-based software stacks that normally run on the device. Its purpose is to provide an inexpensive, convenient platform for various areas of computer science education at a University level, including operating systems, embedded systems, networking, and programming languages. Another goal of XinuPi is to document some of the Raspberry Pi's hardware that has, until this point, been poorly documented or even undocumented. This includes the documentation here as well as XinuPi source code and the documentation generated from comments in it.

Acquiring the Raspberry Pi hardware

See *Raspberry Pi* for information about the hardware itself.

Downloading, compiling, and running XinuPi

Information about downloading and compiling Embedded Xinu can be found in *Getting started with Embedded Xinu*. To compile for the Raspberry Pi platform (that is, to build "XinuPi"), you will need to set `PLATFORM=arm-rpi` when you run **make**. You will also need an ARM cross compiler (i.e. binutils and gcc built with `--target=arm-none-eabi`); more information can be found in *Setting up a cross-compiler*.

Note: currently, the Raspberry Pi support is only present in the development version (from git) and not any released tarballs.

The compilation process will produce a file `compile/xinu.boot`, which can be copied to `kernel.img` on the SD card of a Raspberry Pi to run it (see *Booting the Raspberry Pi*).

XinuPi features and implementation

- The core of XinuPi provides a preemptive multitasking operating system for the Raspberry Pi. See *Preemptive multitasking (ARM)* for more details about how Embedded Xinu implements preemptive multitasking on ARM-based platforms such as the Raspberry Pi; this includes information about thread creation and context switching. Also see *BCM2835 System Timer* for the timer on the Raspberry Pi that XinuPi uses to implement preemptive multitasking.
- Interrupt handling on the Raspberry Pi, required for the timer interrupt as well as many other devices, is described in *Interrupt handling (Raspberry Pi)*.
- USB support was added to Embedded Xinu partly because of its important role in the Raspberry Pi, including to attach the Ethernet Controller on the Raspberry Pi Model B. See USB for general information about USB, or *Synopsys DesignWare High Speed USB 2.0 On The Go Controller* for information specifically about the USB controller the Raspberry Pi provides.
- See *SMSC LAN9512* for information about the built-in USB Ethernet Adapter on the Raspberry Pi Model B, and XinuPi's driver for it.

CHAPTER 6

Teaching with Embedded Xinu

6.1 Monitors

6.1.1 What are Monitors?

Java monitors act as locks guarding fields and methods of an object. Each Java object is associated with one monitor. The *synchronized* keyword requires a thread to acquire the monitor lock associated with a synchronized method's target object before executing the body. Two different synchronized methods belonging to the same object both depend on the same lock as the monitor is associated with the object, and not the methods.

A thread which has already acquired a lock does not wait when attempting to acquire that same lock – this is the primary difference between Java-style monitors and typical counting semaphores. Any thread holding a lock must perform an unlock action once for each corresponding lock action before releasing the lock.

6.1.2 Monitors in Xinu

The monitors we add to Xinu contain an associated semaphore, a thread ownership ID, and a count tracking the number of locks performed without corresponding unlocks. Thus, a monitor count begins at zero, every successful lock action increases the count by one, and every unlock action decreases the count by one. They are handled by a monitor table similar to other structure tables in Xinu such as the mailbox table, semaphore table, and thread table.

The two important functions associated with monitors are `lock()` and `unlock()`. Full C code for these functions can be found in system/lock.c and system/unlock.c. It is important to notice that these functions themselves must be "synchronized" to ensure correctness. In the code we have disabled interrupts, but a more lightweight synchronization mechanism could also be used.

6.2 Compiler Construction With Embedded Xinu

6.2.1 Overview

Having students construct a compiler which targets a runtime that uses their own, or a provided, Xinu operating system is one of the potential tracks for a professor that is *Teaching With Xinu*.

Including Embedded Xinu in a compiler construction course allows students to explore the compilation of high level language constructs that rely on interacting with the underlying runtime. Many traditional compilers courses simply target a processor or simulator, but by targeting a *platform* (a processor and operating system combination) one can extend the source language to include more advanced language features such as I/O operations and thread creation,

manipulation, and concurrency. This also allows students to run their test cases on real hardware and see these programs actually interacting with a real runtime. In modern programming these high level language features are vital, and it is important for students to see what the processor and runtime are doing when they use these features in their own programs.

6.2.2 Course Outcomes

Course development can parallel learning objectives and topics associated with many Programming Language Translation or Compiler Construction courses. [1] However, by targeting a platform with an operating system students can also focus on learning how compilers interact with the runtime to achieve thread concurrency and synchronization; topics which many traditional compilers courses avoid. [2] [3] [4]

Topics

- Lexical Analysis
- Syntax Analysis
- Semantic Analysis
- IR Translation
- Instruction Selection
- Register Allocation

Learning Objectives

- Recognize various classes of grammars, languages, and automata, and employ these to solve common software problems.
- Explain the major steps involved in compiling a high-level programming language down to a low-level target machine language.
- Construct and use the major components of a modern compiler.
- Work together effectively in teams on a substantial software implementation project.

6.2.3 Potential Course Structure

The course outlined below describes a compiler construction course focusing on a semester long project in which students build most of the pieces of a complete working compiler. For this example course we take the compiler project from Appel and Palsberg's *Modern Compiler Implementation in Java* [2] and modify it to target a MIPS platform running the Xinu operating system. We take advantage of the fact that our compiler targets a runtime with an operating system and add high-level I/O and concurrency features to Appel and Palsberg's MiniJava language, creating our own Concurrent MiniJava language.

We allow Java-like threading and synchronization with our added support for class declarations inheriting the built in *Thread* class and with added support for Java's *synchronized* keyword. We also add external operating system calls for I/O operations and for operations to create and manipulate multiple threads of execution. Specifically, we add the ability to print strings with *Xinu.print(String s)*, the ability to print a new line with *Xinu.println()*, the ability to print

[1] Course topics and learning objectives have been adapted from the ACM's Computing Curricula 2001 Computer Science.
[2] Andrew W. Appel and Jens Palsberg, Modern Compiler Implementation in Java, 2nd Edition, Cambridge University Press, 2002
[3] A. V. Aho, M. Lam, R. Sethi, and J. D. Ullman. *Compilers: Principles, Techniques and Tools*. Pearson, 2nd edition, 1985.
[4] S. Muchnick. *Advanced Compiler Design and Implementation*. Morgan Kaufmann, 1997.

an integer with *Xinu.printint(int x)*, the ability to read in an integer input with *Xinu.readint()*, the ability to create a thread of execution with *Xinu.threadCreate(Thread t)*, the ability for a thread to yield control of the processor with *Xinu.yield()*, and the ability for a thread to sleep for a given number of milliseconds with *Xinu.sleep(int time)*.

The links in the outline below describe the changes necessary in each assignment to add these high-level I/O and concurrency features to the language, including the modifications for targeting a Xinu backend instead of the book's intended MIPS simulator. In addition to these compiler changes, modifications must also be made to Xinu to offer the runtime support required by the *synchronized* keyword. Since Java's *synchronized* feature depends on the JVM monitor system, which has subtly different semantics from standard O/S semaphores, *monitor constucts* must be added to Xinu.

Appel and Palsberg's MiniJava language is a subset of the standard Java language, and this means test cases written in MiniJava can be compiled and run using standard Java compilers. To use standard Java compilers to compile programs written in our Concurrent MiniJava language one needs our *Xinu.java* helper class.

Course Outline

Week	Topics	Assignments
01	Introduction	Project 1: Interpreter
02	Lexical Analysis, Automata	*Project 2: Scanner*
03	Syntax Analysis, Grammars	Homework 1: Automata and Grammars
04	Parser Generators	*Project 3: Parser*
05	Abstract Syntax Trees	
06	Semantic Analysis	*Project 4: Semantic Analysis*
07	Activation Records	
08	IR Translation	
09	Basic Blocks	*Project 5: Translation*
10	Instruction Selection	Homework 2: Activation Records
11	Liveness Analysis	
12	Register Allocation	
13	Register Allocation	*Project 6: Instruction Selection*
14	Advanced Topics	
15	Advanced Topics	Homework 3: Register Allocation

Books

- [2]

6.2.4 References

This work funded in part by NSF grant DUE-CCLI-0737476.

6.3 Building a Backend Pool

6.3.1 Summary

This page details how to scale your laboratory environment up to a pool of backend target machines available for remote access.

6.3.2 The Big Picture

Image:XINU-Lab-schematic.gif

XINU Backends

Backend targets upload a student's kernel over a private network on boot, and run the O/S directly. No simulations or emulation are involved; this is real hardware.

MIPS targets: We use Linksys WRT54GL wireless routers (~$60) with *serial port modifications* (~$10) running an embedded MIPS32 200MHz processor, 4 MB flash, 16 MB RAM, two UARTs, wired and wireless network interfaces.

PowerPC targets: We use Apple G3 desktops (recycled) with 512 MB RAM, linear framebuffer, PCI bus, NIC, HD. Apple G4 MiniMac also supported.

CISC targets: Classic XINU runs on Intel x86, Sun 3/Motorola 68K, Sparc, and VAX, among others.

XINU Server

A general purpose server with multiple network interfaces manages a private network for the XINU backends, using standard network protocols like DHCP and TFTP.

Backend serial consoles can connect directly to server's serial ports, or, in larger installations, to a serial annex or concentrator that allows many more serial ports.

A daemon running on the server allows users on frontend workstations to remotely access backend serial consoles, or upload fresh kernels. Optional rebooting hardware allows clients to remotely reset crashed backends.

Our Console Tools are freely available for modern UNIX platforms, including Fedora Linux and Solaris.

XINU Frontends

General purpose computer laboratory workstations can compile the XINU kernel, using a standard GNU C compiler and UNIX toolchain. GCC *cross-compilers* are readily available when the frontend architecture does not match the backend architecture.

Backend consoles can be *connected directly* to frontend serial ports, or frontends can communicate with the server daemon that manages collections of backend serial consoles.

With fully remote console access, kernel upload and powercycling, any machine on the network is a potential frontend, and need not be physically near the XINU server and laboratory hardware. Students can work on their operating system projects from their dorm room computers.

Additional (Optional) hardware

- Terminal Annex (EtherLite 32)
- Serial-Controlled Power Strip (BayTech)
- *Serial adapter diagrams*

6.3.3 Setting Up the Server

Our XINU Server is a PowerPC G5 XServe running Fedora Core Linux. We use this configuration as a model for the information below, but other architecture / O/S combinations are known to work, and there's no reason this shouldn't work for virtually any machine with two network interfaces running a modern UNIX O/S.

The first step in setting up your XINU server is to choose a machine for your server (preferably the one you've been using for the first sections of this tutorial) and download our XINU Console Tools. **NOTE:** some of the following instructions require *root* access on the XINU server machine. After downloading the RPM package, but before installing it, you will need to install a few packages that should be available through your system's package installing utility. On our machine we use the YUM package installer. You will need to install the *tcp_wrappers*, *tcp_wrappers-devel*, and *expect* packages. We used the commands `yum install tcp_wrappers`, `yum install tcp_wrappers-devel`, and `yum install expect`.

After these packages are installed you can install the XINU Console Tools. First navigate to the directory with the RPM file and execute the command `rpmbuild --rebuild xinu-console-latest.src.rpm`. This will create four RPM files: `xinu-console-server-2.05-3.i386.rpm`, `xinu-console-clients-2.05-3.i386.rpm`, `xinu-console-powerd-2.05-3.i386.rpm`, `xinu-console-debuginfo-2.05-3.i386.rpm` `` (**NOTE:** the version numbers in these files could be different). On our machine these files were created in the directory ``/usr/src/redhat/RPMS/i386/`.

To get things up and running you will just need to install the server and client packages. Navigate to the directory where the four RPM files were created and execute the following commands: `rpm -iv xinu-console-server-3.05-3.i386.rpm` and `rpm -iv xinu-console-clients-2.05-3.i386.rpm`. You now have all the necessary tools installed to run your XINU server. You just have to make some changes to some configuration files.

6.3.4 DHCP Daemon

Many modern firmware implementations will allow a device to automatically acquire an IP address using the DHCP protocol even before the O/S kernel begins to boot. The CFE on our Linksys backends will attempt to configure its primary ethernet interface when issued the command,

```
ifconfig -auto eth0
```

over the serial console. See *Deploying Xinu* for more details.

In our configuration, the XINU Server runs a DHCP daemon that is configured to supply addresses to backends on the private network. We use the standard **dhcp** server package that comes stock with our Linux distribution (dhcp-3.0.5-3.fc6, as of this writing). Here is a sample configuration file, dhcpd.conf. Our configuration supplies a fixed IP address for each backend, based upon MAC address.

You will need to change `dhcp.conf` file to match with your backend pool. This requires knowing the MAC addresses of all your backend routers and coming up with distinct fixed IP addresses for each one as well. Also, note that the line `range 192.168.1.200 192.168.1.220;` designates a range of IP addresses to be handed out to machines requesting an IP address that do not have MAC addresses on the list.

It is important to note that the "filename" field designates a unique boot image for each backend; this allows each backend to boot a distinct image, customized by the student currently connected to that backend's serial console.

To get this daemon up and running use the command `service dhcpd start` and remember to restart it after every change to the `dhcp.conf` file with the command `service dhcp restart`.

6.3.5 TFTP Daemon

Many modern firmware implementations will allow a device to upload a boot image over a network device using the Trivial File Transfer Protocol (TFTP). We use the stock TFTP server available with our Linux distribution (tftp-server-0.42-3.1, at this writing,) configured to answer requests on the private network, and with the /tftpboot directory writable by the xinu-console daemon user ID. Most TFTP daemons use TCP wrapper to regulate access; see the notes on security below.

For your server, you will need to configure the permissions of the `/tftpboot` directory (or whatever directory your TFTP server allows client access to) so that the Xinu Console Daemon has writeable access to it. This allows the Xinu Console Daemon to save boot images for the routers to boot off of using the TFTP protocol. To do this you can run the command `chgrp -R xinu /tftpboot` followed by the command `chmod g+w /tftpboot` where `/tftpboot` is your TFTP server directory. **NOTE:** you may need root access to make these changes.

If your XINU server is running an *iptables* firewall (ours with a fresh install of Fedora 9 came running this firewall by default) you may have to configure it to allow clients to access your XINU server's **TFTP Server** running through *xinetd*. The simplest solution is to just tell the *iptables* firewall to allow any activity over the network connection your XINU server is using to connect to the backends. Our XINU server is set up with two network interfaces and configured so that `eth0` is our network connection to the outside world and `eth1` is our connection to our backend pool. To tell the firewall to accept all activity over our network connection with the backend pool we added the line `iptables -I INPUT -i eth1 -j ACCEPT` to the `/etc/rc.local` file. This will automatically run that command every time the system boots up. **NOTE:** this could be very dangerous because the connection between your front end and back end is now **insecure**. This should only be done if you trust all possible users of the backend pool because they now have unchecked access to your XINU server.

See *Configuring the TFTP Server* for more information on changing the configurations of the TFTP server.

6.3.6 Xinu Console Daemon

The Xinu Console Daemon and various associated utilities provide network clients with connectivity to backend consoles that are really only connected directly to the console host. It is freely available from the downloads page.

Allow Frontend Machines to Access the Server

First, you will need to set up some configuration information to allow frontend clients to interact with the Xinu Console Daemon running on the XINU server. Open up the file `/etc/rc.local` and add the following lines to the bottom of the file:

```
TRUSTED_NET="134.48.6.0/255.255.255.0"
XINUD_PORT="2024"
iptables -I INPUT -s $TRUSTED_NET -p tcp --destination-port 1024:65535 -j ACCEPT
iptables -I INPUT -s $TRUSTED_NET -p udp --destination-port $XINUD_PORT -j ACCEPT
```

The `TRUSTED_NET` variable specifies the network of frontend machines that are allowed to access the Xinu Console Daemon on the XINU server. In other words these machines can actually use the Xinu Console Daemon to get a backend and interact with it. You will want to change this variable to match with the range of IP addresses of the frontend machines you want to give access to.

The `XINUD_PORT` variable specifies the port on the XINU server that the Xinu Console Daemon uses. This value will always be "2024" on any machine running any Linux distribution.

The next line sets up the XINU server to allow incoming *tcp* packets from any machine on the trusted network on any port above 1024 because these are the ports that the Xinu Console Daemon expects to use to communicate with frontend machines using our Xinu client programs.

The last line sets up the XINU server to allow incoming *udp* packets from any machine on the trusted network communicating on the `XINUD_PORT` port.

The Xinu Console Daemon uses TCP wrappers to prevent unauthorized access; see the notes on security below.

Give Xinu Console Daemon Permission to use the Serial Devices

Next, you will need to allow the Xinu Console Daemon access to the serial devices which connect the XINU server with the backends. To do this you can change the group to which the devices belong to the "*xinu*" group by running the command `chgrp xinu` followed a list of the serial devices. An example of this command would be `chgrp xinu /dev/ttyS0 /dev/ttyS1 /dev/ttyUSB0` where this example server has three backend routers connected with serial device 0, serial device 1, and USB device 0. **NOTE:** you may need *root* access to make these changes.

Configure Xinu Console Daemon

To get your XINU server up and running you will need to make some changes to the configuration of the Xinu Console Daemon. **NOTE:** you may need *root* access to make some of these changes. First open the file `/etc/profile.d/xinu.sh`. It should look like this:

```
XINU_SERVERS="morbius"
export  XINU_SERVERS
```

You will want to change "morbius" to match your XINU server's name.

Next, open the file `/etc/profile.d/xinu.csh`. It should look like this:

```
setenv XINU_SERVERS morbius
```

Again, you will want to change "morbius" to match your XINU server's name. The changes to these two files ensures that the default value for the `XINU_SERVER` environment variable will be correct when remote users log into the server. **NOTE:** you may need to use the fully qualified domain name of the computer (for example "morbius.mscs.mu.edu") for the Xinu Console Daemon to function correctly.

Then, open the Xinu Console Daemon configuration file `/etc/xinu-consoled.conf`. Here is a sample of the configuration file:

```
#
# This is the configuration file for the connection server.
#
# Lines beginning with # are comments.  Each line specifies a connection
# and has the following form:
#    name class path [ arguments ]*
#
# where
#       name:           name of connection
#       class:          the class of the connection
#       path:           program to run when connection made
#       arguments:      arguments to the program
#
# Each connection should be listed on a separate line
#
#------------------------- Connections -------------------------------

hostname:
#---------------------------------------------------------------------

router1 mips /usr/sbin/tty-connect -r 115200 /dev/ttyS0
```

```
router1-dl DOWNLOAD   /usr/sbin/cp-download /tftpboot/router1.boot
router1-pc POWERCYCLE /usr/bin/xinu-power r01
router1-pf POWEROFF   /usr/bin/xinu-power d01
router1-pn POWERON    /usr/bin/xinu-power u01


router2 mips /usr/sbin/tty-connect -r 115200 /dev/ttyS1
router2-dl DOWNLOAD   /usr/sbin/cp-download /tftpboot/router2.boot
router2-pc POWERCYCLE /bin/echo "Turn off the router, then turn it on"
router2-pf POWEROFF   /bin/echo "Turn off the router"
router2-pn POWERON    /bin/echo "Turn on the router"
```

The line `hostname:` will need to contain your XINU server's name. Following that line will be groups of configuration information for each of the backends connected to your XINU server.

The first line of each entry contains the name of the backend, the architecture it runs on, and the command (along with its arguments) for the server to run in order to connect to the backend. So the line `router1 mips /usr/sbin/tty-connect -r 115200 /dev/ttyS0` tells the Xinu Console Daemon that there is a router called "*router1*" that runs a MIPS processor and that to connect to the backend router the daemon should use `tty-connect` with a baudrate of 115200 on serial device `/dev/ttyS0`. So, when creating your own configuration file you will want to edit the first line of each entry to reflect the name of each of your backend routers and the serial device connecting it to your XINU server. The other parts of the line should already be correct and should not have to be changed for any of your backend routers.

The second line of each entry contains the information regarding what actions the server needs to perform to download the specific boot image for that backend router. So the line `router1-dl DOWNLOAD /usr/sbin/cp-download /tftpboot/router1.boot` tells the Xinu Console Daemon that the *DOWNLOAD* command for "*router1*" will run the program `/usr/sbin/cp-download` which will take a user specified file on the frontend machine (usually their `xinu.boot` file) and copy it into the XINU server's `/tftpboot` directory as the file `router1.boot`. This lets a student create their own modified `xinu.boot` image and then, when the server designates a backend for them to use, the Xinu Console Daemon will copy their boot image onto the server with the specific name of the boot image that will always run on that given backend. For your server you will want to edit the second line of each entry so that the name of the connection and the name of the boot image matches the name of that backend router by changing `router1-dl` to `[backend name]-dl` and by changing `/tftpboot/router1.boot` to `/tftpboot/[backend name].boot`.

The third, fourth, and fifth lines of each entry contain information regarding what actions the server needs to perform to powercycle, power off, and power on each router. However, without special hardware to control the power of the backend pool (such as a Serial-Controlled Power Strip) and special software like our Xinu Power Daemon to oversee the use of that hardware these lines will be useless. If you have a more advanced setup with a way to power on and off the backends remotely, then these lines are where you specify the commands used by the Xinu Console Daemon and Xinu Power Daemon to perform those actions. For more information on setting this up, check out our Xinu Power Daemon wiki. If you are not using any special power control hardware then the user will be responsible for turning on and off the routers by hand.

6.3.7 The Client

This XINU server setup allows for frontend client machines to connect to and run their own Xinu boot images on backends that are really only connected to the XINU server. First, you will need to make sure that each frontend machine has downloaded and installed the Xinu Console Tools client package and that the IP address of the frontend machine is in the *trusted network* set up in the XINU server's `/etc/rc.local` file. Also, you will have to make the same changes to the `/etc/profile.d/xinu.sh` and `/etc/profile.d/xinu.csh` files that you made in the previous steps. That means changing the *XINU_SERVERS* variable in each file to match with your XINU server's name.

Console Access

Clients use the `xinu-console` program to connect their frontend machines to backend routers through the XINU server running the Xinu Console Daemon. To run this program just execute the following command: `xinu-console`. You may also pass as an argument to this program the name of the specific backend you wish to connect to. Once the Xinu Console Daemon has handed the frontend machine a backend to work on and used **tty-connect** to establish a serial connection, the user can use the `xinu-console` program to interact with the backend by using some built-in commands and also by sending characters over the serial connection by just typing on the keyboard. Here is the *help* output for the built-in commands:

```
h, ?    : help message
b       : send break
c       : continue session
z       : suspend
d       : download image
p       : powercycle backend
n       : power on backend
f       : power off backend
s       : spawn a program
x       : quit and leave power on
q       : quit and power down
```

Notice the key words "*download*", "*powercycle*", "*power on*", and "*power off*" and how they match up with the commands listed in the Xinu Console Daemon configuration file `xinu-consoled.conf`. Built-in xinu-console commands with these key words in them will call the associated program listed in the Xinu Console Daemon configuration file for that specific backend. To use these commands first the user will have to enter *command mode* by pressing Ctrl+Space. The user should see the words `(command-mode)`, letting them know that the next character they enter will be interpreted by the xinu-console program as a built-in command and not as just another character to send across the serial connection to the backend. To quit out of the `xinu-console` program, enter command mode and then type either "x" or "q".

Mips-Console Wrapper Script

So, though it is entirely possible to just use the `xinu-console` program to connect to a backend and manually send it all the commands to boot XINU, it includes a lot of repetitive actions. So we have included a script for automating the process of booting XINU on a MIPS backend (like our LinkSys routers). This is our `mips-console` wrapper script located in the file `/usr/bin/mips-console`. Here is a copy of the *mips-console file*. In order to get this script to run with your XINU server you will need to modify the top line `set ip 192.168.1.2` to match the IP address of the network interface your XINU server uses to connect with your backend pool.

Once this change is complete, frontend users can navigate to the directory that contains their `xinu.boot` image and simply run the command `mips-console` to receive, connect to, and boot their own modified XINU image on a backend router from the pool using the completely automated script. It will automatically hand out a backend router to the user from the pool and then download their `xinu.boot` image to the XINU server's `/tftpboot` directory under the appropriate name for the specific backend router. Then it will run that backend's *powercycle* command and send breaks to get to the *CFE* prompt. **NOTE:** if you do not have a hardware rebooter that can be used to remotely turn off and on the backend, then the frontend user will have to manually restart the router at this step. Next it will automatically configure the backend's IP address using the XINU server's **DHCP Server Daemon** and then boot off of the backend's specific boot image located in the `/tftpboot` directory on the XINU server which should now be the same image that the frontend user developed.

6.4 Deploying Xinu

By this point it is assumed you have *obtained a supported router* to use as a back end, have *made the necessary modifications* to use the serial port, have *connected to your backend router* using serial communication software (such as PICOCOM), and have *built a cross-compiler* (from your host computer's architecture to MIPS) and used it to *build a XINU boot image* to run on the back end (a file called `xinu.boot` should be in your `compile/` directory).

6.4.1 TFTP Server

Installing the TFTP Server Package

The first step in running your XINU image is to run a **TFTP Server** on your front end so that it can transfer the boot image onto the back end via the network connection. Getting a **TFTP Server** running on your front end is a fairly simple process on Linux. Use your front end's package install commands to search for a tftp-server package and then install that package. Using Fedora 9 and the YUM package install command, we entered the command `yum list | grep tftp` and obtained the following output:

```
[root@argolis compile]# yum list | grep tftp
tftp.i386                                0.48-6.fc9              mulugupdates
tftp-server.i386                         0.48-6.fc9              mulugupdates
[root@argolis compile]#
```

This command tells the package installer to find any packages with "tftp" in the title. We want the package called *tftp-server.i386* because this will allow us to run a **TFTP-Server** on our front end machine. Next, we need to actually install the package. Again we use our package install command to install the package. Using Fedora 9 and the YUM package install command, we entered the command `yum install tftp-server` and obtained the following output:

```
[root@argolis compile]# yum install tftp-server
Loaded plugins: refresh-packagekit
Setting up Install Process
Parsing package install arguments
Resolving Dependencies
--> Running transaction check
---> Package tftp-server.i386 0:0.48-6.fc9 set to be updated
--> Finished Dependency Resolution
Dependencies Resolved
================================================================================
 Package                 Arch       Version          Repository        Size
================================================================================
Installing:
 tftp-server             i386       0.48-6.fc9       mulugupdates       35 k
Transaction Summary
================================================================================
Install      1 Package(s)
Update       0 Package(s)
Remove       0 Package(s)
Total download size: 35 k
Is this ok [y/N]: yes
Downloading Packages:
(1/1): tftp-server-0.48-6.fc9.i386.rpm                   |  35 kB     00:00
Running rpm_check_debug
Running Transaction Test
Finished Transaction Test
Transaction Test Succeeded
Running Transaction
```

```
  Installing: tftp-server                  ########################## [1/1]
Installed: tftp-server.i386 0:0.48-6.fc9
Complete!
[root@argolis compile]#
```

Configuring the TFTP Server

Now that your **TFTP Server** package is installed, you need to configure some settings to get it to run properly. *xinetd* is a server daemon that can run many different types of servers. Here, though, we're only interested in running a **TFTP Server**, so we want to configure the daemon to run that. The following commands will configure the *xinetd* daemon to run a **TFTP Server** on the front end: The command `chkconfig xinetd on` will configure the *xinetd* daemon to run on the front end. The command `chkconfig tftp on` configures the daemon to run a **TFTP Server** when it is running. The next command, `service xinetd restart` actually restarts the *xinetd* daemon to make sure its up and running. After entering the previous commands we got the following output:

```
[root@argolis trunk]# chkconfig xinetd on
[root@argolis trunk]# chkconfig tftp on
[root@argolis trunk]# service xinetd restart
Stopping xinetd:                                           [  OK  ]
Starting xinetd:                                           [  OK  ]
[root@argolis trunk]#
```

To verify that things worked correctly it is a good idea to type in the command `chkconfig --list` and check to make sure *xinetd* is running and that it is running a **TFTP Server**. You should get output that looks like this:

```
[root@argolis compile]# chkconfig --list
NetworkManager  0:off   1:off   2:off   3:off   4:off   5:off   6:off
acpid           0:off   1:off   2:on    3:on    4:on    5:on    6:off
anacron         0:off   1:off   2:on    3:on    4:on    5:on    6:off
atd             0:off   1:off   2:off   3:on    4:on    5:on    6:off
auditd          0:off   1:off   2:on    3:on    4:on    5:on    6:off
avahi-daemon    0:off   1:off   2:off   3:on    4:on    5:on    6:off
...
...
...
winbind         0:off   1:off   2:off   3:off   4:off   5:off   6:off
wpa_supplicant  0:off   1:off   2:off   3:off   4:off   5:off   6:off
xinetd          0:off   1:off   2:off   3:on    4:on    5:on    6:off
xinu-consoled   0:off   1:off   2:off   3:on    4:on    5:on    6:off
ypbind          0:off   1:off   2:off   3:off   4:off   5:off   6:off
yum-updatesd    0:off   1:off   2:on    3:on    4:on    5:on    6:off

xinetd based services:
        chargen-dgram:  off
        chargen-stream: off
        cvs:            off
        daytime-dgram:  off
        daytime-stream: off
        discard-dgram:  off
        discard-stream: off
        echo-dgram:     off
        echo-stream:    off
        rsync:          off
        tcpmux-server:  off
        tftp:           on
        time-dgram:     off
```

```
        time-stream:    off
[root@argolis compile]#
```

The important lines in this output are the *xinetd* line in the list of services and the *tftp* line at the bottom section of xinetd based services. Make sure that the *xinetd* line says "on" for 3 and 5. Also make sure that the *tftp* line says "on".

By default the **TFTP Server** running on *xinetd* uses the directory `/var/lib/tftpboot` as its directory that will contain files on your server that you wish to make accessible to tftp clients. We will simply refer to this directory as the *tftp server directory* for the remainder of the tutorial. Using this directory is fine, but if you wish to change your *tftp server directory* the process is simple. Opening up the tftp configuration file for *xinetd* (ours was found in the path `/etc/xinetd.d/tftp`) should give you the output:

```
# default: off
# description: The tftp server serves files using the trivial file transfer \
#       protocol.  The tftp protocol is often used to boot diskless \
#       workstations, download configuration files to network-aware printers, \
#       and to start the installation process for some operating systems.
service tftp
{
        disable = no
        socket_type             = dgram
        protocol                = udp
        wait                    = yes
        user                    = root
        server                  = /usr/sbin/in.tftpd
        server_args             = -s /var/lib/tftpboot
        per_source              = 11
        cps                     = 100 2
        flags                   = IPv4
}
```

You need to change the value of the `server_args` variable. Change the value of `server_args` to point to the directory you wish to be your *tftp server directory*. In our lab we use the directory `/tftpboot`. You will need to remember your *tftp server directory* because this is where you will need to put your `xinu.boot` file that you want to run on the back end. After you've made the necessary changes to the file `/etc/xinetd.d/tftp`, it should look like this:

```
# default: off
# description: The tftp server serves files using the trivial file transfer \
#       protocol.  The tftp protocol is often used to boot diskless \
#       workstations, download configuration files to network-aware printers, \
#       and to start the installation process for some operating systems.
service tftp
{
        socket_type             = dgram
        protocol                = udp
        wait                    = yes
        user                    = root
        server                  = /usr/sbin/in.tftpd
        server_args             = -s /tftpboot
        disable                 = no
        per_source              = 11
        cps                     = 100 2
        flags                   = IPv4
}
```

If you are going to use our approach you may need to create a `/tftpboot` directory. To do this execute the following command: `mkdir /tftpboot`. Anytime you make changes to the `/etc/xinetd.d/tftp` file you will need to restart your *xinetd* daemon again with the command `service xinetd restart`.

There are a couple other configurations that you may need to set up in order to get your **TFTP Server** running. If your front end is running an *iptables* firewall (our front end with a fresh install of Fedora 9 came running this firewall by default) you may have to configure it to allow clients to access your front end's **TFTP Server** running through *xinetd*. The simplest solution is to just tell the *iptables* firewall to allow any activity over the network connection your front end is using to connect to the back end. Our front end machine is set up with two network cards and configured so that `eth0` is our network connection to the outside world and `eth1` is our connection to our back end. To tell the firewall to accept all activity over our network connection with the backend we used the command `iptables -I INPUT -i eth1 -j ACCEPT`. If you do not want to run this command every time you restart your machine you can add the line to the `/etc/rc.local` file. This will automatically run that command every time the system boots up. **NOTE:** this could be very dangerous because the connection between your front end and back end is now **insecure**. This should only be done if you trust all possible users of the backend because they now have unchecked access to your frontend machine.

Also, you may need to configure your frontend's IP address. If you are using a DHCP server for your frontend machine you can simply execute `ifconfig eth0 -auto` on your backend's CFE prompt to obtain an IP for your backend automatically. However, most likely this is not the case and you will have to make sure that the network connection that your front end machine is using to communicate with the backend is configured with a static IP address in the 192.168.1.[2-255] range because your backend router will have a default IP address of 192.168.1.1 when it reboots. If it is the case that the IP address of your frontend machine's network connection with the backend is set outside of this range, then check out our quick tutorial for changing the IP address of your network connection.

The last step before actually trying to boot your backend with a XINU image, is to copy the actual `xinu.boot` file to the *tftp server directory*. This is the directory that the `/etc/xinetd.d/tftp` file's `server_args` variable points to. In our example we used the directory `/tftpboot`. This is the directory where you need to copy the `xinu.boot` file. This is easily done by using a command like `cp xinu.boot /tftpboot/xinu.boot`, assuming that your current working directory contains the `xinu.boot` file and that `/tftpboot` is your *tftp server directory*.

6.4.2 Booting XINU on your Backend

By now your **TFTP Server** should be up and running correctly, your `xinu.boot` file should be in the correct directory so your backend can access it through the TFTP protocol, and your frontend machine should either be running as a DHCP server or (more likely) has a static IP address in the 192.168.1.[2-255] range on its network connection with the backend.

To boot your backend router running XINU, first make sure you are connected to the backend with some serial communication software and are at the CFE prompt. If you are not looking at the backend router's CFE prompt follow the instructions on how to *connect to your backend router*. In the CFE prompt type the command `boot -elf [host ip]:xinu.boot` where "[host ip]" is the IP address of the frontend machine's connection to the backend router. If all has gone correctly the router should now be running a XINU image and you will be greeted with a basic shell (xsh$). On our frontend machine running Fedora 9 with an IP address of `192.168.1.2` we optained the following output:

```
CFE> boot -elf 192.168.1.2:xinu.boot
Loader:elf Filesys:tftp Dev:eth0  File:192.168.1.2:xinu.boot  Options:(null)
Loading: 0x80001000/114724 0x8001d024/18480 Entry at 0x80001000
Closing network.
Starting program at 0x80001000
(Mips XINU) #0 (root@argolis.mscs.mu.edu) Mon Jun 23 17:47:42 CDT 2008
  16777216 bytes physical memory.
      4096 bytes reserved system area.
    133204 bytes XINU code.
     32764 bytes stack space.
  16607152 bytes heap space.

------------------------------------------------

    _    _  _____   _______   _     _
   \ \  / /(_____)|  ___ \ | |   | |
    \ \/ /    _   | |   | || |   | |
```

```
     )   (     | |   | |    | || |    | |
    / /\ \   _| |_ | |    | || |___| |
   /_/  \_\(_____)|_|    |_| \_____|
_____________________________________
Welcome to the wonderful world of XINU!
xsh$
```

Within the shell you have some basic commands: exit, gpiostat, help, kill, memstat, led, ps, reset, sleep, uartstat. Each can be described using [command] –help.

```
xsh$ help
Shell Commands:
        clear
        ethstat
        exit
        gpiostat
        help
        kill
        led
        memstat
        memdump
        ps
        reset
        sleep
        test
        testsuite
        uartstat
        nvram
        ?
xsh$
```

Congratulations, You now have a working backend running XINU! You can now make changes to the XINU code, recompile it using the `make` command to get a new `xinu.boot` image, copy that file into the *tftp server directory*, and use the same `boot -elf [host ip]:xinu.boot` command to run your very own, modified version of the XINU operating system.

6.4.3 What to do next?

Now that you have successfully booted and run *Embedded Xinu* on your backend router, you might want to try to *build a pool of backends* to allow multiple users to each run their own version of XINU on a different backend.

6.4.4 Acknowledgements

This work is supported in part by NSF grant DUE-CCLI-0737476.

6.5 Building an Embedded Xinu laboratory

In this section we are developing instructions so that other groups can benefit from the work we are doing. These guides can be followed more or less in order to create a relatively inexpensive platform for a custom operating system. As our work develops further, there will be more Xinu-specific information.

Note: These instructions currently assume you are using the WRT54GL, WRT54Gv4, WRT54Gv8, or WL-330gE routers.

1. Obtain a *supported platform*
2. *Modify the Linksys hardware* or *Modify the ASUS hardware*
3. *Connecting to a modified router*
4. *Build Xinu*
5. *Deploy Xinu*
6. (Optional) *Build a pool of backends*
7. (Recommended) *Backup your router's factory configuration*

6.6 Networking with Xinu

6.6.1 Overview

Having students develop networking aspects with their own, or a provided, Xinu operating system is one of the potential tracks for a professor that is *teaching with Xinu*.

A networking course incorporating Embedded Xinu allows students to build networking functionality into Embedded Xinu over the period of the course. Courses may vary in starting point. Some may begin with a core release of Embedded Xinu, having students implement an Ethernet driver and develop the entire network stack; others may chose to utilize an Embedded Xinu release with the Ethernet driver provided, and have students concentrate on implementing specific protocols within the network stack. Network stack implementation assignments for students can parallel various networking lectures that traverse the stack over the course of the semester, terminating in the students implementing an application that uses the developed network stack.

6.6.2 Course Outcomes

Course development can parallel learning objectives and topics associated with many Communication and Networking courses. [5]

Topics

- History of networking.
- Overview of the specializations within net-centric computing.
- Network standards.
- ISO 7-layer reference model
- Circuit switching and packet switching
- Streams and datagrams
- Concepts and services for specific network layers.
- Protocol and application overview/implementation.
- Overview of network security.

[5] Course topics and learning objectives have been adapted from the ACM's Computing Curricula 2001 Computer Science.

Learning Objectives

- Discuss the evolution of early networks and the Internet.
- Explain the hierarchical, layered structure of network architecture.
- Identify and explain the development of important network standards.
- Discuss the advantages and disadvantages of different types of switching.
- Demonstrate how a packet traverses the Internet.
- Implement a simple network using devices running the Embedded Xinu operating system.
- Discuss and explain the reasoning for network security.

6.6.3 Potential Course Structure

The students will use a base Embedded Xinu release with an Ethernet driver; this kernel can be professor provided or student built in previous courses. All assignments provided below (after the first one) are intended for groups of two or three students.

Optionally, with each new assignment professors may provide students with a proper implementation of the previous assignment. This allows students to concentrate on implementing the current assignment and avoid distractions caused by implementation blunders in previous assignments. Alternatively, students can utilizing their same code base throughout the semester, learning the importance of correcting prior mistakes.

Course Outline

Week	Topics	Assignments
01	History of networking and the Internet & specializations of net-centric computing	*Networking Standards*
02	Networking standards & 7-layer ISO model	*Packet Demultiplexing*
03	Ethernet & Address Resolution Protocol	*Implementing ARP*
04	Internet Protocol	*Implementing IP & ICMP*
05	Internet Protocol and Internet Control Message Protocol	
06	Internet Packet Traversal, Security Concerns for IP & ARP	*IP, ICMP, and ARP Applications*
07	Datagrams - UDP	*UDP Development and Implementation*
08	Datagrams - UDP, Dynamic Host Configuration Protocol	
09	Dynamic Host Configuration Protocol	*DHCP Development and Implementation*
10	Streams - TCP	
11	Security Concerns for UDP and TCP	*TCP Development and Implementation*
12	Interaction Protocols for Networked Devices	
13	Wireless Networking	
14	Network Based Application Development	*Network Based Applications*
15	Networking Future	

Student Outcomes from Completion of Course Assignments

Upon completion of all assignments the student should have a grasp of the networking architecture that he or she implemented over the whole course. The student should be able to answer questions about all implemented protocols as well as general questions about other non-implemented protocols. The student should also be able to understand the

complexities of their implementation. Given the full implementation of the networking architecture the student should be able to pin-point locations in the architecture where optimization is possible and the difficulty involved.

In addition, students that completed all the assignments should have a grasp of devices, user interaction and driver/OS interaction within Embedded Xinu. Other operating system concepts, including threads, memory management, inter-process communication and synchronization, are reinforced through the use of Embedded Xinu.

Books

- Currently this course structure has no suggested books.

6.6.4 References

6.6.5 Acknowledgements

This work funded in part by NSF grant DUE-CCLI-0737476.

6.7 Student Built Xinu

6.7.1 Overview

Having students build their own Xinu is one of the potential tracks presented for a professor that is *teaching with Xinu*.

A student built operating system puts the student in the trenches of operating system development. The student will become intimately involved with the inner workings of an operating system. This will give the student a better understanding of the various systems that work together behind the scenes while an operating system is running. Operating systems topics that can be incorporated in a student built Xinu course include: memory management, scheduling, concurrent processing, device management, file systems and others.

6.7.2 Course Outcomes

Course development can parallel learning objectives and topics associated with many Operating Systems courses. [6]

Topics

- Overview of operating systems
- Operating system principles
- Concurrency
- Scheduling and dispatch
- Memory management
- Device management
- Security and protection
- File systems
- Evaluating system performance

[6] Course topics and learning objectives have been adapted from the ACM's Computing Curricula 2001 Computer Science.

Learning Objectives

- Discuss the history of operating systems.
- Overview of the general and specific purpose of an operating system.
- Understanding concurrency and state flow diagrams.
- Understanding deadlock and starvation.
- Ability to decipher between scheduling algorithms.
- Understanding the use of memory and virtual memory.
- Characteristics of serial and parallel devices.
- Deciphering the concepts behind various file systems
- Understanding the necessity of security and locating potential system security holes

6.7.3 Potential Course Structure

An Operating Systems course using the below course outline or something similar will introduce students to some fundamental concepts of operating systems combined with the basics of networking and communications. Topics include: memory management, scheduling, concurrent processing, device management, file systems, networking, security, and system performance. A similar course structure is followed by Dr. Dennis Brylow at Marquette University in his sophomore level Operating Systems course. Most of the assignments where students are building Embedded Xinu are done in teams of two.

Course Outline

Week	Topics	Assignments Track One	Assignments Track Two	Assignments Track Three
01	C (basics) and OS Structures, Processes	*C Basics*	*C Basics*	*C Basics*
02	C (functions, control flow) and Processes			
03	C (pointers, arrays, structs) and Threads	*C Structs and Pointers*	*C Structs and Pointers*	*C Structs and Pointers*
04	CPU Scheduling	*Synchronous Serial Driver*	*Synchronous Serial Driver*	`SCC Serial Communication`
05	CPU Scheduling			
06	Process Synchronization	*Context Switch and Non-Preemptive Scheduling*	*Context Switch and Non-Preemptive Scheduling*	*Context Switch and Non-Preemptive Scheduling*
07	Deadlocks	*Priority Scheduling and Process Termination*	*Priority Scheduling & Preemption*	*Priority Scheduling & Preemption*
08	Main Memory and Virtual Memory			
09	File System Interface	*Preemption & Synchronization*	*Interprocess Communication* or *LL/SC*	*Interprocess Communication*
10	File System Implementation			
11	Mass-Storage Structure	*Delta Queues*	*Delta Queues*	*Delta Queues*
12	I/O Systems	*Heap Memory*	*Heap Memory*	*Heap Memory*
13	Protection, Security and Distributed System Structures	*Asynchronous Device Driver*	*Ultra-Tiny File System*	Parallel Execution Speedup
14	Distributed System Structures			
15	Distributed File Systems	*Ultra-Tiny File System*	*Basic Networking - Ping*	Inter-core Message Passing

Books

- Abraham Silberschatz, Peter Baer Galvin, and Greg Gagne, Operating Systems Concepts, 7th Edition, John Wiley & Sons, ISBN #0-471-69466-5.
- Brian W. Kernighan and Dennis M. Richie, The C Programming Language, Prentice-Hall, 1978.

6.7.4 References

6.7.5 Acknowledgements

This work funded in part by NSF grant DUE-CCLI-0737476.

6.8 Student Extended Xinu

6.8.1 Overview

Having students integrate advanced operating systems features and develop applications for a their own or a provided Xinu operating system is one of the potential tracks presented for a professor that is *teaching with Xinu*.

Students will learn to extend an operating system by adding kernel level and user level applications. Given a functional Embedded Xinu operating system the students will have to understand and manipulate existing operating system code to create additional operating system features. To add more applications to the operating system students will have to understand the interactions between the program in design and the operating system's device and kernel interaction calls. Programming for embedded devices allows students to engage in development on small resource constrained environments. Through extending the existing Embedded Xinu operating system a student learns to use and understand code not written by the student and develops advanced operating system concepts.

6.8.2 Course Outcomes

Course development can parallel learning objectives and topics associated with many Operating Systems courses. [7]

Topics

- Overview of operating systems
- Operating system principles
- Concurrency
- Scheduling and dispatch
- Memory management
- Device management
- Security and protection
- File systems
- Evaluating system performance

Learning Objectives

- Intimate knowledge of embedded devices.
- Overview of the general and specific purpose of an operating system.
- Understanding concurrency and state flow diagrams.
- Understanding deadlock and starvation.
- Understanding the use of memory and virtual memory.
- Characteristics of serial and parallel devices.

[7] Course topics and learning objectives have been adapted from the ACM's Computing Curricula 2001 Computer Science.

6.8.3 Potential Course Structure

A course where having students integrate advanced operating systems features and develop applications for a their own or a provided Xinu operating system can be outlined to one similar to the one below. The example course layout has the listed applied assignments as well as several written assignments of problems developed with the textbook in mind or taken from the textbook.

Course Outline

Week	Topics	Assignments
01	C (basics) and OS Structures, Processes	Extending Xinu #1
02	C (functions, control flow) and Processes	
03	C (pointers, arrays, structs) and Threads	
04	CPU Scheduling	Extending Xinu #2
05	CPU Scheduling	
06	Process Synchronization	
07	Deadlocks	
08	Main Memory and Virtual Memory	Extending Xinu #3
09	File System Interface	
10	File System Implementation	
11	Mass-Storage Structure	
12	I/O Systems	Extending Xinu #4
13	Protection, Security and Distributed System Structures	
14	Distributed System Structures	
15	Distributed File Systems	

Books

- There are no suggested books for this course outline.

6.8.4 References

6.8.5 Acknowledgements

This work funded in part by NSF grant DUE-CCLI-0737476.

6.9 Xinu Helper Class

Here is the full Java source code for the `Xinu.java` helper class.

```
import java.util.Scanner;
public class Xinu
{
    public static int readint()
    {
        Scanner scanner = new Scanner(System.in);
        return scanner.nextInt();
    }
    public static void printint(int x)
    {
```

```
        System.out.println(x);
    }
    public static void print(String s)
    {
        System.out.print(s);
    }
    public static void println()
    {
        System.out.println();
    }
    public static void yield()
    {
        Thread thisThread = Thread.currentThread();
        try
        {
            thisThread.yield();
        }
        catch (Exception e)
        {
            System.out.println(e);
        }
    }
    public static void sleep(int time)
    {
        Thread thisThread = Thread.currentThread();
        try
        {
            thisThread.sleep(time);
        }
        catch (Exception e)
        {
            System.out.println(e);
        }
    }
    public static void threadCreate(Thread t)
    {
        t.start();
    }
}
```

6.10 Assignments

6.10.1 Assignment: ARP

> The world is a jungle in general, and the networking game contributes many animals.
>
> —David C. Plummer [8]

Overview

This assignment is part of the *Networking with Xinu* track for professors that are *teaching with Xinu* and it is intended to be completed in groups of two or three.

[8] RFC826

Preparation

A new tar-ball is provided with a solution to the previous assignment. If your solution is similar to the one presented, you may choose to continue on with it; but it is suggested that you untar the new project files in a fresh working directory: `tar xvzf`

Address Resolution Protocol

Standard 37 of the Internet Official Protocol Standards is the Address Resolution Protocol. In this assignment students will build the Address Resolution Protocol into Embedded Xinu.

Upon completion of the assignment the students' implementation should:

Required Assignment Parts

- add and remove ARP table entries
- send, receive and process ARP requests
- have ARP entries time out and be removed
- lookup MAC address from table (given an IP) and return it to help fill in packets before sending them

Optional Assignment Parts

- shell integration: add an **arp** command to the shell
  - options for: adding entry, removing entry, sending request and clearing the table

If you choose not to implement the optional assignment parts then placing test case code within the shell's 'test' command will allow you to run one or more tests on your implementation at run-time. Optional portions to an assignment may be required portions of a later assignment.

Student Outcomes

Upon completion of this assignment students should understand the key role this protocol plays in the overall networking architecture. Each student should be able to understand what an Internet Protocol address is and how the protocol uses this address to acquire a MAC address for the network packet before it can proceed through the system and be sent out over the network.

Potential References

- RFC826
- Address Resolution Protocol

Notes

6.10.2 Assignment: Asynchronous Device Driver

This assignment is a Xinu assignment allowing the student to more firmly understand how an operating system works. This assignment is part of the *Student Built Xinu* track for professors that are *teaching with Xinu*. The entire working directory containing your Xinu operating system will be submission for this assignment.

Preparation

First, make a fresh copy of your work thus far:

```
cp -R
```

Untar the new project files on top of this new directory:

```
tar xvzf
```

You should now see the new project files in with your old files. Be certain to `make clean` before compiling for the first time.

Semaphore Loose Ends

Modify `system/scount.c`, `system/sreset.c`, `system/freesem.c`, and `system/signaln.c` to finish off the interface for our semaphore subsystem. The ansynchronous driver will require all of these functions to maintain proper syncronization, but none of these semaphore helper functions is more than a few lines of code.

Dr. Dennis Brylow, quoting one of his students:

> Question: We are looking at `sreset` and `freesem`. When it says" release the process from the semaphore's waiting queue," what exactly are we supposed to do with the processes once they are released from the semaphore? Should we kill them, or put them back into the ready queue?
>
> Answer: Put them back into the ready queue.

Device Driver

The project tarball includes the following files, which comprise the device interface layer for Xinu: `system/devtable.c`, `system/close.c`, `system/control.c`, `system/getc.c`, `system/open.c`, `system/putc.c`, `system/read.c`, `system/write.c`, and a revised `system/initialize.c`. The device layer allows user programs (like the processes in `main.c`) to work with device-specific functions using standard names like `open()` and `read()`, rather than have to explicitly name the underlying device driver.

You do **NOT** need to make any changes to the device interface layer files. However, you do need to know what they are doing. Trace through a few of the high-level device functions. They are very short, and almost all the same. The file `system/devtable.c` contains the master device table declarations.

The Asynchronous TTY Driver

For this project, you will be implementing an asynchronous device driver for an interrupt-driven UART. The difference between the existing synchronous UART driver and the new asynchronous tty driver is that the synchronous driver always waits for the serial port hardware to complete a read or write before returning. A proper asynchronous driver does not wait needlessly for the hardware, but instead only communicates with the UART when a hardware interrupt indicates to the system that it is ready for the next batch of work.

The Universal Asynchronous Receiver/Transmitter (UART) on our hardware seems to be largely compatible with the venerable National Semiconductor 16550 family of UARTs that have been reliably driving serial ports in PC's for decades. The PDF of the device documentation will explain the control and status registers (CSRs) on this device. The base address of its memory-mapped I/O region is noted in the master device table, devtab.

The Upper Half of a driver consists of the functions called by various user-level processes, functions such as `ttyRead` and `ttyWrite`. As much as possible, the upper half functions shield the user from the messy details of the hardware.

The Lower Half of a driver consists of the handler functions run when hardware interrupt requests arrive. Lower half functions must do their work quickly, and deal with data that has been buffered up by the upper half functions.

You will be working on the upper half functions `device/tty/ttyRead.c` and `device/tty/ttyWrite.c` and the lower half function `device/tty/ttyIntr.c`. The `ttyIntr()` function is called via a new hook in `system/xtrap.c` when a hardware interrupt request from the UART hardware arrives.

Look carefully at the structure of the asynchronous driver suggested by the structures in `include/tty.h`. It is critically important that you be able to envision how the upper and lower halves of the driver should interact **before** you start adding code to the system.

Testing

Provide a main program that demonstrates that your asynchronous driver is working properly.

The Marquette University Embedded MIPS backends have two serial port connections. All of the backends in the lab have their second serial port available via the xinu-console system. When running `mips-console` normally, note the name of the backend you are allocated. Append a "2" to the name, and run the command `xinu-console name2` to gain access to the second serial port for backend "name." The xinu-console reservation system tracks these two connections independently. Please be courteous to your neighbors and release any consoles as soon as you are done.

The "2" is assigned for ease of use, a Xinu lab may set up individual names for access to the second serial port on a backend and thus the user should understand what standard the lab he or she works with before assuming a naming convention is used.

The command "`xinu-status`" will list the users on each backend, and "`xinu-status -c uart`" will list the users on each backend's second serial port. Also recall that a user can bump another user off of a specific backend after 10 minutes of activity.

6.10.3 Assignment: Basic Networking (`ping`)

This assignment is a Xinu assignment allowing the student to more firmly understand how an operating system works. This assignment is part of the *Student Built Xinu* track for professors that *teaching with Xinu*. The entire working directory containing your Xinu operating system will be submission for this assignment.

Preparation

First, make a fresh copy of your work thus far:

```
cp -R
```

Untar the new project files on top of this new directory:

```
tar xvzf
```

You should now see the new project files in with your old files. Be certain to `make clean` before compiling for the first time.

The Xinu Shell

With the addition of a full-featured TTY driver in the previous assignment, we can now add the command-line Xinu user interface, the *Xinu Shell* to the system. The new tarball includes a new subdirectory `shell/` that provides the I/O processing necessary to parse user input and launch a small set of commands. Several useful commands are provided as examples. This assignment will be concerned primarily with the **ping** and **pingserver** commands.

Ethernet Driver

This project tarball equips your Xinu kernel with a block-oriented, asynchronous ethernet driver for the router's built-in BCM4713 network interface. You are not required to modify the ethernet driver (directory `device/ether/`), but it wouldn't be a bad idea to familiarize yourself with its workings. It follows the same standard device abstraction as we have seen in the TTY and disk device drivers.

Debugging Tools

For your convenience, we have also provided a `snoop()` function in `network/snoop.c`, which will attempt to provide human-readable interpretations of packets when called. This is provided strictly for debugging purposes. It takes a buffer that contains an ethernet packet and a designated length and prints out various values as well as a hexdump of the packet.

Student Implementation

Your task for this assignment is to implement a version of **ping** that allows your main programs to send *echo request* packets to other machines and allows other machines to send *echo requests* packets to your allocated backend. This project can be split into two distinct parts, the client and the server. You should first implement a server that allows other machines to **ping** your backend while it is running. The second part of this project is to implement the client side which will allow you to write a main process that can **ping** other machines. In each of these parts you will deal with two types of ICMP packets, *echo request* and *echo reply* packets. The *request* packets are sent from a client to a target machine that is running a ping server. The *reply* packets are sent in response to a client's request back to the client.

Echo Reply (Ping) Server

The Ping Server is a process spawned by the **pingserver** shell command to listen to the Ethernet device for ping requests and construct correct replies. (See Echo Reply.) Due to the simplified nature of packet de-multiplexing in our current system, it will not be possible for your Xinu kernel to run both a ping server and a ping client simultaneously. (The two processes will "fight" over incoming packets.) Instead, use a second router to generate ping requests to test your server, or use the Linux command **ping** on a local server which has direct access to the private Xinu Network.

Echo Request (Ping) Client

The project tarball includes a starter stub for a ping command in the shell directory file `shell/xsh_ping.c`. Your ping command should take a single command-line argument consisting of a destination IP address in dotted decimal notation. It should

- generate a sequence of 20 (`MAX_REQUESTS` in `include/network.h`) ping packets at one second intervals;
- watch for ping replies from the target machine;
- print out replies received (see the `icmp_reqreply` function in `network/icmp.c`); and
- print out a summary of results.

The proper term for a "ping packet" is an ICMP Echo Request An answering packet is an Echo Reply. For the sake of simplicity, this project will not implement a full ARP system to resolve IP addresses down to underlying Ethernet MAC Addresses. Instead, we will use a predefined static table, `arp_map` to match requested ping IP addresses for machines local to the private Xinu Network. Any address that is not known to the `arp_map` table will be assumed to be on another network, and the ping packet should instead be addressed to Zardoz, the Xinu Network Gateway. The gateway's MAC address is hard-coded in `network.h` with the constant `PING_GATEWAY`.

Resources

- Wikipedia: Ping
- RFC 792 - Internet Control Message Protocol
- Wikipedia: Internet Control Message Protocol (ICMP)

6.10.4 Assignment: C Basics

6.10.5 All Your Base Are Belong To Us

This assignment is part of the *Student Built Xinu* track for professors that are *teaching with Xinu </teaching/index>*. This particular assignment will help develop the student's proficiency for programming in C.

The Multi-Base Calculator

- Write a calculator program that reads in expressions consisting of integers and the operators +, -, *, /, %, ^ (exponentiation), & (bitwise AND), | (bitwise OR), << (left shift), and >> (right shift), and prints the results when evaluated in simple left-to-right order.
- Your calculator should understand positive integers in binary (starting with "0b",) octal, decimal, and hexadecimal, but all output will be in decimal (base-10).
- You should use the `getchar()` library function to read console input one character at a time. The use of any other library functions for input is not recommended at this time.

Notes

- This project can seem deceptively complex, but is quite tractable if you first take the time to design suitable helper functions, and test those function thoroughly before moving on to the overall calculator. We encourage the disciplined practice of test-driven development.
- The internal data representation of the calculator values can be assumed to be a `signed int`. You are not required to deal with overflow and underflow issues.
- Parsing input is always tedious, particularly when the input is not rigidly constrained with rules like, "all operators must be surrounded by space on both sides," (which is NOT a constraint for this assignment). In lieu of a parser-generator, consider drawing simple state diagrams for how to recognize an integer in octal, or how to recognize an integer in hexadecimal. In many cases with input of this type, it is useful to be able to put back a character of input once you realize you have read too far. Useful C routines for implementing this kind of buffering include `getch()` and `ungetch()`.
- Consider various operational and parsing errors that can take place.
- Devise test cases to discover the expected behavior, and do your best to match it precisely. Creativity will be valued in later assignments, but first one must master the tools.

6.10.6 Assignment: C structs and pointers

A Stroll Down Memory Lane, or A Stunning Reversal

This assignment is intended to develop the student's proficiency for programming in C. This assignment is part of the *Student Built Xinu* track for professors that are *teaching with Xinu*. This assignment may be completed in teams of two.

Program

- Write a C program that reads in an arbitrarily long sequence of positive integers and outputs that same sequence in reverse order.
- Your program should understand positive integers in binary (starting with "0b"), octal, decimal, and hexadecimal, but all output will be in decimal (base 10). This should reuse code from your calculator project.
- Your program should ignore any amount of white space between integers, including tabs, spaces, newlines, etc. See the `isspace()` function in your text or in the man pages for details. However, your output should consist entirely of base 10 representation integers in a line by themselves.
- To store an arbitrary list of integers, your program will need to request more memory from the operating system when the space it already has runs out. This kind of dynamic allocation is performed using the `malloc()` function, as detailed in your text and in the man pages. You may assume that we will test your program with at least 100,000,000 integers. Your program should exit gracefully if a `malloc()` request is denied.
- Billionrandom is a random number generator that takes a single command-line parameter for the number of integers desired, and then outputs a predictable sequence of pseudorandom numbers using a linear congruential generator and rotating through the various bases. This program can be used to generate test inputs of varying sizes.

Notes

- There are a variety of approaches for storing an arbitrarily long list of integers. The approach I recommend is building a linked list of structures that store a reasonable number of integers. So, for example, you could define a struct that contains an array of a few thousand integers. Every time you fill up that structure, request another one and string it into a linked list with all of the previous blocks. This is an excellent balance in efficiency – if your block size were too small (one integer per `malloc()` in the most absurd case) your program would spend all of its time asking the O/S to allocate more memory. If the block size were too large, (say, a Gigabyte,) your program would needlessly waste resources when the input was only a small list, and might not even be able to allocate a single chunk that large.
- This project is inherently dangerous; please exercise both great care and ethical consideration during this assignment. For large numbers of integers, this program is essentially a stress test for the operating system's virtual memory subsystem. On a late model 3 GHz Pentium IV running the program with a test list of 1,000,000,000 runs for over 15 minutes; practically locking up all user interfaces for the last 10 minutes of that. The reference implementation, in combination with the test generator, can bring pretty much any server to its knees in a matter of minutes. As a result, the following are particularly important:
  - list of DO NOTs for this project:
    - DO NOT run your program with a large test size on any other large server relied upon by multiple users.
    - DO NOT pipe the output of billionrandom or your program to a text file for list sizes over a few million. If you do the math, you'll see that this could quickly fill up a lot of the space and clog up the network with file server traffic.
    - DO NOT run large test cases when it is apparent that a bunch of other people are trying to do their work on the same machine. See the **top** and **w** UNIX commands for more info.
  - list of DOs for this project:
    - DO check your dynamic allocation code by adjusting your block size downward to insure that even small numbers of integers will require multiple `malloc()` requests.
    - DO check your `malloc()` error handling by adjusting your block size upward until your first request fails.

* DO run your program with large test input (more than a few million) only once you are relatively certain it is working properly – so that you only have to do it once.

Billionrandom

```
#include <stdio.h>
#include <stdlib.h>
#include <limits.h>

void printNumber(unsigned long num, int base)
{
  unsigned long i = 0UL;

  switch (base)
    {
    case 2:
      printf("0b");
      for (i = INT_MAX; i >= num; i = i >> 1)
    ;
      for (i = (i << 1) & ~i; i > 0; i = i >> 1)
    { printf("%c", (i & num) ? '1' : '0'); }
      printf("\t");
      break;
    case 8:
      printf("0%o\t", num);
      break;
    case 10:
      printf("%u\t", num);
      break;
    case 16:
      printf("0x%X\t", num);
      break;
    }
}

int main(int argc, char **argv)
{
  unsigned long a = 1664525UL,
    b = 1013904223UL,
    c = 0UL,
    d = 0UL,
    e = 1000000000UL;

  char *val = 0;

  if (2 == argc)
    {
      if (('-' == argv[1][0])
      && ('v' == argv[1][1]))
    {
      printf("COSC 125, Spring 2006\n"
         "Linear Congruential Generator, v1.0\n");
      exit(0);
    }
      val = argv[1];
      e = 0UL;
      while (0 != *val)
```

```
    {
      e = e * 10 + *val - '0';
      val++;
    }
    }

  for (c = 0UL; c < e; c++)
    {
      d = a * d + b;
      if (0 == (d % 1000))
    { printf("\n"); }
      switch (c % 4)
    {
    case 0: printNumber(d, 2);  break;
    case 1: printNumber(d, 8);  break;
    case 2: printNumber(d, 10); break;
    case 3: printNumber(d, 16); break;
    }
    }

  printf("\n");
  return c;
}
```

6.10.7 Assignment: Context Switch and Non-Preemptive Scheduling

This assignment is an early Xinu assignment allowing the student to grow a more firm understanding of how the basics of an operating system work. This assignment is part of the *Student Built Xinu* track for professors that are *teaching with Xinu*. This assignment should be completed in teams of two. Students should only turn in the files required for this assignment: `system/create.c`, `system/ctxsw.S`, and a `README` file, as explained below.

Preparation

Untar the new project files in a fresh working directory:

```
tar xvzf
```

Copy your synchronous serial driver file (`kprintf.c`) into the `system/` directory.

Context Switch

The new source files include two new headers, `include/proc.h` (definitions for Process Control Blocks and a process table), and `include/queue.h` (definition for a process ready queue), as well as trivial updates to `include/kernel.h`.

The new source files also include:

system/initialize.c	Updated initialization for Project 4.
system/main.c	A "main program" for testing scheduling.
system/queue.c	An implementation of the queue data structure.
system/create.c	A partial function for creating a new process.
system/ctxsw.S	An incomplete assembly routine for switching process contexts.
system/ready.c	A function for adding a process to the ready queue.
system/resched.c	The primary scheduling code, equivalent to yield().
system/getstk.c	A rudimentary function for dynamically allocating new stacks for new processes.
compile/Makefile	Updated rules for compiling XINU.

The `create()` and `ctxsw()` functions are incomplete and must be filled in. The file `system/initialize.c` contains code to test your context switch with three processes, each of which prints a process ID and then yields. Once your context switch and creation functions are working, you will see these three processes take turns running.

Some Assembly Required

An operating system's context switch function typically must be written in assembly language because the low level manipulations it performs are not modeled well in higher-level languages. If you have not worked in Mips assembly language before, there are many helpful resources available online. Despite its low-level nature, a context switch does not require complex instructions. Our context switch can be completed using only arithmetic opcodes, and the load (`lw`), store (`sw`), and move (`move`) opcodes.

README

There are many possible layouts for your operating system's activation records. It is critical that your `create()` function and your `ctxsw()` agree on the design you choose. Turn in a plain text file, `"README"` that diagrams and explains the activation records created by `create()` and expected by `ctxsw()`. Label the purpose of each field. This design document will be worth 25% of the assignment credit.

Testing

The default test case provided with the tarball is necessary, but not sufficient. Just because it switches between a handful of identical processes does not guarantee correctness. In embedded systems, details matter. (A LOT!) Students in previous terms have found that subtle bugs in this phase of the term project were responsible for nightmares weeks and months down the line. Test your code thoroughly:

- Processes can be passed an arbitrary number of parameters upon creation;
- Processes should terminate cleanly upon exit;
- Stack pointers and activation records should align properly and have known contents at critical check points.

You have a working I/O driver, a `kprintf()` function for formatted output, and code from earlier assignments for parsing integers. Use these to explore every aspect of the operating system structures you are building.

6.10.8 Assignment: DHCP Implementation

Overview

This assignment is part of the *Networking with Xinu* track for professors that are *teaching with Xinu* and it is intended to be completed in groups of two or three.

Preparation

A new tar-ball is provided with a solution to the previous assignment. If your solution is similar to the one presented, you may choose to continue on with it; but it is suggested that you untar the new project files in a fresh working directory:

```
tar xvzf
```

Dynamic Host Configuration Protocol

The Dynamic Host Configuration Protocol provides a framework for passing configuration information to hosts on a TCPIP network. DHCP is based on the Bootstrap Protocol (BOOTP). In this assignment students will build a DHCP client into Embedded Xinu that dynamically acquires networking information for the operating system to use.

Upon completion of the assignment the students' implementation should:

Required Assignment Parts

- implement a functional DHCP client within Embedded Xinu

Student Outcomes

Upon completion of this assignment students should understand the key role this protocol plays in the overall networking architecture.

Potential References

- RFC2131
- Wikipedia - Dynamic Host Configuration Protocol

6.10.9 Assignment: Delta Queues

This assignment is a Xinu assignment allowing the student to grow a more firm understanding of how an operating system works. This assignment is part of the *Student Built Xinu* track for professors that are *teaching with Xinu*. Your entire working directory containing your Xinu operating system will be submission for this assignment.

Preparation

First, make a fresh copy of your work thus far:

```
cp -R
```

Untar the new project files on top of this new directory:

```
tar xvzf
```

You should now see the new project files in with your old files. Be certain to make clean before compiling for the first time.

Sleep

Modify `system/sleep.c`, `system/wakeup.c`, `system/insertd.c`, and `system/clockintr.c` to add the `sleep()` system call to the operating system. A process that calls `sleep(n)` should enter the `PRSLEEP` state for n clock ticks. A clock "tick" is one millisecond in our current system. It corresponds to the raising of the timer interrupt request when interrupts are not disabled. When the clock interrupt handler detects that a process has slept for long enough, the `wakeup` function should move the process back to the ready list.

The appropriate data structure for maintaining a list of sleeping processes is a *delta queue*, as described in lecture. Add a delta queue to the system by increasing the `QENT` constant in `include/queue.h`, declaring a queue called "sleepq" in `include/clock.h`, and and defining and initializing `sleepq` in `system/clockinit.c`. Make sure to test your delta queue in isolation before testing the `sleep()` function.

Grading

Project credit will be weighted evenly between delta queue maintenance, sleeping, and waking processes. By now, you should be aware that rigorous testing is the key to success in these projects. Our test cases will include at least:

- Checking your delta queue insert function with a variety of parameters
- Checking your sleeping and waking functions independently and in concert.

6.10.10 Assignment: Heap Memory

This assignment is a Xinu assignment allowing the student to more firmly understanding of how an operating system works. This assignment is part of the *Student Built Xinu* track for professors that are *teaching with Xinu*. The entire working directory containing your Xinu operating system will be submission for this assignment.

Preparation

First, make a fresh copy of your work thus far. cp -R Untar the new project files on top of this new directory: tar xvzf You should now see the new project files in with your old files. Be certain to make clean before compiling for the first time.

Getmem and Freemem

The files `include/memory.h` and `system/initialize.c` define and initialize a free list of available memory blocks on the heap. Implement `system/getmem.c` and `system/freemem.c` to dole out blocks of requested memory and properly maintain the free list. Use First Fit with simple compaction. (Compaction is the "stretch" problem in this assignment – get everything else working first.)

Delete the file `system/getstk.c` and replace the lone call to this function in `system/create.c` with a proper call to `getmem()` instead. Modify `system/kill.c` to call `freemem()` to deallocate a process stack when a process dies.

Grading

Project credit will be divvied up evenly between getting memory, freeing memory, and compaction. By now, you should be aware that rigorous testing is the key to success in these projects. Our test cases will include at least:

- Verifying that your `getmem()` and `freemem()` functions operate correctly over a variety of request sizes

- Checking your memory free list under a wide variety of conditions; if you are not writing a helper function to print out your free list, you are probably not serious about understanding what your system is doing
- Allocating and freeing as much memory as possible, (How can you tell whether you have a memory leak?)
- Verifying that your `freemem()` compaction works.

6.10.11 Assignment: IP, ICMP

Overview

This assignment is part of the *Networking with Xinu* track for professors that are *teaching with Xinu* and it is intended to be completed in groups of two or three.

Preparation

A new tar-ball is provided with a solution to the previous assignment. If your solution is similar to the one presented, you may choose to continue on with it; but it is suggested that you untar the new project files in a fresh working directory:

```
tar xvzf
```

Internet Protocol

Two parts of standard number 5 of the Internet Official Protocol Standards are the Internet Protocol and the Internet Control Message Protocol (ICMP). In this assignment students will build both IP and ICMP into Embedded Xinu.

Upon completion of the assignment the students' implementation should:

Required Assignment Parts

- send and receive packets of with type IP
- further demultiplex IP packets to find the underlying type
- send and receive ICMP packets

Optional Assignment Parts

- reply to ICMP echo requests properly
- shell integration: add a **ping** command to the shell (sending out echo requests)

If you choose not to implement the optional assignment parts then placing test case code within the shell's **test** command will allow you to run one or more tests on your implementation at run-time. Optional portions to an assignment may be required portions of a later assignment.

Student Outcomes

Upon completion of this assignment students should understand the key role this protocol plays in the overall networking architecture. Each student should also be able to understand the unique ties between the Internet Protocol and the Internet Control Message Protocol.

Potential References

- Internet Protocol - RFC
- Internet Control Message Protocol - RFC
- Internet Protocol - Wikipedia
- Internet Control Message Protocol - Wikipedia

6.10.12 Assignment: IP, ICMP, ARP Applications

Overview

This assignment is part of the *Networking with Xinu* track for professors that are *teaching with Xinu* and it is intended to be completed in groups of two or three.

Preparation

A new tar-ball is provided with a solution to the previous assignment. If your solution is similar to the one presented, you may choose to continue on with it; but it is suggested that you untar the new project files in a fresh working directory:

```
tar xvzf
```

Shell Commands

We have implemented three protocols within our networking portion of Embedded Xinu. In this assignment we will add shell commands to create useful interaction with those protocols. We will be adding four shell commands: **arp**, **ping**, **snoop** and **ethstat**.

Upon completion of the assignment the students' implementation should have all the required shell commands properly implemented and well tested.

Required Assignment Parts

Shell Command Descriptions

- **arp** prints out the arp table or performs the modification specified via an option.
- **ping** uses the ICMP protocol's mandatory ECHO_REQUEST datagram, attempting to elicit an ECHO_RESPONSE from a host or gateway.
- **snoop** displays packet information for incoming and outgoing network packets.

Shell Command Options

- **arp**
  - options for: adding entry, removing entry, sending request and clearing the table
  - add help option that prints usage
- **ping**

  - options for: count of pings to be sent and time to live of packets
  - add help option that prints usage
- **snoop**
  - option for: dumping a packet in hex
  - add help option that prints usage

Optional Assignment Parts

- respond to received traceroute packets with the proper ICMP packet

If you choose not to implement the optional assignment parts then placing test case code within the shell's **test** command will allow you to run one or more tests on your implementation at run-time. Optional portions to an assignment may be required portions of a later assignment.

Student Outcomes

Upon completion of this assignment students should understand how to implement various shell commands that interact with the underlying network interface. Implementing the shell commands should give the student a better grasp of how the various protocols actually work and how user commands, that they have used elsewhere, disguise this reality.

Potential References

- Ethernet Address Resolution Protocol - RFC
- Internet Protocol - RFC
- Internet Control Message Protocol - RFC
- Address Resolution Protocol - Wikipedia
- Internet Protocol - Wikipedia
- Internet Control Message Protocol - Wikipedia

6.10.13 Assignment: Instruction Selection

Overview

In this project students implement a translator that takes the Intermediate Representation (IR) output from the translation in *Project 5* and converts it into MIPS assembly language with an infinite pool of temporaries.

Notes

No changes are required for our modified MiniJava language or to target a Xinu backend provided that the compiler follows standard MIPS calling conventions.

6.10.14 Assignment: LL and SC

Synchronization and Interprocess Communication

This assignment is a Xinu assignment allowing the student to grow a more firm understanding of how an operating system works. This assignment is part of the *Student Built Xinu* track for professors that are *teaching with Xinu*. Written answers to the analysis questions should be put into a file called `system/ANALYSIS.txt` and submitted with the code. The entire directory containing the operating system should be turned in during the submission process.

This assignment includes a LAB REPORT. Include your lab report in a file called `login.pdf`, (with your login name,) in the top-level directory of your xinu-hw6.

After completion of this assignment we will have a basic operating system with preemptive, priority scheduling of processes, counting semaphores with wait queues as synchronization primitives and interprocess communication with bounded buffers.

Atomicity

In a system with preemption, we must now guard against being interrupted while in the middle of an atomic operation. There are many points in operating system code where an unfortunately timed interrupt could leave the system in an inconsistent state.

For example, in the `resched()` function, there are several lines of C code (which translate into many more lines of machine code) between the point where the outgoing running process is put back into the queue of ready processes and the point where an incoming process is dequeued and set to running. If an interrupt were to take place in the midst of this transition, the interrupt handling code might see the system in an inconsistent state, in which there doesn't seem to be a currently running process. For this reason, we consider process rescheduling to be atomic with respect to the rest of the operating system. The easiest way to enforce this is to temporarily disable interrupts during a critical, atomic section of code, and then reenable them when done.

The new file `system/intr.S` contains functions `enable()`, `disable()`, and `restore()` for manipulating the master bit that enables processor interrupts. From this point forward, these functions must be used judiciously to guard atomic sections in the operating system functions you write.

Preparation

First, make a fresh copy of your work thus far:

```
cp -R
```

Untar the new project files on top of this new directory:

```
tar xvzf
```

You should now see the new project files in with your old files. Be certain to make clean before compiling for the first time.

Semaphores

With this assignment you must learn about and understand classic semaphores before using them to implement the remainder of the assignment. An implementation of classic semaphores with waiting queues has been provided for you. Please examine and understand the implementation which can be found across several files including `include/semaphore.h`, `system/newsem.c`, system/signal.c and `system/wait.c`. As part of the analysis portion of this assignment, you will need to write a main file to show your understanding of semaphores.

Producers/Consumers

Using the provided semaphore structure, implement producers and consumers that communicate using a Bounded-Buffer. Your textbook provides discussion of the Bounded-Buffer Problem beginning in section 6.6.1, and outlines this assignment as Programming Project 6.40 - Producer-Consumer Problem.

Segments of the textbook code are already given for you in `system/testcases.c`. Complete the project as specified in the text with slight adjustments as noted in the testcases TODOs. Answer the analysis questions below in your lab report.

Synchronization Hardware

Disabling all interrupts is an effective but heavy-handed approach for providing mutual exclusion. Multicore systems and complex real-time systems often cannot afford to disable interrupts, and rely more on hardware support for atomic updates.

The assembly code in `system/testAndSet.S` implements the `testAndSet()` operation (ala Figure 6.4 in your textbook [9]) using the MIPS LL/SC (load-linked and store-conditional) opcodes. Much more complex synchronization primitives can be built on top of simple atomic opcode combinations such as there.

Build `mutexAcquire()` and `mutexRelease()` in `system/mutex.c` using the bounded-waiting algorithm presented in Figure 6.8 of your textbook [1].

Lab Report

For the lab report portion of this assignment, you should typeset a document containing your analysis of the system components introduced. A sample report format is given HERE. We expect the report to be written with your exemplary literacy skills.

What are we reporting on? Once you have the Producer/Consumer implementation working with the provided semaphore API, consider the following questions:

1. Does it matter which process runs first, the producer or the consumer?
2. What happens when there are multiple producers and consumers?
3. What happens when the producer(s) priority is higher than the consumer(s)? Vice-versa?

For each of these, form a hypothesis, construct an experiment (testcases), and draw appropriate conclusions. There is no benefit in fudging your hypotheses after you know the answer; the quality of a lab report is orthogonal to whether your hypothesis was correct or not.

For part two of the assignment, use your bounded-wait `mutexAcquire()` and `mutexRelease()` to prevent your producers/consumers from breaking up `kprintf()` calls mid-line without additional disabling of interrupts. Consider the following questions:

1. Can your bounded-wait mutex subsystem replace the semaphore subsystem for this task?
2. Under what conditions in the embedded operating system will the mutex subsystem not work as designed?
3. Can you deadlock your producer and consumer?

I rewrote the `testAndSet()` MIPS code from lab today to correspond more closely to the semantics used in the textbook chapter 6 [1]. There is an example of the lab report format, and analysis questions to report upon in the final section. Typeset your lab report with whatever software you are comfortable with.

[9] Silberschatz, A., Galvin, P. B., and Gagne, G. 2009 Operating System Concepts. 8th. John Wiley & Sons, Inc.

References

6.10.15 Assignment: Networking Applications

Overview

This assignment is part of the *Networking With Xinu* track for professors that are *teaching with Xinu* and it is intended to be completed in groups of two or three.

Preparation

A new tar-ball is provided with a solution to the previous assignment. If your solution is similar to the one presented, you may choose to continue on with it; but it is suggested that you untar the new project files in a fresh working directory:

```
tar xvzf
```

Shell Commands

We have a few more protocols within our networking portion of Embedded Xinu. In this assignment we will add shell commands to create useful interaction with those protocols. We will be adding two shell commands: **tcp-con** and **ftp-receive**.

Upon completion of the assignment the students' implementation should have all the required shell commands properly implemented and well tested.

Required Assignment Parts

Shell Command Descriptions

- **tcp-con** establishes a tcp connection with the provided IP address
- **ftp-receive** uses a TCP/IP connection to transfer acquire a file from a provided remote location

Shell Command Options

- **tcp-con**
  - options for: determine whether the connection establishment is active or passive
  - add help option that prints usage
- **ftp-receive**
  - options for: determine whether to use passive or active connection establishment for file transfer
  - add help option that prints usage

Student Outcomes

Upon completion of this assignment students should understand how to implement various shell commands that interact with the underlying network interface. Implementing the shell commands should give the student a better grasp of how the various protocols actually work.

Potential References

- Ethernet Address Resolution Protocol - RFC
- Internet Protocol - RFC
- Internet Control Message Protocol - RFC
- Address Resolution Protocol - Wikipedia
- Internet Protocol - Wikipedia
- Internet Control Message Protocol - Wikipedia

6.10.16 Assignment: Networking Standards

A Standard Way

> The nicest thing about standards is that there are so many of them to choose from.
>
> —Andres S. Tannenbaum

This assignment is part of the *Networking With Xinu* track for professors that are *teaching with Xinu*. Specifically, this assignment will help introduce the student to important networking standards. Since standards are a basis for implementation of the many facets of networking a student should be able to find, read and understand any standard that he or she encounters.

Assignment Notes

- Implementation of the assignment can vary
  - Only reading
  - Reading & Questions
  - Reading & Quiz/Test
- Upon completion of the assignment the student should know how to find standards for networking, be able to read and comprehend these standards, and answer questions about the standards that he or she discovers.

RFC's from IETF.org

- Internet Official Protocol Standards - RFC 5000
- Ethernet Address Resolution Protocol - RFC 826
- Internet Protocol - RFC 791
- Internet Control Message Protocol - RFC 792
- User Datagram Protocol - RFC 768
- Transmission Control Protocol - RFC 793
- Trivial File Transfer Protocol - RFC 1350
- Dynamic Host Configuration Protocol - RFC 2131

6.10.17 Assignment: Packet Demultiplexing

Overview

This assignment is part of the *Networking With Xinu* track for professors that are *teaching with Xinu* and it is intended to be completed in groups of two or three.

Preparation

You will have to familiarize yourself with several common UNIX tools for this assignment. The first of these is **tar**, a utility originally devised to create tape archives for the purpose of backing files up onto computer tapes.

While **tar** is still used to create tape backups of file systems, it has become far more common to use **tar** to group files and/or directories together into a single entity, typically called a "tar-ball." (So common is the use of **tar** that it has been verbed in computer science terminology: We speak of "tarring" files, or files that have been "tarred up.") Tar syntax is somewhat arcane, as **tar** came into existence before modern standards for command-line options.

Change to your working directory and execute the following command. This untars the files into your working directory, if the tar-ball was created properly all the files should go into a subdirectory:

```
tar xvzf
```

For more information on tar, please see the UNIX man pages.

Building

While the **gcc** command-line options provide a great deal of flexibility when compiling programs, things quickly become unmanageable when the number of source files exceeds what you can conveniently type in a few seconds.

The **make** utility can be thought of as a companion to the compiler infrastructure (preprocessor, compiler, assembler, and linker) that allows the build rules for large projects to be explicitly encoded in Makefiles. A Makefile typically consists of common definitions, (such as, which compiler to use), and a set of rules. Each rule has a target, such as the file that is to be built, and can be followed by a list of dependencies and a sequence of steps to perform in order to build that target. In addition, make has quite a few common rules built into it.

You will not have to write your own Makefiles for this course, but you will have to use and possibly modify some for all of our remaining assignments. The Makefile is always human-readable, so feel free to open them up and look around.

To build the Xinu operating system, perform the following steps:

- Change directory into the top level produced by the tar-ball.
- Change directory into the subdirectory "compile". This directory contains the XINU project Makefile, and is where all of the compiled ".o" files will go.
- Execute the the following command:

  ```
  make clean
  ```

- By standard convention, almost all Makefiles include a target called "clean" that removes everything except the source code. The tar-ball you unpacked already should be clean, but it never hurts to make sure that you are starting from a clean slate. You may find yourself using this command often.
- Execute the the following command:

  ```
  make
  ```

This should produce about a page of output as each source file is compiled, and the resulting object files are linked together to form the operating system, a simple set of library functions, and the boot loader. If all goes as it should, you should find the directory full of .o files from all of the source code in the other subdirectories, and most importantly, a newly compiled operating system image called "xinu.boot."

For more information on make, please see the UNIX man pages.

Running

Your Xinu image is now ready to be run on a backend machine. To transfer it there, we have a special utility called mips-console. Execute mips-console in the compile directory where your xinu.boot file resides. Mips-console will connect your terminal to the first available backend machine, and you should see a message like:

```
connection 'xinurouter', class 'mips', host 'xinuserver-hostname'
```

This will be immediately followed by a stream of automated commands as the embedded target system boots, configures its network settings, and uploads your xinu.boot kernel.

The most important thing to remember about mips-console is that it is modal, like vi. You start out in direct connection mode, in which your terminal connects directly through special hardware to the serial console on your backend machine. To get out of mips-console, hit Control-Space, followed by the 'q' key.

Packet Demultiplexing

The packet demultiplexing assignment will have students implement a way for the Embedded Xinu operating system to interact with the ethernet driver, both receiving and sending of packets. Incoming packets should be properly divided up (demultiplexed) and passed along to the next part of the system or stored. Outgoing packets should have the final ethernet header fields filled in before sending it off to the driver.

Assignment Notes

- Implementation can vary based on how the professor intends to grade the assignment
  - Have the students insert print outs of what type of packet is received and print something out when one is sent out
  - Give the students some portion of code so they can pass the packet onward to a piece of the operating system they have yet to write

Student Outcomes

With the completion of the assignment students should understand how demultiplexing works and have knowledge about the complexities of optimizing packet demultiplexing. Students should have a feel for how the Embedded Xinu operating system interacts with the ethernet driver and understand that initial/final crucial step for network communication.

6.10.18 Assignment: Parser

Overview

In this project students use JavaCC to implement the scanner and parser rules for our Concurrent MiniJava language.

Notes

Concurrent MiniJava requires that *Xinu*, *Thread*, *run*, and *synchronized* be added as reserved words for the Scanner and Parser. The external call productions must keep track of the name of the *Xinu* method being called.

Also, since our modified language allows programmers to declare classes which extend the *Thread* class without ever actually declaring a *Thread* class, the compiler must be informed implicitly that there exists a *Thread* class. To avoid the complexity of making the compiler aware of the entire Java *Thread* class, the Parser can automatically generate an Abstract Syntax Tree (AST) node for a *Thread* class with an empty *run* method. This ensures there are no runtime errors when the external call *Xinu.threadCreate* calls the *run* method of a class which extends *Thread* but does not override the *run* method. To do this, class declarations which extend *Thread* are handled by the additional *ThreadClassDeclaration* production in our modified grammar.

Further changes must be made to account for the declaration of the *run* method since *void* return types are not allowed in MiniJava, except in the special case of the main method declaration. To handle this, we add a *RunMethodDeclaration* production to our modified grammar.

To support the *synchronized* keyword the AST node for method declarations needs a new field to keep track of whether a method is synchronized or not.

6.10.19 Assignment: Preemption and Synchronization

This assignment is a Xinu assignment allowing the student to grow a more firm understanding of how an operating system works. This assignment is part of the *Student Built Xinu* track for professors that are *teaching with Xinu*. Written answers to the five analysis questions below should be put into a file called `system/README` and submitted with your code. The entire directory containing the operating system should be turned in during the submission process.

After completion of this assignment we will have a basic operating system with preemptive, priority scheduling of processes, and counting semaphores with wait queues as synchronization primitives. Explore how the system behaves with various numbers of producers and consumers at different levels of priority and with both blocking and non-blocking signals. You will be responsible for making predictions about how such a system behaves in subsequent projects. As an added challenge, you might like to try implementing some of the other classic synchronization problems outlined in the textbook.

Preparation

First, make a fresh copy of your work thus far:

```
cp -R
```

Untar the new project files on top of this new directory:

```
tar xvzf
```

You should now see the new project files in with your old files. Be certain to make clean before compiling for the first time.

Preemption

The new files `system/clock*` (as well as some adjustments to various loader configuration files) will provide you with basic preemption, as discussed in class. Take time to familiarize yourself with the contents of these files, as you will be responsible for understanding how these components of the operating system work.

How can you test that preemption is working in your system? Create a main program that demonstrates preemptive scheduling. Call it `main-preempt.c`, and make sure that it works when copied over `main.c`.

Atomicity

In a system with preemption, we must now guard against being interrupted while in the middle of an atomic operation. There are many points in operating system code where an unfortunately timed interrupt could leave the system in an inconsistent state.

For example, in the `resched()` function, there are several lines of C code (which translate into many more lines of machine code,) between the point where the outgoing running process is put back into the queue of ready processes and the point where an incoming process is dequeued and set to running. If an interrupt were to take place in the midst of this transition, the interrupt handling code might see the system in an inconsistent state, in which there doesn't seem to be a currently running process. For this reason, we consider process rescheduling to be atomic with respect to the rest of the operating system. The easiest way to enforce this is to temporarily disable interrupts during a critical, atomic section of code, and then reenable them when done.

The new file `system/intr.S` contains functions `enable()`, `disable()`, and `restore()` for manipulating the master bit that enables processor interrupts. From this point forward, these functions must be used judiciously to guard atomic sections in the operating system functions you write.

Semaphores

Implement classic semaphores with waiting queues. A definition of the basic semaphore structure is given in `include/semaphore.h`, and is initialized in the new `system/initialize.c`.

Fill in the functions in `system/newsem.c`, `system/signal.c` and `system/wait.c`. A simple `main.c` is given that implements a trivial case of the Producers/Consumers Problem.

Analysis

- Create a main program that spawns multiple producer processes (each producing a distinctive character output) and multiple consumer processes. What happens, and why? (Put your answers in `system/README`.) Save this test case as `system/main-q1.c`.
- Using the same test case as in the previous question, briefly adjust the value of the preemption counter ("QUANTUM" in `include/clock.h`) to be 100 mS. How does this change the output? (Put your answers in `system/README`.)
- Create a test case `system/main-q3.c` in which the consumer processes are all of a higher priority than the producer processes. Repeat the first two questions.
- In the comment blocks for `system/signal.c`, you were directed to reschedule after taking a waiting process off of the semaphore's wait queue. What happens if you call only `ready()` when taking a process off of the wait queue, and do not voluntarily yield at that time? (This is called non-blocking or non-yielding `signal()`.) Repeat the first three questions with non-blocking `signal()`.
- One of the interesting things about the classic Producer/Consumer problem is how finely balanced the solution turns out to be. A variety of simple one-line swaps in either the producer code or the consumer code can produce a system of processes that readily deadlocks. Find one of these combinations, and save it as `system/main-q5.c`

6.10.20 Assignment: Priority Scheduling and Process Termination

This assignment is a Xinu assignment allowing the student to grow a more firm understanding of how the basics of an operating system work. This assignment is part of the *Student Built Xinu* track for professors that are *teaching with Xinu*. This assignment should be completed in teams of two. Students should only turn in the files required

for this assignment: `system/create.c`, `system/ctxsw.S`, and a `README` file, as explained below. The entire directory containing the operating system should be turned in during the submission process.

Preparation

First, make a fresh copy of your work thus far:

```
cp -R
```

Untar the new project files on top of this new directory:

```
tar xvzf
```

You should now see the new project files in with your old files. Be certain to make clean before compiling for the first time.

Priority Scheduling

Add priority scheduling to your operating system. This can be done in 5 easy steps:

- Add a priority field into PCB structure defined in `include/proc.h`.
- Add an effective priority field "`key`" into the process queue structure defined in `include/queue.h`. This effective priority field will be used as a key to sort the queue.
- Add priority parameter to `create()`, and properly initialize the priority field in each new PCB created.
- Build a new function in `system/prioritize.c` to implement a priority sorted ready queue. This does not require making any modifications to the primary queue maintenance functions already in `system/queue.c`. Add your new source file in `compile/Makefile`.
- Modify the `ready()` and `resched()` functions to properly use your new priority scheduler.

New testcases are in `system/main.c`, which should demonstrate priority-order execution once your new scheduler is operational. You will need to create others to fully test your implementation.

Starvation and Aging

One of the chief drawbacks to simple priority scheduling is that low priority processes may be *starved* by high priority processes, that is, they may never get to run at all. One remedy for this it to implement aging, a scheme in which the effective priority of a process increases the longer it sits in the ready list without running.

Add a kernel configuration parameter "`AGING`" into `include/kernel.h` that when `TRUE` causes the effective priority of each process in the ready list to increase by one every time `resched()` is called.

Construct a test case that demonstrates process starvation when `AGING` is `FALSE`, but demonstrates aging when `AGING` is set to `TRUE`. Call your test case function main-starve, and put it in your `main.c`.

Preemption

The new files `system/clock*` (as well as some adjustments to various loader configuration files) will provide you with basic preemption, as discussed in class. Take time to familiarize yourself with the contents of these files, as you will be responsible for understanding how these components of the operating system work.

Activate preemption by changing the `PREEMPT` constant in `include/kernel.h` to `TRUE`. How can you test that preemption is working in your system? Create a main program called `main-preempt` that demonstrates preemptive scheduling. Add it to `main.c`.

Notes

- To submit your project, please run "`make clean`" in your compile directory, change directory back two levels, and submit the entire system via the professor's turn in instructions.
- To complete this assignment, you will have made changes to several header files in the `include/` directory, and half the .c files in the `system/` directory.
- Your professor may set up groups to allow easier collaboration between partners. If groups have been provided the permissions on your files should be modified to allow access to the group that includes both you and your partner.
- When collaborating on a project in a shared directory, good software practice entails revision control, a few options include Subversion, CVS, and RCS. Using a revision control system can be very helpful and times, so you may wish to determine which systems are available in your lab.

6.10.21 Assignment: Priority Scheduling and Process Termination

This assignment is a Xinu assignment allowing the student to grow a more firm understanding of how the basics of an operating system work. This assignment is part of the *Student Built Xinu* track for professors that are *teaching with Xinu*. This assignment should be completed in teams of two. Students should only turn in the files required for this assignment: `system/create.c`, `system/ctxsw.S`, and a `README` file, as explained below. The entire directory containing the operating system should be turned in during the submission process.

Preparation

First, make a fresh copy of your work thus far:

```
cp -R
```

Untar the new project files on top of this new directory:

```
tar xvzf
```

You should now see the new project files in with your old files. Be certain to make clean before compiling for the first time.

Priority Scheduling

Add priority scheduling to your operating system. This can be done in 5 easy steps:

- Add a priority field into PCB structure defined in `include/proc.h`.
- Add an effective priority field into the process queue structure defined in `include/queue.h`. This effective priority field will be used as a key to sort the queue.
- Add priority parameter to `create()`, and properly initialize the priority field in each new PCB created.
- Complete the new function in `system/insert.c` to implement a priority sorted ready queue. This does not require making any modifications to the primary queue maintenance functions already in `system/queue.c`.
- Modify the `ready()` and `resched()` functions to properly use your new priority scheduler.

New testcases are in `system/main.c`, which should demonstrate priority-order execution once your new scheduler is operational. You will need to create others to fully test your implementation.

Starvation and Aging

One of the chief drawbacks to simple priority scheduling is that low priority processes may be *starved* by high priority processes, that is, they may never get to run at all. One remedy for this it to implement *aging*, a scheme in which the effective priority of a process increases the longer it sits in the ready list without running.

Add a kernel configuration parameter "AGING" into `include/kernel.h` that when `TRUE` causes the effective priority of each process in the ready list to increase by one every time `resched()` is called.

Construct a testcase that demonstrates process starvation when `AGING` is `FALSE`, but demonstrates aging when `AGING` is set to `TRUE`. Turn this testcase in as your `main.c`.

Notes

- To submit your project, please run "`make clean`" in your compile directory, change directory back two levels, and submit the entire system via the professor's turn in instructions.
- To complete this assignment, you will have made changes to several header files in the `include/` directory, and half the .c files in the `system/` directory.
- Your professor may set up groups to allow easier collaboration between partners. If groups have been provided the permissions on your files should be modified to allow access to the group that includes both you and your partner.
- When collaborating on a project in a shared directory, good software practice entails revision control, a few options include Subversion, CVS, and RCS. Using a revision control system can be very helpful and times, so you may wish to determine which systems are available in your lab.

6.10.22 Assignment: Scanner

Overview

In this project students build the first step of a full compiler by implementing a Scanner for our Concurrent MiniJava language.

Notes

Our modifications to MiniJava require the addition of the *Xinu*, *Thread*, and *run* reserved words.

6.10.23 Assignment: Semantic Analysis

Overview

In this project students implement a semantic analysis (type checking) pass for our Concurrent MiniJava language.

Notes

Our modifications to MiniJava require an additional step for initializing the class and type environments. The class environment must be initialized with a type-descriptor containing each of the method types in class *Xinu*, and the type environment must be initialized with a binding of identifier *Xinu* to this class type. With this, the type checker can verify that external calls are programmed properly and also verify that only external calls which the compiler knows how to map to the underlying runtime are being used in the program.

6.10.24 Assignment: Synchronization and Interprocess Communication

> Neither snow nor rain nor heat nor gloom of night stays these couriers from the swift completion of their appointed rounds.
>
> — USPS Unofficial Slogan

This assignment is a Xinu assignment allowing the student to grow a more firm understanding of how an operating system works. This assignment is part of the *Student Built Xinu* track for professors that are *teaching with Xinu*. Written answers to the analysis questions should be put into a file called `system/ANALYSIS.txt` and submitted with the code. The entire directory containing the operating system should be turned in during the submission process.

After completion of this assignment we will have a basic operating system with preemptive, priority scheduling of processes, and counting semaphores with wait queues as synchronization primitives and mailboxes for interprocess communication.

Atomicity

In a system with preemption, we must now guard against being interrupted while in the middle of an atomic operation. There are many points in operating system code where an unfortunately timed interrupt could leave the system in an inconsistent state.

For example, in the `resched()` function, there are several lines of C code (which translate into many more lines of machine code) between the point where the outgoing running process is put back into the queue of ready processes and the point where an incoming process is dequeued and set to running. If an interrupt were to take place in the midst of this transition, the interrupt handling code might see the system in an inconsistent state, in which there doesn't seem to be a currently running process. For this reason, we consider process rescheduling to be atomic with respect to the rest of the operating system. The easiest way to enforce this is to temporarily disable interrupts during a critical, atomic section of code, and then reenable them when done.

The new file `system/intr.S` contains functions `enable()`, `disable()`, and `restore()` for manipulating the master bit that enables processor interrupts. From this point forward, these functions must be used judiciously to guard atomic sections in the operating system functions you write.

Preparation

First, make a fresh copy of your work thus far:

```
cp -R
```

Untar the new project files on top of this new directory:

```
tar xvzf
```

You should now see the new project files in with your old files. Be certain to make clean before compiling for the first time.

Semaphores

With this assignment you must learn about and understand classic semaphores before using them to implement the remainder of the assignment. An implementation of classic semaphores with waiting queues has been provided for you. Please examine and understand the implementation which can be found across several files including `include/semaphore.h`, `system/newsem.c`, `system/signal.c` and `system/wait.c`. As part of the analysis portion of this assignment, you will need to write a main file to show your understanding of semaphores.

Mailboxes

Using the provided semaphore structure, implement mailboxes as a means for interprocess communication. A structure outlining mailboxes can be found in `include/mailbox.h`.

For completion of this assignment, your operating system should have a fully functioning mailbox system for interprocess communication. The files for the mailbox system can be found in the mailbox directory, including `mailbox/mailboxAlloc.c`, `mailbox/mailboxFree.c`, `mailbox/mailboxInit.c`, `mailbox/mailboxReceive.c` and `mailbox/mailboxSend.c`.

Analysis

For the analysis portion of this assignment, you will write two main files to show your understanding of the operating system. Previously, you would copy and paste your code over the given `system/main.c` to run it. From this point on, you should add the test files to your Makefile (`compile/Makefile`) to allow them to compile. Then, in `system/initialize.c`, edit the process created when the system is initialized to use the test function instead of `main()`.

- Create a simple `main` program, with function called `main-hw6-q1`, that has multiple processes that use a mutex locking semaphore to alter a shared resource. This program should be saved as `system/main-hw6-q1.c` and should run properly when `system/initialize.c` is altered to `create()` a process for `main-hw6-q1()` instead of `main()`.
- Create another `main` program called `main-hw6-q2()`, that uses mailboxes for effective interprocess communication. This program should be saved as `system/main-hw6-q2.c` and should run properly when `system/initialize.c` is altered to `create()` a process for `main-hw6-q2()` instead of `main()`.
- Give a situation in which mailboxes could be used to model a real-world problem; store your answer as Q3 in `system/ANALYSIS.txt`.
- Give a situation that will deadlock the system using your mailbox implementation. Why does it deadlock? What additional things might be added to the mailbox system or the operating system in general to fix this deadlock situation? Store your answers as Q4 in `system/ANALYSIS.txt`.

6.10.25 Assignment: Synchronous Serial Driver

Overview

This assignment is intended to develop the student's proficiency for programming in C. This assignment is part of the *Student Built Xinu* track for professors that are *teaching with Xinu*. This assignment should be completed in teams of two.

Preparation

You will have to familiarize yourself with several common UNIX tools for this assignment. The first of these is **tar**, a utility originally devised to create tape archives for the purpose of backing files up onto computer tapes.

While **tar** is still used to create tape backups of file systems, it has become far more common to use **tar** to group files and/or directories together into a single entity, typically called a "tar-ball." (So common is the use of **tar** that it has been verbed in computer science terminology: We speak of "tarring" files, or files that have been "tarred up.") Tar syntax is somewhat arcane, as **tar** came into existence before modern standards for command-line options.

Change to your working directory and execute the following command. This untars the files into your working directory, if the tar-ball was created properly all the files should go into a subdirectory:

```
tar xvzf
```

For more information on **tar**, please see the UNIX man pages.

Building

While the gcc command-line options provide a great deal of flexibility when compiling programs, things quickly become unmanageable when the number of source files exceeds what you can conveniently type in a few seconds.

The **make** utility can be thought of as a companion to the compiler infrastructure (preprocessor, compiler, assembler, and linker) that allows the build rules for large projects to be explicitly encoded in Makefiles. A Makefile typically consists of common definitions, (such as, which compiler to use), and a set of rules. Each rule has a target, such as the file that is to be built, and can be followed by a list of dependencies and a sequence of steps to perform in order to build that target. In addition, **make** has quite a few common rules built into it.

You will not have to write your own Makefiles for this course, but you will have to use and possibly modify some for all of our remaining assignments. The Makefile is always human-readable, so feel free to open them up and look around.

To build the Xinu operating system, perform the following steps:

- Change directory into the top level produced by the tar-ball.
- Change directory into the subdirectory "compile". This directory contains the XINU project Makefile, and is where all of the compiled ".o" files will go.
- Execute the the following command:

  ```
  make clean
  ```

- By standard convention, almost all Makefiles include a target called "clean" that removes everything except the source code. The tar-ball you unpacked already should be clean, but it never hurts to make sure that you are starting from a clean slate. You may find yourself using this command often.
- Execute the the following command:

  ```
  make
  ```

This should produce about a page of output as each source file is compiled, and the resulting object files are linked together to form the operating system, a simple set of library functions, and the boot loader. If all goes as it should, you should find the directory full of .o files from all of the source code in the other subdirectories, and most importantly, a newly compiled operating system image called "xinu.boot."

For more information on **make**, please see the UNIX man pages.

Running

Your Xinu image is now ready to be run on a backend machine. To transfer it there, we have a special utility called mips-console. Execute mips-console in the compile directory where your xinu.boot file resides. Mips-console will connect your terminal to the first available backend machine, and you should see a message like:

```
connection 'xinurouter', class 'mips', host 'xinuserver-hostname'
```

This will be immediately followed by a stream of automated commands as the embedded target system boots, configures its network settings, and uploads your xinu.boot kernel.

The most important thing to remember about mips-console is that it is modal, like vi. You start out in direct connection mode, in which your terminal connects directly through special hardware to the serial console on your backend machine. To get out of mips-console, hit Control-Space, followed by the 'q' key.

Embedded Xinu Source

The source tar-ball we are starting with contains only a few files for the operating system proper, in the subdirectory system. We will be adding files into this directory in every subsequent assignment. The other files in the XINU subdirectories break down as follows:

- `compile/` contains the compilation files for XINU.
- `include/` contains all of our local .h header files used throughout the rest of the source code files. At compile time, these are treated as being in a standard location, so they can be included with "#include<...>" rather than "#include"..."". The header file particularly important for this assignment is `include/uart.h`, which contains the structure and constants for the serial port hardware.
- `lib/` contains a small library of standard C functions we can rely upon in the operating system, like `strcmp()` and `atoi()`, etc. Remember – the UNIX system libraries are not available to our operating system running on the backend!
- `loader/` contains the files for the Mips Xinu boot loader, which clears the processor data caches, identifies the processor type, and then passes control to the operating system startup code in the system subdirectory.

Synchronous Serial Driver

Your task for this assignment is to write a simple synchronous serial driver for the embedded operating system, so that you can see what you are doing in all subsequent assignments.

The driver is "synchronous" because it waits for the slow I/O device to do its work, rather than using interrupts to communicate with the hardware. We will write the interrupt-driven, "asynchronous" version of the driver later in the term.

The driver is "serial" because it sends characters one at a time down an RS-232 serial port interface, like the one found on most modern PC's.

The driver is a "driver" because it provides the software interface necessary for the operating system to talk to a hardware I/O device.

This platform's serial port, or UART (Universal Asynchronous Receiver / Transmitter) is a member of the venerable 16550 family of UARTs, documented in the UART Specification. Of particular interest to us is section 8 of the specification, starting on page 14, which describes the registers accessible to programmers. The UART control and status registers are memory-mapped, starting with base address 0xB8000300.

The file `system/kprintf.c` has the skeleton code for four I/O-related functions: kputc(), (puts a single character to the serial port,) kgetc(), (gets a single character from the serial port) kungetc(), (puts "back" a single character) and kcheckc() (checks whether a character is available). Each function contains a "TODO" comment where you should add code. The actual kprintf() is already complete, and will begin working as soon as you complete the kputc() function it relies upon.

6.10.26 Assignment: TCP Implementation

Overview

This assignment is part of the *Networking with Xinu* track for professors that are *teaching with Xinu* and it is intended to be completed in groups of two or three.

Preparation

A new tar-ball is provided with a solution to the previous assignment. If your solution is similar to the one presented, you may choose to continue on with it; but it is suggested that you untar the new project files in a fresh working directory:

```
tar xvzf
```

Transmission Control Protocol

Standard number 7 of the Internet Official Protocol Standards is the Transmission Control Protocol. In this assignment students will build the Transmission Control Protocol into Embedded Xinu by defining a stream device that uses Embedded Xinu device paradigm.

Upon completion of the assignment the students' implementation should:

Required Assignment Parts

- send and receive packets of with type TCP
- determine the status of a specific datagram device and place desired data in its stream buffer if applicable

Optional Assignment Parts

- shell integration: add a **tcp-con** command to the shell (establishes an active or passive TCP connection)

If you choose not to implement the optional assignment parts then placing test case code within the shell's **test** command will allow you to run one or more tests on your implementation at run-time. Optional portions to an assignment may be required portions of a later assignment.

Student Outcomes

Upon completion of this assignment students should understand the key role this protocol plays in the overall networking architecture. Each student should also be able to understand how streams as devices fit into the operating system and the overall networking architecture.

Potential References

- Transmission Control Protocol - RFC 793
- Transmission Control Protocol - Wikipedia

6.10.27 Assignment: Translation

Overview

In this project students implement a translator that takes the Abstract Syntax Tree (AST) output from the semantic analysis pass in *Project 4* and converts it into an Intermediate Representation (IR) tree.

Notes

The AST representations of the Xinu external calls must be mapped to IR nodes that reference the corresponding underlying runtime functions. Care must be taken at this point to choose runtime function names that will not conflict with legitimate source language method names; we follow longstanding tradition and append an underscore to the runtime function names. The mapping of I/O and threading functions is self-explanatory, but also at this point we need to add in a dynamic memory allocation function to support the source language *new* operator for instantiating new objects and arrays. In addition, if the compiler is to support Java-like runtime checking for null pointers and array bounds, corresponding runtime error handlers must be mapped. The figure below gives a brief description of each part of the MiniJava to Xinu Compatability Layer, but the *full C file* is also available.

Changes must also be made to support the *synchronized* key word. First *monitors* must be added to Xinu. The *new* function in the compatibility layer must acquire a monitor from the O/S and associate it with the new object. Also, `lock()` and `unlock()` functions must be added to the compatibility layer which map to the monitor `lock()` and `unlock()` functions added to Xinu. To achieve Java-like thread synchronization the compiler must wrap synchronized method bodies with calls to the compatibility functions `lock()` and `unlock()`. It is important that the compiler ensures that the `lock()` action precedes the evaluation of *any* part of the method body including evaluation of the right hand side of local variable declarations. Similarly, the `unlock()` action must come after *any* part of the method body including the evaluation of the return expression.

MiniJava to Xinu Compatibility Layer

Xinu function	Purpose
`int _readint(void)`	Parse in integer input
`syscall _printint(int i)`	Print an integer
`syscall _print(char *s)`	Print a string literal
`syscall _println(void)`	Print a carriage return
`syscall _threadCreate(int *t)`	Spawn a new thread of execution, running t's `run` method
`syscall _yield(void)`	Yield the processor
`syscall _sleep(int time)`	Sleep `time` number of milliseconds
`syscall _lock(int *obj)`	Lock the monitor associated with object `obj`
`syscall _unlock(int *obj)`	Unlock the monitor associated with object `obj`
`int *_new(int n, int f)`	Allocate array or allocate object and associate a monitor with that object
`void _BADPTR(void)`	Null pointer exception
`void _BADSUB(void)`	Bounds exception

Xinu Compatability Layer

The full C source code for the Xinu Compatibility Layer can be found in system/minijava.c.

6.10.28 Assignment: UDP Implementation

Overview

This assignment is part of the *Networking with Xinu* track for professors that are *teaching with Xinu* and it is intended to be completed in groups of two or three.

Preparation

A new tar-ball is provided with a solution to the previous assignment. If your solution is similar to the one presented, you may choose to continue on with it; but it is suggested that you untar the new project files in a fresh working

directory:

```
tar xvzf
```

User Datagram Protocol

Standard number 6 of the Internet Official Protocol Standards is the User Datagram Protocol. In this assignment students will build the User Datagram Protocol into Embedded Xinu by defining a datagram device that uses Embedded Xinu device paradigm.

Upon completion of the assignment the students' implementation should:

Required Assignment Parts

- send and receive packets of with type UDP
- determine the status of a specific datagram device and place desired datagram in buffer if applicable

Optional Assignment Parts

- shell integration: add a **traceroute** command to the shell (sending out proper UDP packets)

If you choose not to implement the optional assignment parts then placing test case code within the shell's **test** command will allow you to run one or more tests on your implementation at run-time. Optional portions to an assignment may be required portions of a later assignment.

Student Outcomes

Upon completion of this assignment students should understand the key role this protocol plays in the overall networking architecture. Each student should also be able to understand how datagrams as devices fit into the operating system and the overall networking architecture.

Potential References

- User Datagram Protocol - RFC 768
- User Datagram Protocol - Wiki Page

6.10.29 Assignment: Ultra-Tiny File System

This assignment is a Xinu assignment allowing the student to more firmly understand how an operating system works. This assignment is part of the *Student Built Xinu* track for professors that are *teaching with Xinu*. The entire working directory containing your Xinu operating system will be submission for this assignment.

Preparation

First, make a fresh copy of your work thus far:

```
cp -R
```

Untar the new project files on top of this new directory:

```
tar xvzf
```

You should now see the new project files in with your old files. Be certain to `make clean` before compiling for the first time.

Non-blocking ttyRead()

To synchronize complex communications properly, it often helps to be able to "peek" at an I/O device without having to block. Add non-blocking read as an option to your TTY driver. Use the `iflags` field (which should be fetched or set with the `ttyControl()` function). Your `ttyRead()` function should check the flags and the count of the input semaphore before each call to `wait()`. If it looks like the call might block, return the current count of characters instead.

The Disk Driver

The project tarball equips Xinu with a block I/O device driver (running over the second serial port) that speaks to a `xinu-disk` program running on your computer. The `xinu-disk` process maps reading and writing requests from the backend to a locally-stored disk file. In this way, your O/S can behave as though it has a small (64K) disk attached, and the storage is really a file in your home directory.

See below for additional details on the `xinu-disk` command.

The File System

The project tarball includes a partial implementation of a small file system. The first block of the "disk" is expected to contain a **superblock** which contains vital bookkeeping information about the file system, such as:

- A pointer to a list of free disk blocks,
- A pointer to a master directory index,
- Block size, disk size, etc., and
- A magic number, so that it can tell the difference between a blank disk and an initialized disk image.

The new header files `disk.h` and `file.h` contain the necessary constants and structures to build the file system. Take a look at `disk/disk*.c` (disk driver source code,) `file/file*.c` (file source code,) and `file/sb*.c` (superblock source code.)

Our disk has 256 blocks of 256 bytes each. The free disk block list is dynamic, but our directory index is limited to a fixed number of files, with fixed length names, and fixed maximum sizes. (The problems and solutions associated with these limitations would each make excellent final exam questions, by the way.)

You are to add file deletion (`fileDelete()`) and free block removal (`sbFreeBlock()`) into the system.

Testing

Provide a main program that demonstrates that your `fileDelete()` and `sbFreeBlock()` calls are working properly.

The command **xinu-disk** starts up a disk daemon on the local server that can provide disk access to the selected backend machine via its second serial port. Build the disk daemon by running `make xinu-disk` in your `compile/` directory. For example, to test my file system on backend "Dask" using a local disk image called "foo.dat", I would run the command `mips-console dask` in one terminal, and then execute `./xinu-disk foo.dat dask2` in a second terminal within the first ten seconds of my Xinu kernel booting.

Xinu-disk's ability to synchronize with a "moving-target" backend is somewhat rudimentary – you may occasionally see the handshake fail upon startup. Just close out the `mips-console` session normally, close the `xinu-disk` process with a "Control-C", and try again.

The command `xinu-status` will list the users on each backend, and `xinu-status -c uart` will list the users on each backend's second serial port. Also recall that a user can bump another user off of a specific backend after 10 minutes of activity.

The pages linked to here help an instructor understand how to incorporate Embedded Xinu into a course for his or her department's curriculum. Each of the models is based on an existing course that has been run at Marquette or one of our partner schools.

6.11 Operating Systems Tracks

6.11.1 Student Built Xinu

Main article: Student Built Xinu

A student built operating system puts the student in the trenches of operating system development. The student will become intimately involved with the inner workings of an operating system. This will give the student a better understanding of the various systems that work together behind the scenes while an operating system is running. Operating systems topics that can be incorporated in a student built Xinu course include: memory management, scheduling, concurrent processing, device management, file systems and others.

6.11.2 Student Extended Xinu

Main article: Student Extended Xinu

Students will learn to extend an operating system by adding kernel level and user level applications. Given a functional Embedded Xinu operating system the students will have to understand and manipulate existing operating system code to create additional operating system features. To add more applications to the operating system students will have to understand the interactions between the program in design and the operating system's device and kernel interaction calls. Programming for embedded devices allows students to engage in development on small resource constrained environments. Through extending the existing Embedded Xinu operating system a student learns to use and understand code not written by the student and develops advanced operating system concepts.

6.12 Networking

6.12.1 Networking With Xinu

Main article: Networking with Xinu

A networking course incorporating Embedded Xinu can have students build networking functionality into Embedded Xinu over the period of the course. Courses may vary in starting point; some choosing to use a core Embedded Xinu release and having students build the entire network stack and ethernet driver. While others may choose an Embedded Xinu release with the ethernet driver available so that the students can concentrate on other parts of the network stack. Network stack implementation assignments for students can parallel various networking lectures that traverse the stack over the course of the semester, terminating in the students implementing an application that uses the developed network stack.

6.13 Compilers

6.13.1 Compiler Construction With Embedded Xinu

Main article: Compiler Construction With Embedded Xinu

Including Embedded Xinu in a compiler construction course allows students to explore the compilation of high level language constructs that rely on interacting with the underlying runtime. Many traditional compilers courses simply target a processor or simulator, but by targeting a *platform* (a processor and operating system combination) one can extend the source language to include more advanced language features such as I/O operations and thread creation, manipulation, and concurrency. This also allows students to run their test cases on real hardware and see these programs actually interacting with a real runtime. In modern programming these high level language features are vital, and it is important for students to see what the processor and runtime are doing when they use these features in their own programs.

6.14 Building a Backend Pool

Regardless of the exact instructional model chosen, the instructor may wish to set up a classroom or laboratory setting enabling easy modification and use of Embedded Xinu. More information can be found in *Building an Embedded Xinu laboratory*.

6.15 Workshops

Workshops have been held regarding teaching with Embedded Xinu. For example, the Teaching With Embedded Xinu Workshop at ACMSE 2010 in Oxford, Mississippi (Ole Miss campus) shared ready-made curriculum resources that have been used successfully to teach hardware systems, operating systems, realtime/embedded systems, networking, and compilers with the Embedded Xinu platform at several colleges/universities.

6.16 Acknowledgements

This work funded in part by NSF grant DUE-CCLI-0737476.

CHAPTER 7

Projects

These are some of the student projects that have used Embedded Xinu. For some, the contribution is included in the official Embedded Xinu distribution itself.

7.1 Curses

:wikipedia‘Ncurses‘ is a programming library API for implementing text user interfaces. Currently, XINU’s interface for output is limited to sequential lines of output using the *TTY driver* and *serial driver*. The addition of an ncurses library in XINU would allow for more advanced text based interfaces.

7.1.1 Why it is called curses

Ncurses is designed to be a terminal independent API for text based interfaces. This terminal independence requires a multi-layered internal implementation of the ncurses library. Adding the actual ncurses implementation into XINU would double the size of XINU boot image. Also, the standard ncurses implementation is highly complex, a contrast to XINU’s clean code base. XINU only has one terminal so the additional complexity of terminal independence is unnecessary for XINU. Therefore, attempts are being made to implement a clean ncurses library for XINU.

Starting from the original curses library is fairly straight forward. However, original curses does not provide color, text formatting, or other “cool” features that would make a text based interface for XINU worthwhile. Instead, the ncurses API, which includes these additional features, must be implemented for XINU. The ncurses API is much more complex. For example, multiple functions add characters to the screen: `addch`, `waddch`, and `mvaddch`, `mvwaddch`. The main function is `waddch`, while the other three are macroed to move the cursor or specifing a specific window to which the character should be added.

7.1.2 Major aspects

Refresh

Refreshing the terminal to display the desired output is the most crucial aspect of the curses library.

Display output

Format output

The curses library can change colors and text decoration (bold, underline, etc.) to provide output other than plain text.

Receive input

7.1.3 Resources

- Strang, John. *Programming with curses*. Sebastopol, CA: O'Reilly, 1986.
- Gookin, Dan. *Programmer's Guide to nCurses*. Indianapolis: Wiley, 2007.
- Announcing ncurses 5.6

7.2 WinX

7.2.1 About WinX

WinX was the working name of WinXINU while it was in the development stages.

Working in coordination with Dr. Dennis Brylow a senior design project was set up to create a piece of software to allow the direct inclusion of Windows based computers in the development and testing of XINU operating systems. The goal is to create a front end program that has all the functionally of current shell based front end tied into a graphical user interface. The project codename, WinX, was installed at the beginning of the implementation phase; ultimately the software may be released under a different name for various legal reasons.

- Working Objective Statement
  - Design and implement a Windows program to allow Windows-based computers to participate directly in the MSCS Systems Lab for remote testing and execution of embedded operating system kernels by 28 April 2008 at a cost of $0.
- Current developers include:
  - Adam Koehler
  - Nicholas McMillan
  - Matthew Thomson
  - Christopher Swiderski

7.2.2 Phases of WinX

- Design
  - The design phase spanned the whole first academic semester starting in September 2007 and ending in December 2007.
- Implementation
  - The implementation stage will span the whole second academic semester starting in January 2008 and ending in late April 2008.
- Major Implemenation Phases
  - Internal: January - Alpha Stage (Completed)
  - Alpha: March 12, 2008 (Completed)
  - Beta: [STRIKEOUT:April 9, 2008] April 16, 2008 (Active)
  - Live: April 28, 2008

7.2.3 WinX Development

WinX implementation is an ongoing process and members of the software development team can access the subversion repository at http://xinu.mscs.mu.edu/svn/winx/ to view the current status of the software.

7.2.4 WinXINU Testing

The team has uploaded several files for external beta testing of WinXINU.

- Step 1: Copy the WinXINU-Installer folder via SSH to your desktop: web location ~ http://www.mscs.mu.edu/~nmcmilla/WinXINU-Installer/
- Step 2: Go into Cygwin Install Folder
  - 2a) Run Setup.exe
  - 2b) Select Install from Local - Folder is the only other folder in the Cygwin Install directory
  - 2c) Click ALL to set it to Uninstall all packages its at top of package selection screen
  - 2d) Click Devel package to set it to Install it is found within in the package listings
- Step 3: Change the first line of the compiler/makeVars file (found in your XINU code directory) to the location of the WinXINU cross compiler bin

```
  Example:

MIPS_ROOT = "C:\Documents and Settings\nmcmilla\Desktop\winx\compiler\cross\bin"
```

- Step 4: Run WinXINU executable
- Step 5: Navigate to config tab, change location of cygwin\bin to location on local machine
- Step 6: Navigate to config tab, change location of compile directory where the Makefile is located for final image build

7.2.5 WinXINU Testing Feedback

```
  Use a structure similar to the following:
   *name
   **Error/Comment Title
   ***Description of error/comment
```

---

mschul

- Improve cygwin installation process.
  - (Didn't work very well on a computer that had already been setup.) - Outside scope, no its not
  - Get rid of stuff in devel package that is unnecessary

compile pane

- [STRIKEOUT:I should be able to click 'make' or 'make clean' whenever a damn well feel like.] **Fixed: 4/19/08 by cswiders**
  - [STRIKEOUT:and there should be a mechanism for making other targets as well.] - Outside scope
- [STRIKEOUT:Implement 'Errors and Warnings' checkbox.] **Fixed: 4/19/08 by cswiders**

xinu-status

- Perhaps only query morbius at most once per second (disabling the 'update now' button for a second)

xinu interaction

- [STRIKEOUT:Connect to backend, select mips-console, program complains and goes on anyway. No good.] **Fixed: 4/21/08 by nmcmilla** - Checks whether connected to backend or not, if connected, continues with process, if not, then runs normally.
- [STRIKEOUT:Run 'testsuite' and compare output to linux version (ignoring the VT100 thing).] **Fixed: 4/16/08 by akoehler**
  - [STRIKEOUT:also typing a single \ should produce a single slash. Not typing \\ to produce] **Fixed: 4/22/08 by akoehler**
- [STRIKEOUT:Verify *ALL* control characters are not printed.] **Fixed: 4/16/08 by akoehler**
- [STRIKEOUT:Is there any way that hitting backspace won't jump to the top and back down?]
- [STRIKEOUT:Something with 'mips-console' and xinu just going, seems...odd.]
  - [STRIKEOUT:if the download fails it still keeps on a truckin'.] **Fixed: 4/22/08 by akoehler**
- [STRIKEOUT:Continue session doesn't continue session until a client side character is typed.] ''Fixed: 4/22/08 by nmcmilla ''
  - [STRIKEOUT:Also, I can backspace over previous characters after typing ctrl-space.] ''Fixed: 4/22/08 by nmcmilla ''
  - [STRIKEOUT:Perhaps, ctrl-space should also be the continue code (once will pause, twice will continue).] ''Fixed: 4/22/08 by nmcmilla ''
- [STRIKEOUT:Clear history in the interaction tabs (or even have a value to specify lines of scrollback).] **Fixed: 4/18/08 by akoehler**
- [STRIKEOUT:xsh$ clear (makes WinX go boom).] **Fixed: 4/16/08 by akoehler**
- 'Command request timed out' ... clearly it did not.

serial port 2

- [STRIKEOUT:Should have option to connect to same backend2 name as serial port 1 (if connected on 1)]. **Fixed: 4/18/08 by akoehler**
- [STRIKEOUT:Clicking cancel in the select specific backend2 should not produce an error message.] **Fixed: 4/17/08 by nmcmilla**
- [STRIKEOUT:Connect to preferred when already connected produces no warnings.] **Fixed: 4/17/08 by nmcmilla**

- [STRIKEOUT:Connecting to backend2 hops to the top of the textbox.] **Fixed: 4/21/08 by nmcmilla**
- [STRIKEOUT:Is there any way that hitting backspace won't jump to the top and back down?] - NO
- [STRIKEOUT:Ctrl-space should work here too. And make sure continue session still works on this pane.]**Fixed: 4/21/08 by nmcmilla**

config

- [STRIKEOUT:New user profile should auto-set in config after creation.] **Fixed: 4/18/08 by akoehler**

GUI

- [STRIKEOUT:The color seems funky (tab color doesn't match background color).]
- Needs icon.
- [STRIKEOUT:Needs About.]**Fixed 4/23/08 by mthomson**
- Needs 'command descriptions'
- Possibly needs a quick start guide in the help menu.-should be covered on the Wiki
- [STRIKEOUT:No keybindings for 'New Profile,' 'Save Profile,' etc.]**Fixed 4/21/08 by nmcmilla**

7.3 WinXinu

7.3.1 WinXINU Installation

Please check the WinXINU Installation Wiki Page for installation instructions.

7.3.2 About WinXINU

As part of a senior design project working in coordination with Dr. Dennis Brylow a frontend interface was successfully created for use under the a Windows operating system. Project members include Adam Koehler, Nicholas McMillan, and Christopher Swiderski, Matt Thomson. The software created incorporates the basic functionality of the UNIX variant toolset allowing computers with a Windows operating system installed to directly participate in the development and testing of the Embedded XINU operating system. Version 1.0 of WinXINU was released on May 1, 2008.

System Requirements

- Operating System: Windows XP or Windows Vista
- Ability to connect to XINU server
- Microsoft .Net Framework v3.0 or higher
- HDD Space
  - 60 megabytes (WinXINU)
  - 1310 megabytes (Cygwin)

  - Total ~1.4 gigabytes

WinXINU Software User's Manual

- WinXINU Manual

7.3.3 WinXINU Development

Initial Development

- Goal
  - To design and develop frontend client that is graphically oriented and Windows compatible. This client should maintain all functionality of the currently implemented fronted software tools that run on any UNIX variant operating system. This will allow computers with the Windows XP or Windows Vista operating system installed to directly participate in the remote testing of Embedded XINU operating system kernels.
- Subversion Repository
  - https://xinu.mscs.mu.edu/svn/projects/windows-tools/

Continued Development

The continued development of WinXINU will bring the more advanced entities of the XINU Console toolset to the Windows frontend client. Along with the addition of more advanced features any fixes to bugs will be processed within the Windows toolset subversion repository.

7.3.4 WinXINU Feedback

Please leave your feedback for WinXINU on the WinXINU Feedback Page.

7.4 WinXinu Installation

7.4.1 System Requirements

- Operating System: Windows XP or Windows Vista
- Ability to connect to XINU server
- Microsoft .Net Framework v3.0 or higher
- Cygwin w/ Development package
- HDD Space
  - 60 megabytes (WinXINU)
  - 1310 megabytes (Cygwin)
  - Total ~1.4 gigabytes

7.4.2 Installation Instructions

Installation Guide

- WinXINU + Cygwin Installation & Configuration Guide

Installing Cygwin

- Step 1: Go to Cygwin.com
- Step 2: Download the installation file, setup.exe
- Step 3: Run Cygwin Setup
  - Note: During setup, the only package that needs to be set to install is the devel package; all others can be set to uninstall or default

Installing WinXINU

- Step 1: Download the setup file
- Step 2: Run the WinXINU setup file and follow the Instruction Gude

7.4.3 Program Setup Instructions

- Modify the make file of your code
  - Change the first line of the mipsVars file to the location of the WinXINU cross compiler bin
    - NOTE: this should be found within your XINU code directory in the compile subdirectory
    - e.g. xinu/compile/mipsVars

```
Example:
 MIPS_ROOT = "C:/WinXINU/cross/bin"
```

- Modify the server settings XML file
  - Ensure the server IP is correct
  - Ensure that the server port number is correct
  - Ensure that the IP address in the automation command is correct
- Modify the configuration profile settings within the program
  - Navigate to the config tab, then change:
    - the location of cygwin\bin to its location on local machine
    - the location of compile directory where the Makefile is located for final image build

7.5 XinuPhone

XinuPhone is an innovative hardware/software platform for Internet telephony education and research. In the classroom, XinuPhone promotes hands-on interactive learning that is both cross-discipline and application oriented. As a research tool, XinuPhone is a versatile and open-source platform useful for benchmarking experimental methods against industry standards. Furthermore, the XinuPhone platform features inexpensive commodity hardware that is easy to assemble making it an idea choice for users on tight budgets and in diverse educational backgrounds.

7.5.1 How It Works

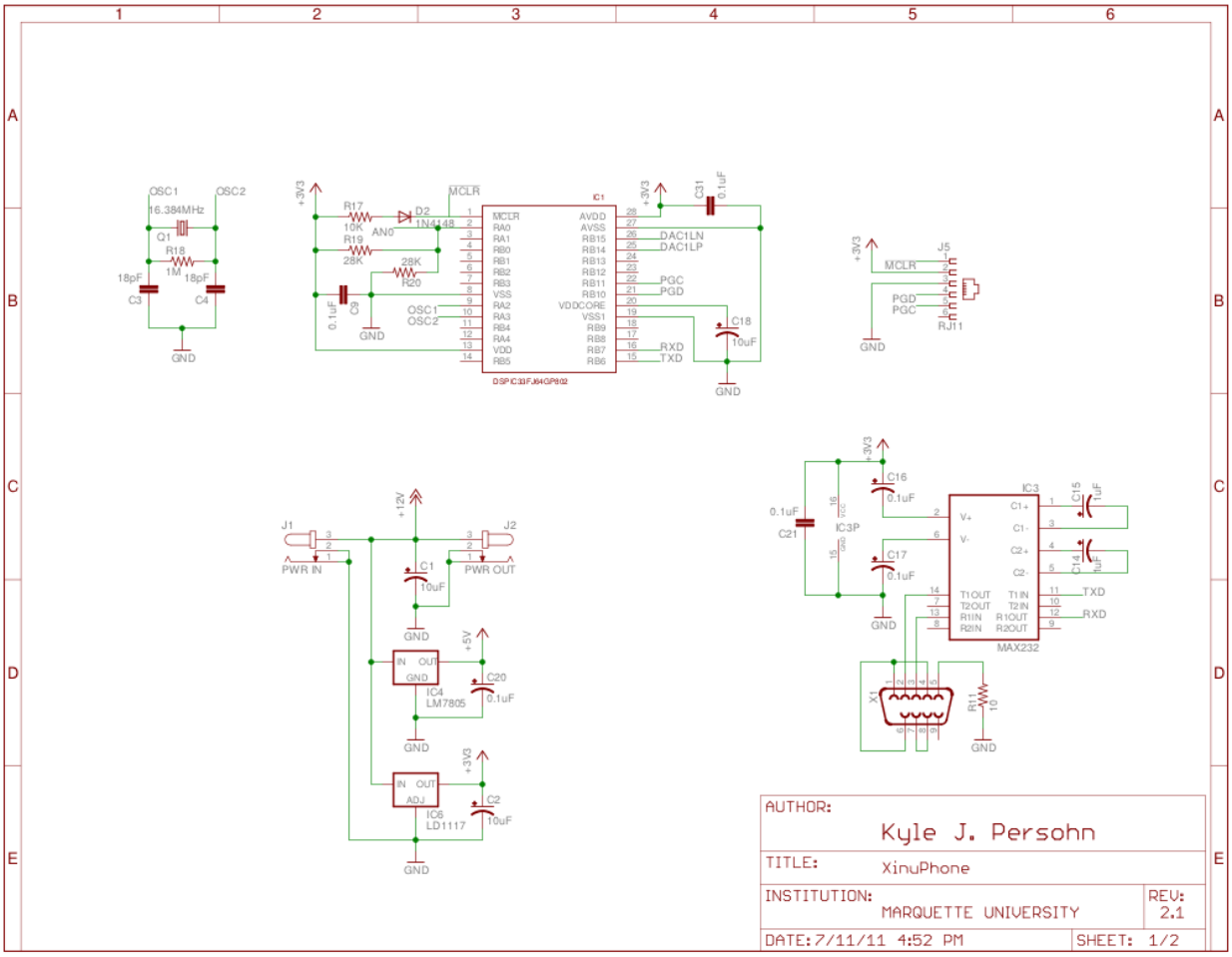
Most of the Embedded Xinu *supported platforms* do not have the ability to directly sample analog signals or reconstruct analog waveforms from digital bitstreams. Likewise, typical digital signal processing (DSP) chips lack Ethernet networking hardware and protocol support. XinuPhone pairs a simple external sampling module with a network-enabled backend running the Embedded Xinu operating system in order to provide both functionalities.

The XinuPhone audio module consists of filters, a digital signal controller (DSC), an audio amplifier, and a serial transceiver. Speech first passes through an analog low-pass anti-aliasing filter before it enters the analog to digital converter (ADC) on the DSC. The DSC can be programed with a variety of software CODECs that compress the sampled audio for efficient transmission across the serial bus. The serial transceiver allows the audio module to interface directly with an RS-232 capable network device, such as a slightly modified Linksys WRT54GL router. The audio module sends serial samples to the network device; then, the Embedded Xinu operating system VoIP tools packetize the serial data and send the voice packets to a remote host. On the receiving end, another network device buffers incoming packets and translates the payloads back into a stream of serial data. The external audio module uses the same CODECs to uncompress the serial data back into raw audio samples. Lastly, a digital to analog converter (DAC) on-board the DSC converts the audio samples back to an analog waveform that can be amplified and played back.

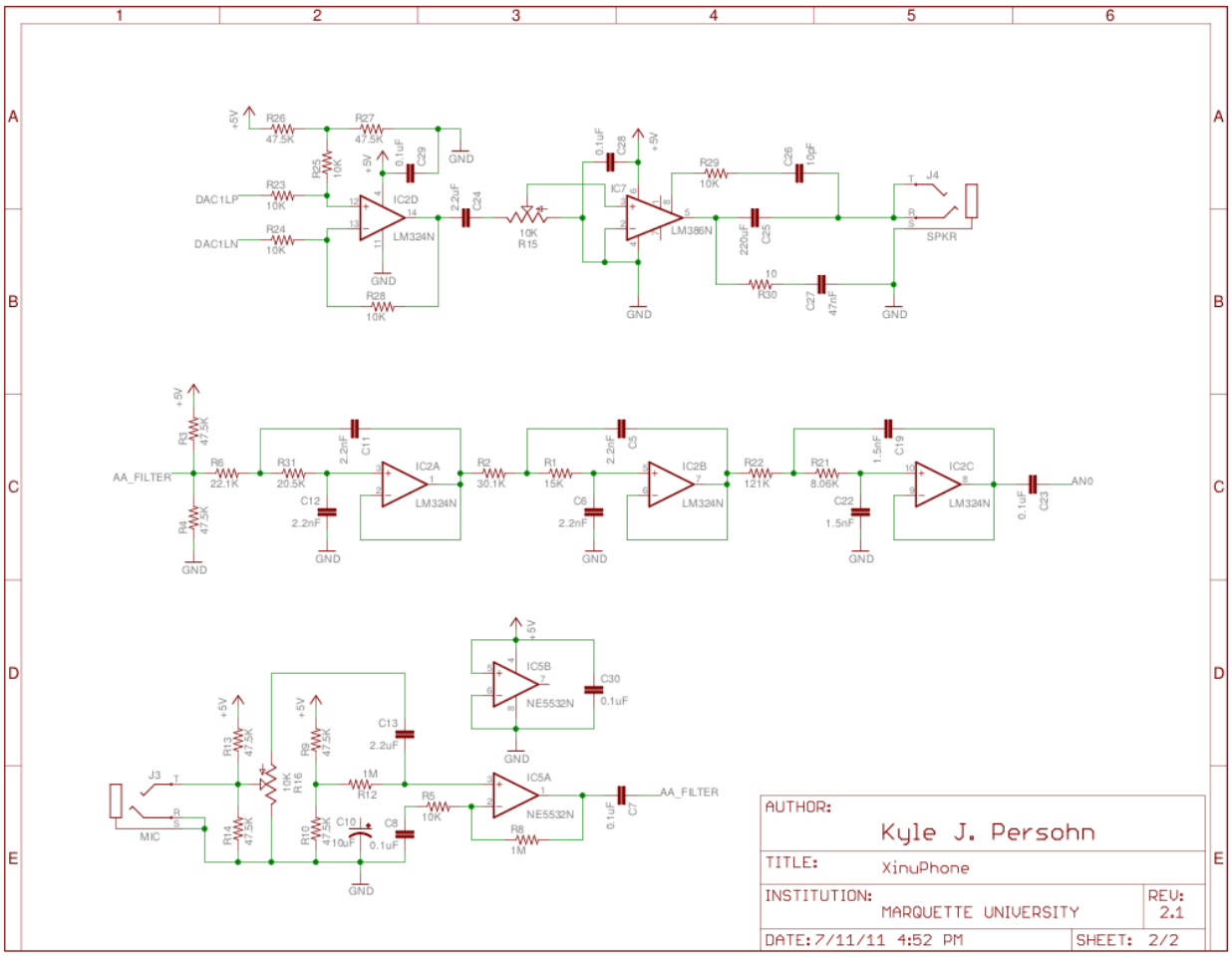
7.5.2 Hardware

You can build your own XinuPhone with readily available discrete components!

Schematics



Sheet 1 shows the basic DSC core, power supply, crystal oscillator, debug interface, and serial transceiver connections.



Sheet 2 illustrates the headphone amplifier, microphone pre-amplifier, and low-pass anti-aliasing filter.

Click on the sheet for a higher resolution image or see the downloads below for a PDF rendering.

Design Notes

- Components are specified to EIA E96 standard values for resistors (1% tolerance) and E24 values for capacitors.
- For capacitors in the audio path, temperature coefficient X7R, NP0, C0G, or better are recommended.

7.5.3 Downloads

File	Download Link	Checksum (SHA1)
XinuPhone Firmware 1.0 (Binary+Source)	gzip bzip2	8aa4b4d7ed38c4c641e920905aabfee1a9d2dbc0 6ecfecbb9d9bc399b961d0764923ce609b4c569a
XinuPhone Hardware Schematic Rev 2.1	pdf	a0f07d543f2b85440c31daa7d530066f682a8a5a
Embedded Xinu Operating System	url	

7.5.4 Instructional Resources

- Interactive Real-Time Embedded Systems Education Infused with Applied Internet Telephony. Kyle Persohn, Dennis Brylow. COMPSAC 2011: Proceedings of 35th IEEE Computer Software and Applications Conference, pages 199-204, Munich, Germany, July 2011. link
- *Teaching with Embedded Xinu*

7.5.5 Future Work

- Real-Time Transport Protocol support in Embedded Xinu
- Analog Telephone Adapter (ATA) interface
- Simple XinuPhone discovery protocol / address book

7.5.6 External Links

Some additional resources you may find useful

Microchip

- dsPIC33FJ64GP802 Product Home
- MPLAB IDE
- Audio & Speech Application Libraries

Standards & RFCs

- ITU-T Test Signals for Telecommunication Systems
- ITU-T G.711 - Pulse Code Modulation (PCM) of Voice Frequencies
- RFC 3550 - RTP: A Transport Protocol for Real-Time Applications

PCB Fabrication

- Advanced Circuits
- CadSoft EAGLE Schematic Capture & Board Layout Software
- SparkFun Tutorials

7.6 Xipx

For now, I'm just putting information here that I think is important and is at risk of being lost. Someday, this should probably be a more polished and complete page. ...yes, someday, someone will have to make it that... someone...

User threads global variables problem: User threads cannot have global variables because global variables apparently don't survive the objcopy to binary, or something. The discovery: assigning to a global variable in a usrthr causes a pagefault, because that write tries to go to some high memory address, but apparently that memory address doesn't get put into the binary, so the codesize (that gets prepended to the user thread binary) isn't large enough to cover that

address, so when the thread is created it doesn't map a page for that spot, so pagefault. It's probably just a matter of changing some build options or something, but I haven't dug into it yet.

Limits on code locations: The GETPROT_ADDR in the Makefile defines where the binary image for getprotected.S/initPaging.c gets put in memory. This must be low enough so that the whole image stays within a 16-bit address range because it all executes in 16-bit real mode. Also, keep IMG_ADDR low enough to not exceed 0x28ffffff (there is no safety check to make sure that IMG_ADDR + [xipx image size] < 0x29000000, so things will just break (probably page fault) if you mess that up.)

Custom memcpy: a memcpy optimized for x86 is used in place of the libxc implementation. So my libxc memcpy.c has a #ifndef _SCC_ in it.

TODO: talk about details of ut_to_k_view() and justify why it does everything it does in the order it does it. (This might end up in the thesis.)

TODO: describe the interaction of x86 interrupts and privilege levels, etc. (Might also be in the thesis.)

Syscalls (and maybe all interrupts?) currently push CR3 before switching to kernel memory mapping, then pop it when switching back. This seems dumb – why not just use the thrtab[thrcurrent].pdloc instead? Then you don't need to push it, and that hacky addition to the prepmigthr() function in lutmigd.c is not needed.

Room to improve: Probably not EVERY syscall needs to switch to kernel view of memory. Figure out which ones don't need to (probably everything that won't involve using the kernel heap or stack) and make it so they don't. Make sure this won't break anything else, e.g. will context switching to another thread while in the memory view of the current thread be a problem?

CHAPTER 8

Development

8.1 Git repository

Embedded Xinu previously used a Subversion repository, but in 2013 switched to git as the preferred source code management system.

The official public repository is hosted on Github. To get the code, install git and run:

```
$ git clone https://github.com/xinu-os/xinu
```

This will generate the directory `xinu/` containing a local copy of the repository. Note that this is a standalone repository that can be used without Internet access to the Github repository. This constitutes a difference from Subversion, which is more centralized.

Git is documented extensively in many locations, for example in the "Pro Git" book. But briefly, a very basic workflow is to modify files, use either `git add` and `git commit` or `git commit -a` to commit the changes to the repository, then use `git push` to push changes to a remote repository.

Branches in git are fast and easy to use, so it is recommended to develop experimental features in their own branches. Code pushed to the "master" branch should not be broken.

At least if you plan to push your changes to the master branch, please use descriptive commit messages for all commits and use the *preferred coding style*.

8.2 Kernel Normal Form (KNF)

This section describes major aspects of the preferred style for kernel source files in the Xinu operating system source tree.

8.2.1 Comments

General

Generally, code should be well-commented. However, comments should only mention things that are *not* already obvious.

Doxygen is used to automatically generate documentation from comments. Comments beginning with 2 asterisks are recognized by Doxygen; other comments are not. Doxygen-style comments should generally be used to document files as well as any functions, variables, definitions, and structures that are meant to be an external interface— that is, not internal to a file or component. "Regular" comments should be used in other cases, such as explaining the code.

The following shows the main forms of comments:

```
/*
 * Immensely important comments look like this.
 */

/* Typical single-line comments look like this. */

/**
 * Multi-line comments that should appear in the autogenerated documentation
 * should look like this.
 */

/** Single-line comments to appear in documentation look like this. */
/**< or they look like this, if appearing on the same line as code. */
```

The first form of single-line comments must be placed above the code that it pertains to, whereas the second form may be placed either above the code or on the same line as the code it describes (if it fits).

Files

At the top of all source files, there should be a file comment, followed by a copyright comment, like the following:

```
/**
 * @file somefile.c
 * This is a description of the file.
 */
/* Embedded Xinu, Copyright (C) 2013.  All rights reserved. */
```

The double asterisks opening the comment as well as the @file declaration are essential, since they inform Doxygen that the comment documents the file itself. Although not strictly necessary, please do include the filename in the @file declaration.

Previous releases used a @provides tag to declare all publicly visible symbols from each file. This is no longer done because Doxygen automatically determines what functions and variables are in each file.

Also, previous releases used the Subversion Id keyword in each file, but these are no longer used because they duplicate the purpose of version control systems.

The copyright comment is not intended to be parsed by Doxygen, so it must only use one asterisk. If changes are made to any file with a copyright year prior to the current year, then, legally speaking, the current year must be added to the copyright comment if those changes are legally significant for copyright purposes. However, note that the code does not use the lengthy 20+-line copyright statements used in many other projects, as the authors believe these clutter up the files and the license is already made clear in the COPYING file.

8.2.2 Preprocessor

As a precaution against multiple definitions every include file should protect itself against redefining its material.

```
#ifndef _INCLUDE_H_
#define _INCLUDE_H_
[...]
#endif                              /* _INCLUDE_H_ */
```

After the opening comment block and copyright of a file, include one blank line and begin including non-local header files.

```
#include <kernel.h>
#include <device.h>
#include <memory.h>
#include <string.h>
```

Following that, if there are local header files include a blank line and then continue including files.

```
#include "local.h"
```

Macro definitions should be in ALL CAPS unless it goes against a standard. This includes macros that are used in lieu of a function. If the macro consumes multiple lines, align the backslashes one space to the right of the longest line. Any final statement-terminating semicolon should not appear in the macro, rather it will be supplied by the invocation of the macro to allow easier parsing of the code by humans and editors alike.

```
#define MACRO(x, y)       \
    (x) = (x) + 5 * (y); \
    (x) /= 3
```

When using conditional directives such as `#if` or `#ifdef`, it is recommended to place a comment following the matching `#else` or `#endif` to make the reader have an easier time discerning where conditionally compiled code begins and ends.

```
#ifdef MIPS
/* MIPS specific code goes here. */
#else                               /* not MIPS */
/* generic code goes here. */
#endif                              /* MIPS */
```

8.2.3 Structs and Typedefs

Structures should have logically named members with a comment describing what each member is for. Structures do not have to have a typedef, but if they do have one it should be inline with the structure definition.

```
typedef struct dentry
{
    int major;                      /**< major device number          */
    int minor;                      /**< minor device number          */
    void *csr;                      /**< control and status registers */
    [...]
} device;
```

8.2.4 Functions

Functions used in more than one file are "global" and *must* have a prototype in a header file.

Functions used in only one file are "local" and must be declared with the `static` modifier. This prevents namespace pollution and lets the compiler possibly inline the function. If local functions are used before being defined, a prototype must be placed towards the top of the file.

Global functions must be documented by Doxygen using a comment similar to the following:

```
/**
 * The main function of the program will parse the input for the arguments
 * passed.
 * @param argc   number of arguments passed to function
 * @param argv   array of char *s containing passed arguments
 * @param func   pointer to function that takes two int parameters
 * @param offset offset into char * array to read
 * @param length length to read at offset
 * @return zero on successful completion, non-zero if unsuccessful.
 */
int foo(int argc, char **argv, devcall (*func)(int, int), int offset,
        int length)
{
    /* well written code. */
}
```

Note that Doxygen comments for global functions should focus on what a developer would need to know to call the function. They should generally *not* discuss implementation details.

Local functions need not be documented as formally. However, they may have regular (not Doxygen) comments that help explain the code.

8.2.5 Spacing

Languages keywords (such as `if`, `while`, `for`, `switch`) all have one space following their use. This helps differentiate keywords from function calls. Braces (`{` and `}`) should always be used in control statements. The use of brackets in all cases helps minimize the risk of bugs occurring when adding new lines to a statement.

```
for (i = 0; i < length; i++)
{
    a = i + 1;
    b *= a;
}

if (NULL != value)
{
    *value = new_value;
}

while (TRUE)
{
    /* Do nothing. */
}
```

Avoid declarations within new statement blocks when possible, certain versions of compilers may not recognize them for what they are.

Indentations are done using 4 spaces per level. If a conditional statement wraps around place the operator at the beginning of the next line (lining up with first variable above).

```
while (count > 30 && TRUE == this_variable_is_true
       && NULL != value)
{
```

```
    /* Do something. */
}

if (foo)
{
    /* foo case. */
}
else if (bar)
{
    /* bar case. */
}
else
{
    /* else case. */
}
```

Switch statements should be formatted with each case lining up with the braces as follows:

```
switch (test)
{
case 0:
case 1:
    /* Process. */
    break;
default:
    /* Normal case. */
    break;
}
```

There should be no spaces after function names. Commas should be followed by a space. Typically there are only spaces with more complex statements. Code readability is king. Binary operators should be padded with a space on either side.

```
error = function(a1, a2);
if ((OK != error) && (5 < error))
{
    exit(error);
}
```

Unary operators do not require a space.

In cases where operator precedence is unclear, always error on the side of including additional parentheses.

8.2.6 Miscellaneous

It is permissible to declare multiple variables on one line, but do not initialize variables until everything has been declared.

```
struct foo one, *two;
int three, four, five;

five = 5;
four = four();
```

Type casts and `sizeof` should not be followed by a space. `sizeof` should always be written with parentheses.

```
a = (ushort)sizeof(struct memblock);
```

Committed code should never produce warnings or errors.

Function names should use lowerCamelCase. Avoid unnecessary abbreviation in function names as reasonable.

Pointers which are used solely as references to memory locations (and not to a structure or array of a specific type) should be declared of type `void *`.

8.3 Trace

To assist with debugging of XINU modules, a standard trace interface has been implemented. Each module should have code of the following form located in its main header:

```
//#define TRACE_[MODULE]     TTY1

#ifdef TRACE_[MODULE]
#include <stdio.h>
#define [MODULE]_TRACE(...)     { \
                fprintf(TRACE_[MODULE], "%s:%d (%d) ", __FILE__, __LINE__, gettid()); \
                fprintf(TRACE_[MODULE], __VA_ARGS__); \
                fprintf(TRACE_[MODULE], "\n"); }
#else
#define [MODULE]_TRACE(...)
#endif
```

For example, the *Routing* module declares `TRACE_RT` and `RT_TRACE(...)` in include/route.h.

`TRACE_[MODULE]` defines the device to which `[MODULE]_TRACE(...)` writes. If undefined, no tracing is performed. The line defining `TRACE_[MODULE]` can be undefined or defined as needed to disable or enable tracing for a particular module. However, please note that changes enabling tracing should not be checked into revision control.

8.4 Build System

Building *Embedded Xinu* is as simple as typing `make` in the `compile` directory. However, if you want to understand how the build system works you'll need to acquaint yourself with the `Makefile`. It should be noted that this is not a recursive build process (make only calls another make process when building the libraries and a few other special cases), but rather a single Makefile that sources rules to build logically separated components.

This is a description of the build process for building the trunk version of XINU and may not be applicable to all versions.

8.4.1 Makefile

Open `compile/Makefile` and you'll discover numerous variables and settings for building XINU. The first is the directive to `include mipsVars`. This simply adds the contents of the `compile/mipsVars` file to the Makefile. We chose to `include` this file so that moving from system to system is easier by storing dynamic variables in an external file. The less we change the Makefile the better.

`mipsVars` defines the location of the cross-compiler and various flags for compiling C and assembly source files.

After the local configuration is included we set a number of variables giving the final compiled image name, an archive file to create (if requested), where the main program is located, flags to pass to the loader, and file locations. Then there is the default make target which will be called when `make` with no arguments is typed at the shell prompt.

Now, the next two variables are very important. `COMPS` is a listing of the major system components we should include while building. Similarly `LIBS` is a listing of the libraries we will include when building the system. From the `COMPS` line we use another `include` directive, this time sourcing a `Makerules` file located in the directory to which each component points. Each Makerules file will append the source files to build that component into the kernel image. After all the source files are loaded, the Makefile converts the collection of C source files and assembly files to make one massive listing of object files.

Now, that all the important variables are set up there are a number of targets that can be executed. The most common target is `${BOOTIMAGE}` (which is typically `xinu.boot`), this depends on all the object files, library files, and the loader script. Then it will link all the object files together to create the boot image. There is also a `objects` target that will only build the object files for the system (and not link them).

There are several ways of cleaning the source tree. `make clean` will remove all the object files and the bootimage. `make libclean` will call the clean target for all the libraries. `make depclean` removes all the header file dependencies from the Makefile. `make docclean` will remove the documentation generated by the `make docs` command. `make realclean` will do all of the above and remove the `vn` and `version` files as well.

Moving above and beyond those targets, there are also a few special targets that can be called. `make [component]` will create object files only for the specified subsystem (useful during development). `make [libname]` will build the library archive, and `make [libname]-clean` will clean the library.

8.4.2 Makerules

As mentioned above a `Makerules` file resides in each component directory. This file will append a listing of the source files for the component. There are two important factors about this file:

1. At the top of the file, make sure that `COMP` is the name of the component **and** the name of the directory.
2. Make sure you append all the files to the `COMP_SRC` variable and that they are prefixed with the proper directory (so gcc can find them.)

Within the file itself you can breakup files as you see fit. Typically, assembly files are stored in local `S_FILES` variables while C source is stored in `C_FILES` variables. This is not strictly needed, but makes it easier to read in some cases.

8.4.3 Library

XINU libraries are built using the recursive make paradigm. Since the libraries do not change commonly they are not removed between builds unless specially requested. In the master Makefile all relevant variables are exported (including the location of the cross-compiler, C and assembly flags), the library Makefile then uses those to build its files and create an archive of the object files.

This allows all important build variables to be in one location and not leave possible dependency issues if something were to change in the build system.

8.5 Porting Embedded Xinu

8.5.1 Build system

This section documents how to set up the build system for a new Embedded Xinu port.

The majority of the build logic is in the Makefile in `compile/`. This file is intended to be platform-independent and you should not need to modify it. Instead, you should create a new directory in `compile/platforms/` containing the files `platformVars`, `xinu.conf`, and `ld.script` for your platform.

platformVars

`platformVars` is in Makefile syntax and must contain the following definitions:

- A Makefile rule to generate the file `$(BOOTIMAGE)`, which is by default `xinu.boot`, from `xinu.elf`. `xinu.elf` will be the kernel in ELF format, while `xinu.boot` is normally expected to be the actual bootable kernel that is the final result of the build. This rule may simply copy the file, or it may use **objcopy** to change the binary format. (Use `$(OBJCOPY)` to get the correct **objcopy** for the target platform.) If your platform does things very differently you can override `$(BOOTIMAGE)` to something else.
- `APPCOMPS` must be set to the list of Xinu application components to build in. Each item in the list corresponds to a toplevel directory, such as `network`. Note that certain toplevel directories, such as `lib/` and `system/`, are not considered "application" components and should not be listed here.
- `DEVICES` must be set to the list of Xinu device drivers to build in. Each item in the list corresponds to the name of a directory in `device/`. Device drivers added here in many cases also require configuration in `xinu.conf`; see the section below.
- `BUGFLAG` must be set to an appropriate compiler flag to enable debugging information.
- `ARCH_ROOT` must be set to the default directory containing the compiler binary (ending with a slash). The exact value is not important because it can be overridden on build.
- `ARCH_PREFIX` must be set to the default compiler target prefix.
- `OCFLAGS` must be set to the appropriate flags to pass to **objcopy** to turn a raw binary file into an object file that can be linked into the kernel.

`platformVars` may modify the following definitions:

- `FLAGS` can be modified to add additional compiler flags.
- `ASFLAGS` can be modified to add additional assembler flags. These will be passed directly to the assembler, so do *not* prefix these with `-Wa,`. For the GNU assembler see `man as` or `info as` for available flags.
- `LDFLAGS` can be modified to add additional linker flags. These will be passed directly to the linker, so do not prefix these with `-Wl,`. For the GNU linker see `man ld`` or ``info ld` for available flags.
- `LDLIBS` can be modified to add needed external libraries. Besides possibly adding libgcc (`-lgcc`) if your architecture has certain quirks like the need for division to be emulated in software, you probably don't need to add anything here.
- `INCLUDE` can be modified to add additional include directories. Prefix each with `-I`. The toplevel Makefile handles adding these to `CFLAGS` and `ASFLAGS` as appropriate. You probably don't need to add anything here, especially because `system/platforms/$(PLATFORM)` is already added by default.
- `DEFS` can be modified to add additional defines. Prefix each with `-D`. The toplevel Makefile handles adding these to `CFLAGS` and `ASFLAGS` as appropriate. If you need to add conditional C code specifically for your platform in existing source code (please avoid it whenever possible...) you should define a constant like `_XINU_PLATFORM_???_`, where `???` is your platform.

Still furthermore, you can optionally set the following variables:

- `PLATCLEAN` to be the name of a platform-specific target that will be executed when `make realclean` is run.
- `LIBXC_OVERRIDE_CFILES` (see *Platform-specific overrides* for explanation).
- `PLATFORM_NAME` to change the release provided at the top of the generated documentation.

xinu.conf

`xinu.conf` is the file used for configuring Xinu's static device table. See the existing examples in the `compile/platforms/` directory for the format. This file is used to generate `system/conf.c` and `system/conf.h`. You should keep the devices defined in `xinu.conf` in sync with the components actually compiled into the kernel via the `DEVICES` variable in `platformVars`.

ld.script

`ld.script` is the linker script used to link the kernel. This is used to customize the layout of the resulting kernel image, including the address at which it is compiled to run at. See the existing examples in `compile/platforms/`.

Architectures

Multiple Xinu platforms may have the same underlying "architecture", such as ARM or MIPS. If the architecture of your platform is already listed in `compile/arch/`, then there are two shortcuts you may be able to take:

- `platformVars` can be shortened by including the corresponding `platformVars` in `compile/arch/`, which will handle many of the definitions for you.
- If you do not include a linker script (`ld.script`) in `compile/platforms/`, then the linker script in `compile/arch/` will be used, if present. (This requires including the corresponding architecture `platformVars`.) This script may be sufficient for your platform.

The exact contents of the `platformVars` in `compile/arch/` is dependent on the architecture; see the existing examples.

8.6 Documentation

Welcome to the documentation documentation! Embedded Xinu contains two main forms of documentation:

1. "reStructuredText" (.rst) files located under the top-level `docs/` directory.
2. Comments in the source code itself, including Doxygen-compatible comments describing function parameters and behaviors.

This section focuses on (1); for information about (2) see *Kernel Normal Form (KNF)*.

8.6.1 Building the documentation

The documentation for the latest development version of Embedded Xinu can be read at http://embedded-xinu.readthedocs.org/en/latest/, and it is automatically updated.

To build the documentation locally, you will need to install the Sphinx documentation tool. On Linux systems you should find it in the repositories.

HTML

Build the HTML documentation with:

```
$ cd docs
$ make html
```

Point your browser at `_build/html/index.html`.

PDF

LaTeX is required for generating the PDF documentation. Build it with:

```
$ cd docs
$ make latexpdf
```

The generated PDF file will be `_build/latex/EmbeddedXinu.pdf`.

8.6.2 Editing and writing documentation

reStructuredText is designed to be relatively easy to edit. Much information can be found online, so the basics about headings, lists, tables, external and internal links, footnotes, etc. will not be repeated here.

Suggestions

A documentation page should be clear and reasonably understandable to people who may not be familiar with the project and may not have read many other pages.

The documentation should *supplement the source code*, not be redundant with it.

Extensions

The file `xinusource.py` defines several extensions, namely a `:source:` command to generate links to XINU source files (for example, in the github web interface). Use it like:

```
:source:`PATH`
```

or

```
:source:`DISPLAYTEXT <PATH>`
```

The command `:rfc:` generates a link to the specified Request for Comments (RFC). Use it like:

```
:rfc:`RFCNUM`
```

or

```
:rfc:`DISPLAYTEXT <RFCNUM>`
```

Similarly, the command `:wikipedia:` generates a link to the specified Wikipedia article. Use it like:

```
:wikipedia:`ARTICLETITLE`
```

or

```
:wikipedia:`DISPLAYTEXT <ARTICLETITLE>`
```

Organization

Platform-dependent documentation (e.g. in `arm/` and `mips/`) is separated from the generic documentation (e.g. in `features/`).

Although not all platforms support networking, networking above the device driver level is more or less platform independent and should be documented in `features/networking/`.

Every file is supposed to be listed in a TOC tree. However, the `index.rst` files containing these lists usually use globs, so no action should be needed when adding a documentation file to an existing directory.

8.6.3 Resources

- reStructuredText Primer
- Quick reStructuredText

8.7 Systems Laboratory

8.7.1 About the Systems Laboratory

Marquette's Systems Laboratory, under the direction of Dr. Dennis Brylow in the Department of Mathematics, Statistics, and Computer Science, is housed on the third floor of Cudahy Hall.

The lab creates new tools and methods for building and studying complex computer systems. Our emphasis is on embedded, real-time, and network systems, with strong ties to the electrical and computer engineering community, and the computer science education community. Current and recent projects include:

- Experimental Embedded Networking Platform. Creation of laboratory infrastructure and software for research and education in the area of embedded networking appliances, particularly wireless routers and IP telephony. Collaboration with Cisco Systems Advanced Research Division.
- Experimental Embedded Operating System Laboratory. Creation of laboratory infrastructure and software for research and education in area of embedded operating systems. Collaboration with University of Buffalo and University of Mississippi, with funding from the National Science Foundation.
- Embedded Software Transactional Memory. Exploration of an innovative transactional memory model for guaranteeing process synchronization in embedded operating systems. Collaboration with Intel Research.
- Many-core Embedded Operating System Laboratory. A port of Embedded Xinu to the 48-core SCC processor.

The Systems Lab hosts undergraduate REU (Research Experience for Undergraduates) students each summer, funded by a variety of sources including MU's College of Arts and Sciences and the National Science Foundation.

See the MSCS Research Labs page for more research laboratories in our department.

8.7.2 Publications

Conference Proceedings and Journals

- Eric Biggers, Farzeen Haruani, Tyler Much, and Dennis Brylow. XinuPi: Porting a Lightweight Educational Operating System to the Raspberry Pi. In proceedings of WESE 2013: the 2013 Workshop on Embedded and

Cyber-Physical Systems Education, Organized as a part of Embedded Systems Week, October 2013, Montreal, Canada.

- Michael Ziwisky and Dennis Brylow. BareMichael: A Minimalistic Bare-metal Framework for the Intel SCC. In Proceedings of MARC Symposium 2012: 6th Many-core Applications Research Community (MARC) Symposium, Eric Noulard and Simon Vernhes (Ed.), ONERA - Toulouse, France, July 2012. (link)
- Paul Ruth and Dennis Brylow. An Experimental Nexos Laboratory Using Virtual Xinu. In Proceedings of FIE 2011: 41st ASEE/IEEE Frontiers in Education Conference, pages S2E-1-S2E-6, Rapid City, South Dakota, October 2011. (link)
- Kyle Persohn and Dennis Brylow. Interactive Real-Time Embedded Systems Education Infused with Applied Internet Telephony. In Proceedings of COMPSAC 2011: 35th IEEE Computer Software and Applications Conference, pages 199-204, Munich, Germany, July 2011. (link)
- Dennis Brylow and Kyle Thurow. Hands-on Networking Labs With Embedded Routers. In Proceedings of SIGCSE 2011: The 42nd ACM Technical Symposium on Computer Science Education, pages 399-404, Dallas, Texas, March 2011. (link)
- Matt Netkow and Dennis Brylow. Xest: An Automated Framework for Regression Testing of Embedded Software. In Proceedings of WESE 2010 6th Workshop on Embedded Systems Education, pages 40-47, Scottsdale, Arizona, October 2010. (link)
- Adam Mallen and Dennis Brylow. Compiler Construction With A Dash of Concurrency and An Embedded Twist. In Proceedings of SPLASH 2010: Systems, Programming, Languages, and Applications: Software for Humanity (formerly OOPSLA) Educators' and Trainers' Symposium, pages 161-168, Reno, Nevada, October 2010. (link)
- Dennis Brylow and Bina Ramamurthy. Nexos: A Next Generation Embedded Systems Laboratory, In Proceedings of WESE 2008: 4th Workshop on Embedded Systems Education, pages 10-17, Atlanta, Georgia, October 2008. (link) | Extended version in SIGBED Review, Volume 6, Number 1, January 2009. (link)
- Dennis Brylow. An Experimental Laboratory Environment for Teaching Embedded Operating Systems, In Proceedings of SIGCSE 2008: The 39th ACM Technical Symposium on Computer Science Education, pages 192-196, Portland, Oregon, March 2008. (link)
- Dennis Brylow. An Experimental Laboratory Environment for Teaching Embedded Hardware Systems, In Proceedings of WCAE 2007: Workshop on Computer Architecture Education, pages 44-51, San Diego, California, June 2007. (link)

Posters and Undergraduate Research

- Kyle Thurow and Dennis Brylow. A Network Emulator on Embedded Xinu. Poster presentation and research talk presented at SIGCSE 2010 ACM Student Research Competition, undergraduate division, Milwaukee, Wisconsin, March 2010. Kyle placed in the top five and advanced to the semi-finals round.
- Gabe Van Eyck and Dennis Brylow. Xinu as a Multi-Core Operating System on the PlayStation 3. Poster presentation at SIGCSE 2010 ACM Student Research Competition, undergraduate division, Milwaukee, Wisconsin, March 2010.
- Aaron Gember and Dennis Brylow. Real-Time TCP Extensions. Poster presentation and research talk presented at SIGCSE 2009 ACM Student Research Competition, undergraduate division, Chattanooga, Tennessee. Aaron advanced to semi-finals, placed in top three finalists, and advanced to the grand finals.
- Dennis Brylow. Experimental Operating System Lab On A Dime. SIGCSE 2007: Technical Symposium on Computer Science Education, Covington, Kentucky, March 2007. (link).

Workshops

- Paul Ruth and Dennis Brylow. Teaching With Embedded Xinu. Workshop accepted at ACMSE 2010: The 48th ACM Southeast Conference, Oxford, Mississippi, April 2010.
- Dennis Brylow and Paul Ruth. Teaching With Embedded Xinu. Workshop accepted at SIGCSE 2010: The 41st ACM Technical Symposium on Computer Science Education, Milwaukee, Wisconsin, March 2010.

8.7.3 Lab Equipment

The Systems Laboratory is populated with dual-headed Linux boxes running the latest version of Fedora Linux. Other workstations in the lab include a dual-core Apple G5 running OS X, and several multi-core boxes for higher-end computation.

The Xinu Laboratory component of the Systems Lab includes a pool of 24 WRT54GL wireless routers organized into a managed embedded backend pool, as well as smaller quantities of half a dozen other router types. Embedded development kits available include the Freescale/Motorola 68HC12 Dragon12 board, the Atmel AT91 Series ARM Thumb AT91EB40A board, the ATmega169 Butterfly, a Zilog Z86 Emulator Z86CCP01ZEM, and the Zilog Z8 Encore XP Dev Kit Z8F04A28100KIT-C.

The Systems Lab includes both a private research network with our own gateway and firewall, and connections to each of the MSCS department production networks. The Lab also hosts Subversion, Trac, and Web service for the Marquette Student ACM Chapter, the Marquette University Linux Users Group, and a stratum 2 NTP server for campus.

8.7.4 Lab Personnel

2013

Summer 2013: Eric Biggers, Tyler Much, and Farzeen Haruani

2012

Systems Lab students in 2012: Kyle Persohn, Matt Bajzek, Mike Ziwisky, Ethan Weber, Teddy Sudol, Alex Becherer, Heather Bort.

2011

Alumni

Paul Hinze, B.S. 2008. Currently works as a developer for Braintree.

Mike Schultz, M.S. 2009. Now at Washington University in St. Louis doctoral program.

Tim Blattner, B.S. 2009. Now at University of Maryland - Baltimore County doctoral program.

Aaron Gember, B.S. 2009. Now at University of Wisconsin-Madison doctoral program.

Matt Netkow, B.S. 2009. Now works as a developer for The SAVO Group.

Adam Mallen, B.S. 2009. Now at Marquette University doctoral program in Computational Sciences with an emphasis in Math.

Adam Koehler, M.S. 2010. Now at University of California Riverside doctoral program.

Zachary Lund, M.S. 2010. Now works as the lead developer for SAV Transportation Group.

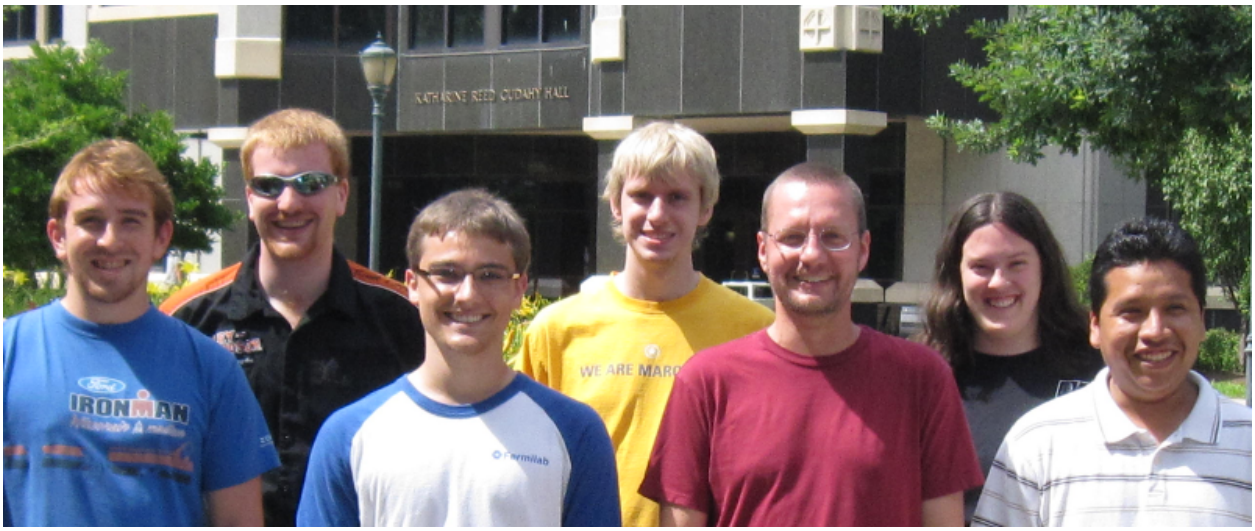


Figure 8.1: The Xinu Team in Summer 2011. From left, Jason Cowdy, Kyle Persohn, Matt Bajzek, Paul Spillane, Dr. Dennis Brylow, Anna Whitley, and Victor Blas. Not pictured: Mike Ziwisky.

Joseph Pintozzi, B.S. 2010. Now works as a developer for Core-Apps, LLC.

Paul Spillane, B.S. 2010, M.S. 2012. Now works as a quality assurance analyst at Zywave.

Victor Blas, B.S. 2012. Now works as a developer at Acuity.

Kyle Persohn, M.S. 2012. Embedded Software Engineer at Rockwell Automation.