Pintos

by Ben Pfaff

Short Contents

1 Introduction 1
2 Project 1: Threads 9
3 Project 2: User Programs 22
4 Project 3: Virtual Memory 39
5 Project 4: File Systems 50
A Reference Guide 58
B 4.4BSD Scheduler 91
C Coding Standards 96
D Project Documentation 99
E Debugging Tools 102
F Development Tools 113
G Installing Pintos 114
Bibliography 117
License 119

Table of Contents

1 Introduction 1

1.1 Getting Started 1
1.1.1 Source Tree Overview 1
1.1.2 Building Pintos 2
1.1.3 Running Pintos 3
1.1.4 Debugging versus Testing 4
1.2 Grading 5
1.2.1 Testing 5
1.2.2 Design 5
1.2.2.1 Design Document 6
1.2.2.2 Source Code 7
1.3 Legal and Ethical Issues 7
1.4 Acknowledgements 8
1.5 Trivia 8

2 Project 1: Threads 9

2.1 Background 9
2.1.1 Understanding Threads 9
2.1.2 Source Files 10
2.1.2.1 '`devices`' code 11
2.1.2.2 '`lib`' files 12
2.1.3 Synchronization 14
2.1.4 Development Suggestions 14
2.2 Requirements 15
2.2.1 Design Document 15
2.2.2 Alarm Clock 15
2.2.3 Priority Scheduling 16
2.2.4 Advanced Scheduler 16
2.3 FAQ 17
2.3.1 Alarm Clock FAQ 19
2.3.2 Priority Scheduling FAQ 19
2.3.3 Advanced Scheduler FAQ 20

3 Project 2: User Programs 22

3.1 Background 22
3.1.1 Source Files 22
3.1.2 Using the File System 23
3.1.3 How User Programs Work 25
3.1.4 Virtual Memory Layout 25
3.1.4.1 Typical Memory Layout 26
3.1.5 Accessing User Memory 27
3.2 Suggested Order of Implementation 28

3.3 Requirements . . . 28
3.3.1 Design Document . . . 28
3.3.2 Process Termination Messages . . . 29
3.3.3 Argument Passing . . . 29
3.3.4 System Calls . . . 29
3.3.5 Denying Writes to Executables . . . 32
3.4 FAQ . . . 33
3.4.1 Argument Passing FAQ . . . 34
3.4.2 System Calls FAQ . . . 35
3.5 80x86 Calling Convention . . . 35
3.5.1 Program Startup Details . . . 36
3.5.2 System Call Details . . . 37

4 Project 3: Virtual Memory . . . 39
4.1 Background . . . 39
4.1.1 Source Files . . . 39
4.1.2 Memory Terminology . . . 39
4.1.2.1 Pages . . . 39
4.1.2.2 Frames . . . 40
4.1.2.3 Page Tables . . . 40
4.1.2.4 Swap Slots . . . 40
4.1.3 Resource Management Overview . . . 41
4.1.4 Managing the Supplemental Page Table . . . 42
4.1.5 Managing the Frame Table . . . 42
4.1.5.1 Accessed and Dirty Bits . . . 43
4.1.6 Managing the Swap Table . . . 43
4.1.7 Managing Memory Mapped Files . . . 44
4.2 Suggested Order of Implementation . . . 44
4.3 Requirements . . . 45
4.3.1 Design Document . . . 45
4.3.2 Paging . . . 45
4.3.3 Stack Growth . . . 46
4.3.4 Memory Mapped Files . . . 47
4.3.5 Accessing User Memory . . . 47
4.4 FAQ . . . 48

5 Project 4: File Systems . . . 50
5.1 Background . . . 50
5.1.1 New Code . . . 50
5.1.2 Testing File System Persistence . . . 51
5.2 Suggested Order of Implementation . . . 51
5.3 Requirements . . . 51
5.3.1 Design Document . . . 51
5.3.2 Indexed and Extensible Files . . . 52
5.3.3 Subdirectories . . . 52
5.3.4 Buffer Cache . . . 54
5.3.5 Synchronization . . . 54
5.4 FAQ . . . 55

5.4.1 Indexed Files FAQ 56
5.4.2 Subdirectories FAQ 56
5.4.3 Buffer Cache FAQ 56

Appendix A Reference Guide 58

A.1 Loading 58
A.1.1 The Loader 58
A.1.2 Low-Level Kernel Initialization 59
A.1.3 High-Level Kernel Initialization 59
A.1.4 Physical Memory Map 60
A.2 Threads 61
A.2.1 `struct thread` 61
A.2.2 Thread Functions 63
A.2.3 Thread Switching 65
A.3 Synchronization 66
A.3.1 Disabling Interrupts 66
A.3.2 Semaphores 67
A.3.3 Locks 68
A.3.4 Monitors 68
A.3.4.1 Monitor Example 69
A.3.5 Optimization Barriers 70
A.4 Interrupt Handling 71
A.4.1 Interrupt Infrastructure 72
A.4.2 Internal Interrupt Handling 73
A.4.3 External Interrupt Handling 74
A.5 Memory Allocation 75
A.5.1 Page Allocator 75
A.5.2 Block Allocator 76
A.6 Virtual Addresses 77
A.7 Page Table 79
A.7.1 Creation, Destruction, and Activation 79
A.7.2 Inspection and Updates 79
A.7.3 Accessed and Dirty Bits 80
A.7.4 Page Table Details 80
A.7.4.1 Structure 80
A.7.4.2 Page Table Entry Format 82
A.7.4.3 Page Directory Entry Format 83
A.8 Hash Table 84
A.8.1 Data Types 84
A.8.2 Basic Functions 85
A.8.3 Search Functions 86
A.8.4 Iteration Functions 87
A.8.5 Hash Table Example 88
A.8.6 Auxiliary Data 89
A.8.7 Synchronization 89

Appendix B 4.4BSD Scheduler 91
B.1 Niceness 91
B.2 Calculating Priority 91
B.3 Calculating *recent_cpu* 92
B.4 Calculating *load_avg* 93
B.5 Summary 93
B.6 Fixed-Point Real Arithmetic 94

Appendix C Coding Standards 96
C.1 Style 96
C.2 C99 96
C.3 Unsafe String Functions 97

Appendix D Project Documentation 99
D.1 Sample Assignment 99
D.2 Sample Design Document 99

Appendix E Debugging Tools 102
E.1 `printf()` 102
E.2 `ASSERT` 102
E.3 Function and Parameter Attributes 102
E.4 Backtraces 103
E.4.1 Example 103
E.5 GDB 105
E.5.1 Using GDB 105
E.5.2 Example GDB Session 108
E.5.3 FAQ 110
E.6 Triple Faults 111
E.7 Modifying Bochs 111
E.8 Tips 112

Appendix F Development Tools 113
F.1 Tags 113
F.2 cscope 113
F.3 Git 113
F.4 VNC 113

Appendix G Installing Pintos 114
G.1 Building Bochs for Pintos 115

Bibliography 117
Hardware References 117
Software References 117
Operating System Design References 118

License 119

1 Introduction

Welcome to Pintos. Pintos is a simple operating system framework for the 80x86 architecture. It supports kernel threads, loading and running user programs, and a file system, but it implements all of these in a very simple way. In the Pintos projects, you and your project team will strengthen its support in all three of these areas. You will also add a virtual memory implementation.

Pintos could, theoretically, run on a regular IBM-compatible PC. Unfortunately, it is impractical to supply every CS 326 student a dedicated PC for use with Pintos. Therefore, we will run Pintos projects in a system simulator, that is, a program that simulates an 80x86 CPU and its peripheral devices accurately enough that unmodified operating systems and software can run under it. In class we will use the Bochs and QEMU simulators. Pintos has also been tested with VMware Player.

These projects are hard. CS 326 has a reputation of taking a lot of time, and deservedly so. We will do what we can to reduce the workload, such as providing a lot of support material, but there is plenty of hard work that needs to be done. We welcome your feedback. If you have suggestions on how we can reduce the unnecessary overhead of assignments, cutting them down to the important underlying issues, please let us know.

This chapter explains how to get started working with Pintos. You should read the entire chapter before you start work on any of the projects.

1.1 Getting Started

To get started, you'll have to log into a machine that Pintos can be built on. The CS 326 "officially supported" Pintos development machines are the machines in the Harney CS Labs (HR 235 and HR 530) managed by the Department of Computer Science. We will test your code on these machines, and the instructions given here assume this environment. We cannot provide support for installing and working on Pintos on your own machine, but we provide instructions for doing so nonetheless (see Appendix G [Installing Pintos], page 114).

Once you've logged into one of these machines, either locally or remotely, start out by adding our binaries directory to your `PATH` environment. Under `bash`, USF's login shell, you can do so with this command:

```
export PATH = $PATH:/home/web/benson/cs326/pintos/bin
```

It is a good idea to add this line to the '`.bash_profile`' file in your home directory. Otherwise, you'll have to type it every time you log in.

1.1.1 Source Tree Overview

Now you can extract the source for Pintos into a directory named '`pintos/src`', by executing

```
zcat /home/web/benson/cs326/pintos/pintos.tar.gz | tar x
```

Alternatively, fetch `http://www.cs.usfca.edu/~benson/cs326/pintos/pintos.tar.gz` and extract it in a similar way.

Let's take a look at what's inside. Here's the directory structure that you should see in '`pintos/src`':

'`threads/`'
: Source code for the base kernel, which you will modify starting in project 1.

‘`userprog/`’
: Source code for the user program loader, which you will modify starting with project 2.

‘`vm/`’
: An almost empty directory. You will implement virtual memory here in project 3.

‘`filesys/`’
: Source code for a basic file system. You will use this file system starting with project 2, but you will not modify it until project 4.

‘`devices/`’
: Source code for I/O device interfacing: keyboard, timer, disk, etc. You will modify the timer implementation in project 1. Otherwise you should have no need to change this code.

‘`lib/`’
: An implementation of a subset of the standard C library. The code in this directory is compiled into both the Pintos kernel and, starting from project 2, user programs that run under it. In both kernel code and user programs, headers in this directory can be included using the `#include <...>` notation. You should have little need to modify this code.

‘`lib/kernel/`’
: Parts of the C library that are included only in the Pintos kernel. This also includes implementations of some data types that you are free to use in your kernel code: bitmaps, doubly linked lists, and hash tables. In the kernel, headers in this directory can be included using the `#include <...>` notation.

‘`lib/user/`’
: Parts of the C library that are included only in Pintos user programs. In user programs, headers in this directory can be included using the `#include <...>` notation.

‘`tests/`’
: Tests for each project. You can modify this code if it helps you test your submission, but we will replace it with the originals before we run the tests.

‘`examples/`’
: Example user programs for use starting with project 2.

‘`misc/`’

‘`utils/`’
: These files may come in handy if you decide to try working with Pintos on your own machine. Otherwise, you can ignore them.

1.1.2 Building Pintos

As the next step, build the source code supplied for the first project. First, `cd` into the ‘`threads`’ directory. Then, issue the ‘`make`’ command. This will create a ‘`build`’ directory under ‘`threads`’, populate it with a ‘`Makefile`’ and a few subdirectories, and then build the kernel inside. The entire build should take less than 30 seconds.

Watch the commands executed during the build. On the Linux machines, the ordinary system tools are used. On a Mac, special build tools are used, whose names begin with ‘`i386-elf-`’, e.g. `i386-elf-gcc`, `i386-elf-ld`. These are “cross-compiler” tools. That is, the build is running on a Mac machine (called the *host*), but the result will run on a

simulated 80x86 machine (called the *target*). The '`i386-elf-program`' tools are specially built for this configuration.

Following the build, the following are the interesting files in the '`build`' directory:

'`Makefile`'
: A copy of '`pintos/src/Makefile.build`'. It describes how to build the kernel. See [Adding Source Files], page 17, for more information.

'`kernel.o`'
: Object file for the entire kernel. This is the result of linking object files compiled from each individual kernel source file into a single object file. It contains debug information, so you can run GDB (see Section E.5 [GDB], page 105) or `backtrace` (see Section E.4 [Backtraces], page 103) on it.

'`kernel.bin`'
: Memory image of the kernel, that is, the exact bytes loaded into memory to run the Pintos kernel. This is just '`kernel.o`' with debug information stripped out, which saves a lot of space, which in turn keeps the kernel from bumping up against a 512 kB size limit imposed by the kernel loader's design.

'`loader.bin`'
: Memory image for the kernel loader, a small chunk of code written in assembly language that reads the kernel from disk into memory and starts it up. It is exactly 512 bytes long, a size fixed by the PC BIOS.

Subdirectories of '`build`' contain object files ('`.o`') and dependency files ('`.d`'), both produced by the compiler. The dependency files tell `make` which source files need to be recompiled when other source or header files are changed.

1.1.3 Running Pintos

We've supplied a program for conveniently running Pintos in a simulator, called `pintos`. In the simplest case, you can invoke `pintos` as `pintos` *`argument`*`...`. Each *argument* is passed to the Pintos kernel for it to act on.

Try it out. First `cd` into the newly created '`build`' directory. Then issue the command `pintos run alarm-multiple`, which passes the arguments `run alarm-multiple` to the Pintos kernel. In these arguments, `run` instructs the kernel to run a test and `alarm-multiple` is the test to run.

This command creates a '`bochsrc.txt`' file, which is needed for running Bochs, and then invoke Bochs. Bochs opens a new window that represents the simulated machine's display, and a BIOS message briefly flashes. Then Pintos boots and runs the `alarm-multiple` test program, which outputs a few screenfuls of text. When it's done, you can close Bochs by clicking on the "Power" button in the window's top right corner, or rerun the whole process by clicking on the "Reset" button just to its left. The other buttons are not very useful for our purposes.

(If no window appeared at all, then you're probably logged in remotely and X forwarding is not set up correctly. In this case, you can fix your X setup, or you can use the '`-v`' option to disable X output: `pintos -v -- run alarm-multiple`.)

The text printed by Pintos inside Bochs probably went by too quickly to read. However, you've probably noticed by now that the same text was displayed in the terminal you used

to run `pintos`. This is because Pintos sends all output both to the VGA display and to the first serial port, and by default the serial port is connected to Bochs's `stdin` and `stdout`. You can log serial output to a file by redirecting at the command line, e.g. `pintos run alarm-multiple > logfile`.

The `pintos` program offers several options for configuring the simulator or the virtual hardware. If you specify any options, they must precede the commands passed to the Pintos kernel and be separated from them by '`--`', so that the whole command looks like `pintos` *`option`*`...` `--` *`argument`*`...`. Invoke `pintos` without any arguments to see a list of available options. Options can select a simulator to use: the default is Bochs, but '`--qemu`' selects QEMU. You can run the simulator with a debugger (see Section E.5 [GDB], page 105). You can set the amount of memory to give the VM. Finally, you can select how you want VM output to be displayed: use '`-v`' to turn off the VGA display, '`-t`' to use your terminal window as the VGA display instead of opening a new window (Bochs only), or '`-s`' to suppress serial input from `stdin` and output to `stdout`.

The Pintos kernel has commands and options other than `run`. These are not very interesting for now, but you can see a list of them using '`-h`', e.g. `pintos -h`.

1.1.4 Debugging versus Testing

When you're debugging code, it's useful to be able to run a program twice and have it do exactly the same thing. On second and later runs, you can make new observations without having to discard or verify your old observations. This property is called "reproducibility." One of the simulators that Pintos supports, Bochs, can be set up for reproducibility, and that's the way that `pintos` invokes it by default.

Of course, a simulation can only be reproducible from one run to the next if its input is the same each time. For simulating an entire computer, as we do, this means that every part of the computer must be the same. For example, you must use the same command-line argument, the same disks, the same version of Bochs, and you must not hit any keys on the keyboard (because you could not be sure to hit them at exactly the same point each time) during the runs.

While reproducibility is useful for debugging, it is a problem for testing thread synchronization, an important part of most of the projects. In particular, when Bochs is set up for reproducibility, timer interrupts will come at perfectly reproducible points, and therefore so will thread switches. That means that running the same test several times doesn't give you any greater confidence in your code's correctness than does running it only once.

So, to make your code easier to test, we've added a feature, called "jitter," to Bochs, that makes timer interrupts come at random intervals, but in a perfectly predictable way. In particular, if you invoke `pintos` with the option '`-j` *`seed`*', timer interrupts will come at irregularly spaced intervals. Within a single *seed* value, execution will still be reproducible, but timer behavior will change as *seed* is varied. Thus, for the highest degree of confidence you should test your code with many seed values.

On the other hand, when Bochs runs in reproducible mode, timings are not realistic, meaning that a "one-second" delay may be much shorter or even much longer than one second. You can invoke `pintos` with a different option, '`-r`', to set up Bochs for realistic timings, in which a one-second delay should take approximately one second of real time. Simulation in real-time mode is not reproducible, and options '`-j`' and '`-r`' are mutually exclusive.

The QEMU simulator is available as an alternative to Bochs (use '`--qemu`' when invoking `pintos`). The QEMU simulator is much faster than Bochs, but it only supports real-time simulation and does not have a reproducible mode.

1.2 Grading

We will grade your assignments based on test results and design quality, each of which comprises 50% of your grade.

1.2.1 Testing

Your test result grade will be based on our tests. Each project has several tests, each of which has a name beginning with '`tests`'. To completely test your submission, invoke `make check` from the project '`build`' directory. This will build and run each test and print a "pass" or "fail" message for each one. When a test fails, `make check` also prints some details of the reason for failure. After running all the tests, `make check` also prints a summary of the test results.

For project 1, the tests will probably run faster in Bochs. For the rest of the projects, they will run much faster in QEMU. `make check` will select the faster simulator by default, but you can override its choice by specifying '`SIMULATOR=--bochs`' or '`SIMULATOR=--qemu`' on the `make` command line.

You can also run individual tests one at a time. A given test *t* writes its output to '*t*`.output`', then a script scores the output as "pass" or "fail" and writes the verdict to '*t*`.result`'. To run and grade a single test, `make` the '`.result`' file explicitly from the '`build`' directory, e.g. `make tests/threads/alarm-multiple.result`. If `make` says that the test result is up-to-date, but you want to re-run it anyway, either run `make clean` or delete the '`.output`' file by hand.

By default, each test provides feedback only at completion, not during its run. If you prefer, you can observe the progress of each test by specifying '`VERBOSE=1`' on the `make` command line, as in `make check VERBOSE=1`. You can also provide arbitrary options to the `pintos` run by the tests with '`PINTOSOPTS='...'`', e.g. `make check PINTOSOPTS='-j 1'` to select a jitter value of 1 (see Section 1.1.4 [Debugging versus Testing], page 4).

All of the tests and related files are in '`pintos/src/tests`'. Before we test your submission, we will replace the contents of that directory by a pristine, unmodified copy, to ensure that the correct tests are used. Thus, you can modify some of the tests if that helps in debugging, but we will run the originals.

All software has bugs, so some of our tests may be flawed. If you think a test failure is a bug in the test, not a bug in your code, please point it out. We will look at it and fix it if necessary.

Please don't try to take advantage of our generosity in giving out our test suite. Your code has to work properly in the general case, not just for the test cases we supply. For example, it would be unacceptable to explicitly base the kernel's behavior on the name of the running test case. Such attempts to side-step the test cases will receive no credit. If you think your solution may be in a gray area here, please ask us about it.

1.2.2 Design

We will judge your design based on the design document and the source code that you submit. We will read your entire design document and much of your source code.

Don't forget that design quality, including the design document, is 50% of your project grade. It is better to spend one or two hours writing a good design document than it is to spend that time getting the last 5% of the points for tests and then trying to rush through writing the design document in the last 15 minutes.

1.2.2.1 Design Document

We provide a design document template for each project. For each significant part of a project, the template asks questions in four areas:

Data Structures

The instructions for this section are always the same:

> Copy here the declaration of each new or changed `struct` or `struct` member, global or static variable, `typedef`, or enumeration. Identify the purpose of each in 25 words or less.

The first part is mechanical. Just copy new or modified declarations into the design document, to highlight for us the actual changes to data structures. Each declaration should include the comment that should accompany it in the source code (see below).

We also ask for a very brief description of the purpose of each new or changed data structure. The limit of 25 words or less is a guideline intended to save your time and avoid duplication with later areas.

Algorithms

This is where you tell us how your code works, through questions that probe your understanding of your code. We might not be able to easily figure it out from the code, because many creative solutions exist for most OS problems. Help us out a little.

Your answers should be at a level below the high level description of requirements given in the assignment. We have read the assignment too, so it is unnecessary to repeat or rephrase what is stated there. On the other hand, your answers should be at a level above the low level of the code itself. Don't give a line-by-line run-down of what your code does. Instead, use your answers to explain how your code works to implement the requirements.

Synchronization

An operating system kernel is a complex, multithreaded program, in which synchronizing multiple threads can be difficult. This section asks about how you chose to synchronize this particular type of activity.

Rationale

Whereas the other sections primarily ask "what" and "how," the rationale section concentrates on "why." This is where we ask you to justify some design decisions, by explaining why the choices you made are better than alternatives. You may be able to state these in terms of time and space complexity, which

can be made as rough or informal arguments (formal language or proofs are unnecessary).

An incomplete, evasive, or non-responsive design document or one that strays from the template without good reason may be penalized. Incorrect capitalization, punctuation, spelling, or grammar can also cost points. See Appendix D [Project Documentation], page 99, for a sample design document for a fictitious project.

1.2.2.2 Source Code

Your design will also be judged by looking at your source code. We will typically look at the differences between the original Pintos source tree and your submission, based on the output of a command like `diff -urpb pintos.orig pintos.submitted`. We will try to match up your description of the design with the code submitted. Important discrepancies between the description and the actual code will be penalized, as will be any bugs we find by spot checks.

The most important aspects of source code design are those that specifically relate to the operating system issues at stake in the project. For example, the organization of an inode is an important part of file system design, so in the file system project a poorly designed inode would lose points. Other issues are much less important. For example, multiple Pintos design problems call for a "priority queue," that is, a dynamic collection from which the minimum (or maximum) item can quickly be extracted. Fast priority queues can be implemented many ways, but we do not expect you to build a fancy data structure even if it might improve performance. Instead, you are welcome to use a linked list (and Pintos even provides one with convenient functions for sorting and finding minimums and maximums).

Pintos is written in a consistent style. Make your additions and modifications in existing Pintos source files blend in, not stick out. In new source files, adopt the existing Pintos style by preference, but make your code self-consistent at the very least. There should not be a patchwork of different styles that makes it obvious that three different people wrote the code. Use horizontal and vertical white space to make code readable. Add a brief comment on every structure, structure member, global or static variable, typedef, enumeration, and function definition. Update existing comments as you modify code. Don't comment out or use the preprocessor to ignore blocks of code (instead, remove it entirely). Use assertions to document key invariants. Decompose code into functions for clarity. Code that is difficult to understand because it violates these or other "common sense" software engineering practices will be penalized.

In the end, remember your audience. Code is written primarily to be read by humans. It has to be acceptable to the compiler too, but the compiler doesn't care about how it looks or how well it is written.

1.3 Legal and Ethical Issues

Pintos is distributed under a liberal license that allows free use, modification, and distribution. Students and others who work on Pintos own the code that they write and may use it for any purpose. Pintos comes with NO WARRANTY, not even for MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See [License], page 119, for details of the license and lack of warranty.

In the context of USF's CS 326 course, please respect the spirit and the letter of the honor code by refraining from reading any homework solutions available online or elsewhere. Reading the source code for other operating system kernels, such as Linux or FreeBSD, is allowed, but do not copy code from them literally. Please cite the code that inspired your own in your design documentation.

1.4 Acknowledgements

The Pintos core and this documentation were originally written by Ben Pfaff `blp@cs.stanford.edu`.

Additional features were contributed by Anthony Romano `chz@vt.edu`.

The GDB macros supplied with Pintos were written by Godmar Back `gback@cs.vt.edu`, and their documentation is adapted from his work.

The original structure and form of Pintos was inspired by the Nachos instructional operating system from the University of California, Berkeley ([Christopher]).

The Pintos projects and documentation originated with those designed for Nachos by current and former CS 140 teaching assistants at Stanford University, including at least Yu Ping, Greg Hutchins, Kelly Shaw, Paul Twohey, Sameer Qureshi, and John Rector.

Example code for monitors (see Section A.3.4 [Monitors], page 68) is from classroom slides originally by Dawson Engler and updated by Mendel Rosenblum.

1.5 Trivia

Pintos originated as a replacement for Nachos with a similar design. Since then Pintos has greatly diverged from the Nachos design. Pintos differs from Nachos in two important ways. First, Pintos runs on real or simulated 80*x*86 hardware, but Nachos runs as a process on a host operating system. Second, Pintos is written in C like most real-world operating systems, but Nachos is written in C++.

Why the name "Pintos"? First, like nachos, pinto beans are a common Mexican food. Second, Pintos is small and a "pint" is a small amount. Third, like drivers of the eponymous car, students are likely to have trouble with blow-ups.

2 Project 1: Threads

In this assignment, we give you a minimally functional thread system. Your job is to extend the functionality of this system to gain a better understanding of synchronization problems.

You will be working primarily in the '`threads`' directory for this assignment, with some work in the '`devices`' directory on the side. Compilation should be done in the '`threads`' directory.

Before you read the description of this project, you should read all of the following sections: Chapter 1 [Introduction], page 1, Appendix C [Coding Standards], page 96, Appendix E [Debugging Tools], page 102, and Appendix F [Development Tools], page 113. You should at least skim the material from Section A.1 [Pintos Loading], page 58 through Section A.5 [Memory Allocation], page 75, especially Section A.3 [Synchronization], page 66. To complete this project you will also need to read Appendix B [4.4BSD Scheduler], page 91.

2.1 Background

2.1.1 Understanding Threads

The first step is to read and understand the code for the initial thread system. Pintos already implements thread creation and thread completion, a simple scheduler to switch between threads, and synchronization primitives (semaphores, locks, condition variables, and optimization barriers).

Some of this code might seem slightly mysterious. If you haven't already compiled and run the base system, as described in the introduction (see Chapter 1 [Introduction], page 1), you should do so now. You can read through parts of the source code to see what's going on. If you like, you can add calls to `printf()` almost anywhere, then recompile and run to see what happens and in what order. You can also run the kernel in a debugger and set breakpoints at interesting spots, single-step through code and examine data, and so on.

When a thread is created, you are creating a new context to be scheduled. You provide a function to be run in this context as an argument to `thread_create()`. The first time the thread is scheduled and runs, it starts from the beginning of that function and executes in that context. When the function returns, the thread terminates. Each thread, therefore, acts like a mini-program running inside Pintos, with the function passed to `thread_create()` acting like `main()`.

At any given time, exactly one thread runs and the rest, if any, become inactive. The scheduler decides which thread to run next. (If no thread is ready to run at any given time, then the special "idle" thread, implemented in `idle()`, runs.) Synchronization primitives can force context switches when one thread needs to wait for another thread to do something.

The mechanics of a context switch are in '`threads/switch.S`', which is 80*x*86 assembly code. (You don't have to understand it.) It saves the state of the currently running thread and restores the state of the thread we're switching to.

Using the GDB debugger, slowly trace through a context switch to see what happens (see Section E.5 [GDB], page 105). You can set a breakpoint on `schedule()` to start out,

and then single-step from there.[1] Be sure to keep track of each thread's address and state, and what procedures are on the call stack for each thread. You will notice that when one thread calls `switch_threads()`, another thread starts running, and the first thing the new thread does is to return from `switch_threads()`. You will understand the thread system once you understand why and how the `switch_threads()` that gets called is different from the `switch_threads()` that returns. See Section A.2.3 [Thread Switching], page 65, for more information.

Warning: In Pintos, each thread is assigned a small, fixed-size execution stack just under 4 kB in size. The kernel tries to detect stack overflow, but it cannot do so perfectly. You may cause bizarre problems, such as mysterious kernel panics, if you declare large data structures as non-static local variables, e.g. '`int buf[1000];`'. Alternatives to stack allocation include the page allocator and the block allocator (see Section A.5 [Memory Allocation], page 75).

2.1.2 Source Files

Here is a brief overview of the files in the '`threads`' directory. You will not need to modify most of this code, but the hope is that presenting this overview will give you a start on what code to look at.

'`loader.S`'
'`loader.h`'
: The kernel loader. Assembles to 512 bytes of code and data that the PC BIOS loads into memory and which in turn finds the kernel on disk, loads it into memory, and jumps to `start()` in '`start.S`'. See Section A.1.1 [Pintos Loader], page 58, for details. You should not need to look at this code or modify it.

'`start.S`'
: Does basic setup needed for memory protection and 32-bit operation on 80x86 CPUs. Unlike the loader, this code is actually part of the kernel. See Section A.1.2 [Low-Level Kernel Initialization], page 59, for details.

'`kernel.lds.S`'
: The linker script used to link the kernel. Sets the load address of the kernel and arranges for '`start.S`' to be near the beginning of the kernel image. See Section A.1.1 [Pintos Loader], page 58, for details. Again, you should not need to look at this code or modify it, but it's here in case you're curious.

'`init.c`'
'`init.h`'
: Kernel initialization, including `main()`, the kernel's "main program." You should look over `main()` at least to see what gets initialized. You might want to add your own initialization code here. See Section A.1.3 [High-Level Kernel Initialization], page 59, for details.

'`thread.c`'
'`thread.h`'
: Basic thread support. Much of your work will take place in these files. '`thread.h`' defines `struct thread`, which you are likely to modify in all four projects. See Section A.2.1 [struct thread], page 61 and Section A.2 [Threads], page 61 for more information.

[1] GDB might tell you that `schedule()` doesn't exist, which is arguably a GDB bug. You can work around this by setting the breakpoint by filename and line number, e.g. `break thread.c:`*ln* where *ln* is the line number of the first declaration in `schedule()`.

‘`switch.S`’
‘`switch.h`’
: Assembly language routine for switching threads. Already discussed above. See Section A.2.2 [Thread Functions], page 63, for more information.

‘`palloc.c`’
‘`palloc.h`’
: Page allocator, which hands out system memory in multiples of 4 kB pages. See Section A.5.1 [Page Allocator], page 75, for more information.

‘`malloc.c`’
‘`malloc.h`’
: A simple implementation of `malloc()` and `free()` for the kernel. See Section A.5.2 [Block Allocator], page 76, for more information.

‘`interrupt.c`’
‘`interrupt.h`’
: Basic interrupt handling and functions for turning interrupts on and off. See Section A.4 [Interrupt Handling], page 71, for more information.

‘`intr-stubs.S`’
‘`intr-stubs.h`’
: Assembly code for low-level interrupt handling. See Section A.4.1 [Interrupt Infrastructure], page 72, for more information.

‘`synch.c`’
‘`synch.h`’ Basic synchronization primitives: semaphores, locks, condition variables, and optimization barriers. You will need to use these for synchronization in all four projects. See Section A.3 [Synchronization], page 66, for more information.

‘`io.h`’ Functions for I/O port access. This is mostly used by source code in the ‘`devices`’ directory that you won’t have to touch.

‘`vaddr.h`’
‘`pte.h`’ Functions and macros for working with virtual addresses and page table entries. These will be more important to you in project 3. For now, you can ignore them.

‘`flags.h`’ Macros that define a few bits in the 80x86 “flags” register. Probably of no interest. See [IA32-v1], section 3.4.3, “EFLAGS Register,” for more information.

2.1.2.1 ‘`devices`’ code

The basic threaded kernel also includes these files in the ‘`devices`’ directory:

‘`timer.c`’
‘`timer.h`’ System timer that ticks, by default, 100 times per second. You will modify this code in this project.

‘`vga.c`’
‘`vga.h`’ VGA display driver. Responsible for writing text to the screen. You should have no need to look at this code. `printf()` calls into the VGA display driver for you, so there’s little reason to call this code yourself.

‘`serial.c`’
‘`serial.h`’
: Serial port driver. Again, `printf()` calls this code for you, so you don’t need to do so yourself. It handles serial input by passing it to the input layer (see below).

‘`block.c`’
‘`block.h`’
: An abstraction layer for *block devices*, that is, random-access, disk-like devices that are organized as arrays of fixed-size blocks. Out of the box, Pintos supports two types of block devices: IDE disks and partitions. Block devices, regardless of type, won’t actually be used until project 2.

‘`ide.c`’
‘`ide.h`’
: Supports reading and writing sectors on up to 4 IDE disks.

‘`partition.c`’
‘`partition.h`’
: Understands the structure of partitions on disks, allowing a single disk to be carved up into multiple regions (partitions) for independent use.

‘`kbd.c`’
‘`kbd.h`’
: Keyboard driver. Handles keystrokes passing them to the input layer (see below).

‘`input.c`’
‘`input.h`’
: Input layer. Queues input characters passed along by the keyboard or serial drivers.

‘`intq.c`’
‘`intq.h`’
: Interrupt queue, for managing a circular queue that both kernel threads and interrupt handlers want to access. Used by the keyboard and serial drivers.

‘`rtc.c`’
‘`rtc.h`’
: Real-time clock driver, to enable the kernel to determine the current date and time. By default, this is only used by ‘`thread/init.c`’ to choose an initial seed for the random number generator.

‘`speaker.c`’
‘`speaker.h`’
: Driver that can produce tones on the PC speaker.

‘`pit.c`’
‘`pit.h`’
: Code to configure the 8254 Programmable Interrupt Timer. This code is used by both ‘`devices/timer.c`’ and ‘`devices/speaker.c`’ because each device uses one of the PIT’s output channel.

2.1.2.2 ‘`lib`’ files

Finally, ‘`lib`’ and ‘`lib/kernel`’ contain useful library routines. (‘`lib/user`’ will be used by user programs, starting in project 2, but it is not part of the kernel.) Here’s a few more details:

‘ctype.h’
‘inttypes.h’
‘limits.h’
‘stdarg.h’
‘stdbool.h’
‘stddef.h’
‘stdint.h’
‘stdio.c’
‘stdio.h’
‘stdlib.c’
‘stdlib.h’
‘string.c’
‘string.h’
: A subset of the standard C library. See Section C.2 [C99], page 96, for information on a few recently introduced pieces of the C library that you might not have encountered before. See Section C.3 [Unsafe String Functions], page 97, for information on what's been intentionally left out for safety.

‘debug.c’
‘debug.h’
: Functions and macros to aid debugging. See Appendix E [Debugging Tools], page 102, for more information.

‘random.c’
‘random.h’
: Pseudo-random number generator. The actual sequence of random values will not vary from one Pintos run to another, unless you do one of three things: specify a new random seed value on the ‘-rs’ kernel command-line option on each run, or use a simulator other than Bochs, or specify the ‘-r’ option to `pintos`.

‘round.h’
: Macros for rounding.

‘syscall-nr.h’
: System call numbers. Not used until project 2.

‘kernel/list.c’
‘kernel/list.h’
: Doubly linked list implementation. Used all over the Pintos code, and you'll probably want to use it a few places yourself in project 1.

‘kernel/bitmap.c’
‘kernel/bitmap.h’
: Bitmap implementation. You can use this in your code if you like, but you probably won't have any need for it in project 1.

‘kernel/hash.c’
‘kernel/hash.h’
: Hash table implementation. Likely to come in handy for project 3.

‘`kernel/console.c`’
‘`kernel/console.h`’
‘`kernel/stdio.h`’
Implements `printf()` and a few other functions.

2.1.3 Synchronization

Proper synchronization is an important part of the solutions to these problems. Any synchronization problem can be easily solved by turning interrupts off: while interrupts are off, there is no concurrency, so there's no possibility for race conditions. Therefore, it's tempting to solve all synchronization problems this way, but **don't**. Instead, use semaphores, locks, and condition variables to solve the bulk of your synchronization problems. Read the tour section on synchronization (see Section A.3 [Synchronization], page 66) or the comments in ‘`threads/synch.c`’ if you're unsure what synchronization primitives may be used in what situations.

In the Pintos projects, the only class of problem best solved by disabling interrupts is coordinating data shared between a kernel thread and an interrupt handler. Because interrupt handlers can't sleep, they can't acquire locks. This means that data shared between kernel threads and an interrupt handler must be protected within a kernel thread by turning off interrupts.

This project only requires accessing a little bit of thread state from interrupt handlers. For the alarm clock, the timer interrupt needs to wake up sleeping threads. In the advanced scheduler, the timer interrupt needs to access a few global and per-thread variables. When you access these variables from kernel threads, you will need to disable interrupts to prevent the timer interrupt from interfering.

When you do turn off interrupts, take care to do so for the least amount of code possible, or you can end up losing important things such as timer ticks or input events. Turning off interrupts also increases the interrupt handling latency, which can make a machine feel sluggish if taken too far.

The synchronization primitives themselves in ‘`synch.c`’ are implemented by disabling interrupts. You may need to increase the amount of code that runs with interrupts disabled here, but you should still try to keep it to a minimum.

Disabling interrupts can be useful for debugging, if you want to make sure that a section of code is not interrupted. You should remove debugging code before turning in your project. (Don't just comment it out, because that can make the code difficult to read.)

There should be no busy waiting in your submission. A tight loop that calls `thread_yield()` is one form of busy waiting.

2.1.4 Development Suggestions

In the past, many groups divided the assignment into pieces, then each group member worked on his or her piece until just before the deadline, at which time the group reconvened to combine their code and submit. **This is a bad idea. We do not recommend this approach.** Groups that do this often find that two changes conflict with each other, requiring lots of last-minute debugging. Some groups who have done this have turned in code that did not even compile or boot, much less pass any tests.

Instead, we recommend integrating your team's changes early and often, using a source code control system such as Git. This is less likely to produce surprises, because everyone can see everyone else's code as it is written, instead of just when it is finished. These systems also make it possible to review changes and, when a change introduces a bug, drop back to working versions of code.

You should expect to run into bugs that you simply don't understand while working on this and subsequent projects. When you do, reread the appendix on debugging tools, which is filled with useful debugging tips that should help you to get back up to speed (see Appendix E [Debugging Tools], page 102). Be sure to read the section on backtraces (see Section E.4 [Backtraces], page 103), which will help you to get the most out of every kernel panic or assertion failure.

2.2 Requirements

2.2.1 Design Document

Before you turn in your project, you must copy the project 1 design document template into your source tree under the name '`pintos/src/threads/DESIGNDOC`' and fill it in. We recommend that you read the design document template before you start working on the project. See Appendix D [Project Documentation], page 99, for a sample design document that goes along with a fictitious project.

2.2.2 Alarm Clock

Reimplement `timer_sleep()`, defined in '`devices/timer.c`'. Although a working implementation is provided, it "busy waits," that is, it spins in a loop checking the current time and calling `thread_yield()` until enough time has gone by. Reimplement it to avoid busy waiting.

`void timer_sleep (`*int64_t* `ticks``)` [Function]

Suspends execution of the calling thread until time has advanced by at least *x* timer ticks. Unless the system is otherwise idle, the thread need not wake up after exactly *x* ticks. Just put it on the ready queue after they have waited for the right amount of time.

`timer_sleep()` is useful for threads that operate in real-time, e.g. for blinking the cursor once per second.

The argument to `timer_sleep()` is expressed in timer ticks, not in milliseconds or any another unit. There are `TIMER_FREQ` timer ticks per second, where `TIMER_FREQ` is a macro defined in `devices/timer.h`. The default value is 100. We don't recommend changing this value, because any change is likely to cause many of the tests to fail.

Separate functions `timer_msleep()`, `timer_usleep()`, and `timer_nsleep()` do exist for sleeping a specific number of milliseconds, microseconds, or nanoseconds, respectively, but these will call `timer_sleep()` automatically when necessary. You do not need to modify them.

If your delays seem too short or too long, reread the explanation of the '`-r`' option to `pintos` (see Section 1.1.4 [Debugging versus Testing], page 4).

The alarm clock implementation is not needed for later projects, although it could be useful for project 4.

2.2.3 Priority Scheduling

Implement priority scheduling in Pintos. When a thread is added to the ready list that has a higher priority than the currently running thread, the current thread should immediately yield the processor to the new thread. Similarly, when threads are waiting for a lock, semaphore, or condition variable, the highest priority waiting thread should be awakened first. A thread may raise or lower its own priority at any time, but lowering its priority such that it no longer has the highest priority must cause it to immediately yield the CPU.

Thread priorities range from `PRI_MIN` (0) to `PRI_MAX` (63). Lower numbers correspond to lower priorities, so that priority 0 is the lowest priority and priority 63 is the highest. The initial thread priority is passed as an argument to `thread_create()`. If there's no reason to choose another priority, use `PRI_DEFAULT` (31). The `PRI_` macros are defined in '`threads/thread.h`', and you should not change their values.

One issue with priority scheduling is "priority inversion". Consider high, medium, and low priority threads H, M, and L, respectively. If H needs to wait for L (for instance, for a lock held by L), and M is on the ready list, then H will never get the CPU because the low priority thread will not get any CPU time. A partial fix for this problem is for H to "donate" its priority to L while L is holding the lock, then recall the donation once L releases (and thus H acquires) the lock.

Implement priority donation. You will need to account for all different situations in which priority donation is required. Be sure to handle multiple donations, in which multiple priorities are donated to a single thread. You must also handle nested donation: if H is waiting on a lock that M holds and M is waiting on a lock that L holds, then both M and L should be boosted to H's priority. If necessary, you may impose a reasonable limit on depth of nested priority donation, such as 8 levels.

You must implement priority donation for locks. You need not implement priority donation for the other Pintos synchronization constructs. You do need to implement priority scheduling in all cases.

Finally, implement the following functions that allow a thread to examine and modify its own priority. Skeletons for these functions are provided in '`threads/thread.c`'.

`void thread_set_priority (`*int new_priority*`)` [Function]
: Sets the current thread's priority to *new_priority*. If the current thread no longer has the highest priority, yields.

`int thread_get_priority (`*void*`)` [Function]
: Returns the current thread's priority. In the presence of priority donation, returns the higher (donated) priority.

You need not provide any interface to allow a thread to directly modify other threads' priorities.

The priority scheduler is not used in any later project.

2.2.4 Advanced Scheduler

Implement a multilevel feedback queue scheduler similar to the 4.4BSD scheduler to reduce the average response time for running jobs on your system. See Appendix B [4.4BSD Scheduler], page 91, for detailed requirements.

Like the priority scheduler, the advanced scheduler chooses the thread to run based on priorities. However, the advanced scheduler does not do priority donation. Thus, we recommend that you have the priority scheduler working, except possibly for priority donation, before you start work on the advanced scheduler.

You must write your code to allow us to choose a scheduling algorithm policy at Pintos startup time. By default, the priority scheduler must be active, but we must be able to choose the 4.4BSD scheduler with the '`-mlfqs`' kernel option. Passing this option sets `thread_mlfqs`, declared in '`threads/thread.h`', to true when the options are parsed by `parse_options()`, which happens early in `main()`.

When the 4.4BSD scheduler is enabled, threads no longer directly control their own priorities. The *priority* argument to `thread_create()` should be ignored, as well as any calls to `thread_set_priority()`, and `thread_get_priority()` should return the thread's current priority as set by the scheduler.

The advanced scheduler is not used in any later project.

2.3 FAQ

How much code will I need to write?

Here's a summary of our reference solution, produced by the `diffstat` program. The final row gives total lines inserted and deleted; a changed line counts as both an insertion and a deletion.

The reference solution represents just one possible solution. Many other solutions are also possible and many of those differ greatly from the reference solution. Some excellent solutions may not modify all the files modified by the reference solution, and some may modify files not modified by the reference solution.

```
devices/timer.c       |   42 +++++-
threads/fixed-point.h |  120 ++++++++++++++++++
threads/synch.c       |   88 ++++++++++++-
threads/thread.c      |  196 ++++++++++++++++++++++++++----
threads/thread.h      |   23 +++
5 files changed, 440 insertions(+), 29 deletions(-)
```

'`fixed-point.h`' is a new file added by the reference solution.

How do I update the '`Makefile`'s when I add a new source file?

To add a '`.c`' file, edit the top-level '`Makefile.build`'. Add the new file to variable '*dir*`_SRC`', where *dir* is the directory where you added the file. For this project, that means you should add it to `threads_SRC` or `devices_SRC`. Then run `make`. If your new file doesn't get compiled, run `make clean` and then try again.

When you modify the top-level '`Makefile.build`' and re-run `make`, the modified version should be automatically copied to '`threads/build/Makefile`'. The converse is not true, so any changes will be lost the next time you run `make clean` from the '`threads`' directory. Unless your changes are truly temporary, you should prefer to edit '`Makefile.build`'.

A new '`.h`' file does not require editing the '`Makefile`'s.

What does `warning: no previous prototype for 'func'` mean?

It means that you defined a non-`static` function without preceding it by a prototype. Because non-`static` functions are intended for use by other '`.c`' files, for safety they should be prototyped in a header file included before their definition. To fix the problem, add a prototype in a header file that you include, or, if the function isn't actually used by other '`.c`' files, make it `static`.

What is the interval between timer interrupts?

Timer interrupts occur `TIMER_FREQ` times per second. You can adjust this value by editing '`devices/timer.h`'. The default is 100 Hz.

We don't recommend changing this value, because any changes are likely to cause many of the tests to fail.

How long is a time slice?

There are `TIME_SLICE` ticks per time slice. This macro is declared in '`threads/thread.c`'. The default is 4 ticks.

We don't recommend changing this value, because any changes are likely to cause many of the tests to fail.

How do I run the tests?

See Section 1.2.1 [Testing], page 5.

Why do I get a test failure in `pass()`?

You are probably looking at a backtrace that looks something like this:

```
0xc0108810: debug_panic (lib/kernel/debug.c:32)
0xc010a99f: pass (tests/threads/tests.c:93)
0xc010bdd3: test_mlfqs_load_1 (...threads/mlfqs-load-1.c:33)
0xc010a8cf: run_test (tests/threads/tests.c:51)
0xc0100452: run_task (threads/init.c:283)
0xc0100536: run_actions (threads/init.c:333)
0xc01000bb: main (threads/init.c:137)
```

This is just confusing output from the `backtrace` program. It does not actually mean that `pass()` called `debug_panic()`. In fact, `fail()` called `debug_panic()` (via the `PANIC()` macro). GCC knows that `debug_panic()` does not return, because it is declared `NO_RETURN` (see Section E.3 [Function and Parameter Attributes], page 102), so it doesn't include any code in `fail()` to take control when `debug_panic()` returns. This means that the return address on the stack looks like it is at the beginning of the function that happens to follow `fail()` in memory, which in this case happens to be `pass()`.

See Section E.4 [Backtraces], page 103, for more information.

How do interrupts get re-enabled in the new thread following `schedule()`?

Every path into `schedule()` disables interrupts. They eventually get re-enabled by the next thread to be scheduled. Consider the possibilities: the new thread is running in `switch_thread()` (but see below), which is called by `schedule()`, which is called by one of a few possible functions:

- `thread_exit()`, but we'll never switch back into such a thread, so it's uninteresting.

- `thread_yield()`, which immediately restores the interrupt level upon return from `schedule()`.
- `thread_block()`, which is called from multiple places:
  - `sema_down()`, which restores the interrupt level before returning.
  - `idle()`, which enables interrupts with an explicit assembly STI instruction.
  - `wait()` in '`devices/intq.c`', whose callers are responsible for reenabling interrupts.

There is a special case when a newly created thread runs for the first time. Such a thread calls `intr_enable()` as the first action in `kernel_thread()`, which is at the bottom of the call stack for every kernel thread but the first.

2.3.1 Alarm Clock FAQ

Do I need to account for timer values overflowing?

Don't worry about the possibility of timer values overflowing. Timer values are expressed as signed 64-bit numbers, which at 100 ticks per second should be good for almost 2,924,712,087 years. By then, we expect Pintos to have been phased out of the CS 326 curriculum.

2.3.2 Priority Scheduling FAQ

Doesn't priority scheduling lead to starvation?

Yes, strict priority scheduling can lead to starvation because a thread will not run if any higher-priority thread is runnable. The advanced scheduler introduces a mechanism for dynamically changing thread priorities.

Strict priority scheduling is valuable in real-time systems because it offers the programmer more control over which jobs get processing time. High priorities are generally reserved for time-critical tasks. It's not "fair," but it addresses other concerns not applicable to a general-purpose operating system.

What thread should run after a lock has been released?

When a lock is released, the highest priority thread waiting for that lock should be unblocked and put on the list of ready threads. The scheduler should then run the highest priority thread on the ready list.

If the highest-priority thread yields, does it continue running?

Yes. If there is a single highest-priority thread, it continues running until it blocks or finishes, even if it calls `thread_yield()`. If multiple threads have the same highest priority, `thread_yield()` should switch among them in "round robin" order.

What happens to the priority of a donating thread?

Priority donation only changes the priority of the donee thread. The donor thread's priority is unchanged. Priority donation is not additive: if thread A (with priority 5) donates to thread B (with priority 3), then B's new priority is 5, not 8.

Can a thread's priority change while it is on the ready queue?

Yes. Consider a ready, low-priority thread L that holds a lock. High-priority thread H attempts to acquire the lock and blocks, thereby donating its priority to ready thread L.

Can a thread's priority change while it is blocked?

Yes. While a thread that has acquired lock L is blocked for any reason, its priority can increase by priority donation if a higher-priority thread attempts to acquire L. This case is checked by the `priority-donate-sema` test.

Can a thread added to the ready list preempt the processor?

Yes. If a thread added to the ready list has higher priority than the running thread, the correct behavior is to immediately yield the processor. It is not acceptable to wait for the next timer interrupt. The highest priority thread should run as soon as it is runnable, preempting whatever thread is currently running.

How does `thread_set_priority()` affect a thread receiving donations?

It sets the thread's base priority. The thread's effective priority becomes the higher of the newly set priority or the highest donated priority. When the donations are released, the thread's priority becomes the one set through the function call. This behavior is checked by the `priority-donate-lower` test.

Doubled test names in output make them fail.

Suppose you are seeing output in which some test names are doubled, like this:

```
(alarm-priority) begin
(alarm-priority) (alarm-priority) Thread priority 30 woke up.
Thread priority 29 woke up.
(alarm-priority) Thread priority 28 woke up.
```

What is happening is that output from two threads is being interleaved. That is, one thread is printing `"(alarm-priority) Thread priority 29 woke up.\n"` and another thread is printing `"(alarm-priority) Thread priority 30 woke up.\n"`, but the first thread is being preempted by the second in the middle of its output.

This problem indicates a bug in your priority scheduler. After all, a thread with priority 29 should not be able to run while a thread with priority 30 has work to do.

Normally, the implementation of the `printf()` function in the Pintos kernel attempts to prevent such interleaved output by acquiring a console lock during the duration of the `printf` call and releasing it afterwards. However, the output of the test name, e.g., `(alarm-priority)`, and the message following it is output using two calls to `printf`, resulting in the console lock being acquired and released twice.

2.3.3 Advanced Scheduler FAQ

How does priority donation interact with the advanced scheduler?

It doesn't have to. We won't test priority donation and the advanced scheduler at the same time.

Can I use one queue instead of 64 queues?

Yes. In general, your implementation may differ from the description, as long as its behavior is the same.

Some scheduler tests fail and I don't understand why. Help!

If your implementation mysteriously fails some of the advanced scheduler tests, try the following:

- Read the source files for the tests that you're failing, to make sure that you understand what's going on. Each one has a comment at the top that explains its purpose and expected results.
- Double-check your fixed-point arithmetic routines and your use of them in the scheduler routines.
- Consider how much work your implementation does in the timer interrupt. If the timer interrupt handler takes too long, then it will take away most of a timer tick from the thread that the timer interrupt preempted. When it returns control to that thread, it therefore won't get to do much work before the next timer interrupt arrives. That thread will therefore get blamed for a lot more CPU time than it actually got a chance to use. This raises the interrupted thread's recent CPU count, thereby lowering its priority. It can cause scheduling decisions to change. It also raises the load average.

3 Project 2: User Programs

Now that you've worked with Pintos and are becoming familiar with its infrastructure and thread package, it's time to start working on the parts of the system that allow running user programs. The base code already supports loading and running user programs, but no I/O or interactivity is possible. In this project, you will enable programs to interact with the OS via system calls.

You will be working out of the '`userprog`' directory for this assignment, but you will also be interacting with almost every other part of Pintos. We will describe the relevant parts below.

You can build project 2 on top of your project 1 submission or you can start fresh. No code from project 1 is required for this assignment. The "alarm clock" functionality may be useful in projects 3 and 4, but it is not strictly required.

You might find it useful to go back and reread how to run the tests (see Section 1.2.1 [Testing], page 5).

3.1 Background

Up to now, all of the code you have run under Pintos has been part of the operating system kernel. This means, for example, that all the test code from the last assignment ran as part of the kernel, with full access to privileged parts of the system. Once we start running user programs on top of the operating system, this is no longer true. This project deals with the consequences.

We allow more than one process to run at a time. Each process has one thread (multi-threaded processes are not supported). User programs are written under the illusion that they have the entire machine. This means that when you load and run multiple processes at a time, you must manage memory, scheduling, and other state correctly to maintain this illusion.

In the previous project, we compiled our test code directly into your kernel, so we had to require certain specific function interfaces within the kernel. From now on, we will test your operating system by running user programs. This gives you much greater freedom. You must make sure that the user program interface meets the specifications described here, but given that constraint you are free to restructure or rewrite kernel code however you wish.

3.1.1 Source Files

The easiest way to get an overview of the programming you will be doing is to simply go over each part you'll be working with. In '`userprog`', you'll find a small number of files, but here is where the bulk of your work will be:

'`process.c`'
'`process.h`'
: Loads ELF binaries and starts processes.

'`pagedir.c`'
'`pagedir.h`'
: A simple manager for 80x86 hardware page tables. Although you probably won't want to modify this code for this project, you may want to call some of its functions. See Section 4.1.2.3 [Page Tables], page 40, for more information.

'`syscall.c`'
'`syscall.h`'
: Whenever a user process wants to access some kernel functionality, it invokes a system call. This is a skeleton system call handler. Currently, it just prints a message and terminates the user process. In part 2 of this project you will add code to do everything else needed by system calls.

'`exception.c`'
'`exception.h`'
: When a user process performs a privileged or prohibited operation, it traps into the kernel as an "exception" or "fault."[1] These files handle exceptions. Currently all exceptions simply print a message and terminate the process. Some, but not all, solutions to project 2 require modifying `page_fault()` in this file.

'`gdt.c`'
'`gdt.h`'
: The 80*x*86 is a segmented architecture. The Global Descriptor Table (GDT) is a table that describes the segments in use. These files set up the GDT. You should not need to modify these files for any of the projects. You can read the code if you're interested in how the GDT works.

'`tss.c`'
'`tss.h`'
: The Task-State Segment (TSS) is used for 80*x*86 architectural task switching. Pintos uses the TSS only for switching stacks when a user process enters an interrupt handler, as does Linux. You should not need to modify these files for any of the projects. You can read the code if you're interested in how the TSS works.

3.1.2 Using the File System

You will need to interface to the file system code for this project, because user programs are loaded from the file system and many of the system calls you must implement deal with the file system. However, the focus of this project is not the file system, so we have provided a simple but complete file system in the '`filesys`' directory. You will want to look over the '`filesys.h`' and '`file.h`' interfaces to understand how to use the file system, and especially its many limitations.

There is no need to modify the file system code for this project, and so we recommend that you do not. Working on the file system is likely to distract you from this project's focus.

Proper use of the file system routines now will make life much easier for project 4, when you improve the file system implementation. Until then, you will have to tolerate the following limitations:

- No internal synchronization. Concurrent accesses will interfere with one another. You should use synchronization to ensure that only one process at a time is executing file system code.

[1] We will treat these terms as synonyms. There is no standard distinction between them, although Intel processor manuals make a minor distinction between them on 80*x*86.

- File size is fixed at creation time. The root directory is represented as a file, so the number of files that may be created is also limited.
- File data is allocated as a single extent, that is, data in a single file must occupy a contiguous range of sectors on disk. External fragmentation can therefore become a serious problem as a file system is used over time.
- No subdirectories.
- File names are limited to 14 characters.
- A system crash mid-operation may corrupt the disk in a way that cannot be repaired automatically. There is no file system repair tool anyway.

One important feature is included:

- Unix-like semantics for `filesys_remove()` are implemented. That is, if a file is open when it is removed, its blocks are not deallocated and it may still be accessed by any threads that have it open, until the last one closes it. See [Removing an Open File], page 35, for more information.

You need to be able to create a simulated disk with a file system partition. The `pintos-mkdisk` program provides this functionality. From the '`userprog/build`' directory, execute `pintos-mkdisk filesys.dsk --filesys-size=2`. This command creates a simulated disk named '`filesys.dsk`' that contains a 2 MB Pintos file system partition. Then format the file system partition by passing '`-f -q`' on the kernel's command line: `pintos -f -q`. The '`-f`' option causes the file system to be formatted, and '`-q`' causes Pintos to exit as soon as the format is done.

You'll need a way to copy files in and out of the simulated file system. The `pintos` '`-p`' ("put") and '`-g`' ("get") options do this. To copy '*`file`*' into the Pintos file system, use the command '`pintos -p` *`file`* `-- -q`'. (The '`--`' is needed because '`-p`' is for the `pintos` script, not for the simulated kernel.) To copy it to the Pintos file system under the name '*`newname`*', add '`-a` *`newname`*': '`pintos -p` *`file`* `-a` *`newname`* `-- -q`'. The commands for copying files out of a VM are similar, but substitute '`-g`' for '`-p`'.

Incidentally, these commands work by passing special commands `extract` and `append` on the kernel's command line and copying to and from a special simulated "scratch" partition. If you're very curious, you can look at the `pintos` script as well as '`filesys/fsutil.c`' to learn the implementation details.

Here's a summary of how to create a disk with a file system partition, format the file system, copy the `echo` program into the new disk, and then run `echo`, passing argument `x`. (Argument passing won't work until you implemented it.) It assumes that you've already built the examples in '`examples`' and that the current directory is '`userprog/build`':

```
pintos-mkdisk filesys.dsk --filesys-size=2
pintos -f -q
pintos -p ../../examples/echo -a echo -- -q
pintos -q run 'echo x'
```

The three final steps can actually be combined into a single command:

```
pintos-mkdisk filesys.dsk --filesys-size=2
pintos -p ../../examples/echo -a echo -- -f -q run 'echo x'
```

If you don't want to keep the file system disk around for later use or inspection, you can even combine all four steps into a single command. The `--filesys-size=`*`n`* option creates

a temporary file system partition approximately *n* megabytes in size just for the duration of the `pintos` run. The Pintos automatic test suite makes extensive use of this syntax:

```
pintos --filesys-size=2 -p ../../examples/echo -a echo -- -f -q run 'echo x'
```

You can delete a file from the Pintos file system using the `rm` *`file`* kernel action, e.g. `pintos -q rm` *`file`*. Also, `ls` lists the files in the file system and `cat` *`file`* prints a file's contents to the display.

3.1.3 How User Programs Work

Pintos can run normal C programs, as long as they fit into memory and use only the system calls you implement. Notably, `malloc()` cannot be implemented because none of the system calls required for this project allow for memory allocation. Pintos also can't run programs that use floating point operations, since the kernel doesn't save and restore the processor's floating-point unit when switching threads.

The '`src/examples`' directory contains a few sample user programs. The '`Makefile`' in this directory compiles the provided examples, and you can edit it compile your own programs as well. Some of the example programs will only work once projects 3 or 4 have been implemented.

Pintos can load *ELF* executables with the loader provided for you in '`userprog/process.c`'. ELF is a file format used by Linux, Solaris, and many other operating systems for object files, shared libraries, and executables. You can actually use any compiler and linker that output 80*x*86 ELF executables to produce programs for Pintos. (We've provided compilers and linkers that should do just fine.)

You should realize immediately that, until you copy a test program to the simulated file system, Pintos will be unable to do useful work. You won't be able to do interesting things until you copy a variety of programs to the file system. You might want to create a clean reference file system disk and copy that over whenever you trash your '`filesys.dsk`' beyond a useful state, which may happen occasionally while debugging.

3.1.4 Virtual Memory Layout

Virtual memory in Pintos is divided into two regions: user virtual memory and kernel virtual memory. User virtual memory ranges from virtual address 0 up to `PHYS_BASE`, which is defined in '`threads/vaddr.h`' and defaults to `0xc0000000` (3 GB). Kernel virtual memory occupies the rest of the virtual address space, from `PHYS_BASE` up to 4 GB.

User virtual memory is per-process. When the kernel switches from one process to another, it also switches user virtual address spaces by changing the processor's page directory base register (see `pagedir_activate()` in '`userprog/pagedir.c`'). `struct thread` contains a pointer to a process's page table.

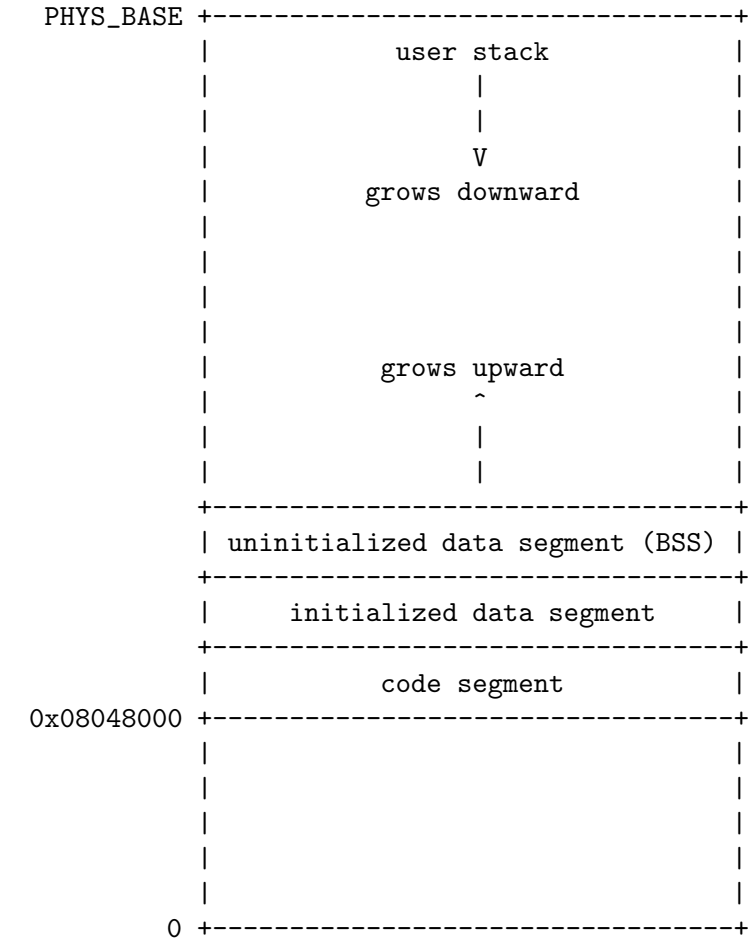
Kernel virtual memory is global. It is always mapped the same way, regardless of what user process or kernel thread is running. In Pintos, kernel virtual memory is mapped one-to-one to physical memory, starting at `PHYS_BASE`. That is, virtual address `PHYS_BASE` accesses physical address 0, virtual address `PHYS_BASE + 0x1234` accesses physical address `0x1234`, and so on up to the size of the machine's physical memory.

A user program can only access its own user virtual memory. An attempt to access kernel virtual memory causes a page fault, handled by `page_fault()` in '`userprog/exception.c`', and the process will be terminated. Kernel threads can access both kernel virtual memory

and, if a user process is running, the user virtual memory of the running process. However, even in the kernel, an attempt to access memory at an unmapped user virtual address will cause a page fault.

3.1.4.1 Typical Memory Layout

Conceptually, each process is free to lay out its own user virtual memory however it chooses. In practice, user virtual memory is laid out like this:



In this project, the user stack is fixed in size, but in project 3 it will be allowed to grow. Traditionally, the size of the uninitialized data segment can be adjusted with a system call, but you will not have to implement this.

The code segment in Pintos starts at user virtual address `0x08084000`, approximately 128 MB from the bottom of the address space. This value is specified in [SysV-i386] and has no deep significance.

The linker sets the layout of a user program in memory, as directed by a "linker script" that tells it the names and locations of the various program segments. You can learn more about linker scripts by reading the "Scripts" chapter in the linker manual, accessible via '`info ld`'.

To view the layout of a particular executable, run `objdump` (80x86) or `i386-elf-objdump` (SPARC) with the '`-p`' option.

3.1.5 Accessing User Memory

As part of a system call, the kernel must often access memory through pointers provided by a user program. The kernel must be very careful about doing so, because the user can pass a null pointer, a pointer to unmapped virtual memory, or a pointer to kernel virtual address space (above `PHYS_BASE`). All of these types of invalid pointers must be rejected without harm to the kernel or other running processes, by terminating the offending process and freeing its resources.

There are at least two reasonable ways to do this correctly. The first method is to verify the validity of a user-provided pointer, then dereference it. If you choose this route, you'll want to look at the functions in '`userprog/pagedir.c`' and in '`threads/vaddr.h`'. This is the simplest way to handle user memory access.

The second method is to check only that a user pointer points below `PHYS_BASE`, then dereference it. An invalid user pointer will cause a "page fault" that you can handle by modifying the code for `page_fault()` in '`userprog/exception.c`'. This technique is normally faster because it takes advantage of the processor's MMU, so it tends to be used in real kernels (including Linux).

In either case, you need to make sure not to "leak" resources. For example, suppose that your system call has acquired a lock or allocated memory with `malloc()`. If you encounter an invalid user pointer afterward, you must still be sure to release the lock or free the page of memory. If you choose to verify user pointers before dereferencing them, this should be straightforward. It's more difficult to handle if an invalid pointer causes a page fault, because there's no way to return an error code from a memory access. Therefore, for those who want to try the latter technique, we'll provide a little bit of helpful code:

```
/* Reads a byte at user virtual address UADDR.
   UADDR must be below PHYS_BASE.
   Returns the byte value if successful, -1 if a segfault
   occurred. */
static int
get_user (const uint8_t *uaddr)
{
  int result;
  asm ("movl $1f, %0; movzbl %1, %0; 1:"
       : "=&a" (result) : "m" (*uaddr));
  return result;
}

/* Writes BYTE to user address UDST.
   UDST must be below PHYS_BASE.
   Returns true if successful, false if a segfault occurred. */
static bool
put_user (uint8_t *udst, uint8_t byte)
{
  int error_code;
  asm ("movl $1f, %0; movb %b2, %1; 1:"
       : "=&a" (error_code), "=m" (*udst) : "q" (byte));
  return error_code != -1;
```

```
}
```

Each of these functions assumes that the user address has already been verified to be below `PHYS_BASE`. They also assume that you've modified `page_fault()` so that a page fault in the kernel merely sets `eax` to `0xffffffff` and copies its former value into `eip`.

3.2 Suggested Order of Implementation

We suggest first implementing the following, which can happen in parallel:

- Argument passing (see Section 3.3.3 [Argument Passing], page 29). Every user program will page fault immediately until argument passing is implemented.

  For now, you may simply wish to change

  ```
  *esp = PHYS_BASE;
  ```

  to

  ```
  *esp = PHYS_BASE - 12;
  ```

  in `setup_stack()`. That will work for any test program that doesn't examine its arguments, although its name will be printed as `(null)`.

  Until you implement argument passing, you should only run programs without passing command-line arguments. Attempting to pass arguments to a program will include those arguments in the name of the program, which will probably fail.
- User memory access (see Section 3.1.5 [Accessing User Memory], page 27). All system calls need to read user memory. Few system calls need to write to user memory.
- System call infrastructure (see Section 3.3.4 [System Calls], page 29). Implement enough code to read the system call number from the user stack and dispatch to a handler based on it.
- The `exit` system call. Every user program that finishes in the normal way calls `exit`. Even a program that returns from `main()` calls `exit` indirectly (see `_start()` in '`lib/user/entry.c`').
- The `write` system call for writing to fd 1, the system console. All of our test programs write to the console (the user process version of `printf()` is implemented this way), so they will all malfunction until `write` is available.
- For now, change `process_wait()` to an infinite loop (one that waits forever). The provided implementation returns immediately, so Pintos will power off before any processes actually get to run. You will eventually need to provide a correct implementation.

After the above are implemented, user processes should work minimally. At the very least, they can write to the console and exit correctly. You can then refine your implementation so that some of the tests start to pass.

3.3 Requirements

3.3.1 Design Document

Before you turn in your project, you must copy the project 2 design document template into your source tree under the name '`pintos/src/userprog/DESIGNDOC`' and fill it in. We recommend that you read the design document template before you start working on the project. See Appendix D [Project Documentation], page 99, for a sample design document that goes along with a fictitious project.

3.3.2 Process Termination Messages

Whenever a user process terminates, because it called `exit` or for any other reason, print the process's name and exit code, formatted as if printed by `printf ("%s: exit(%d)\n", ...);`. The name printed should be the full name passed to `process_execute()`, omitting command-line arguments. Do not print these messages when a kernel thread that is not a user process terminates, or when the `halt` system call is invoked. The message is optional when a process fails to load.

Aside from this, don't print any other messages that Pintos as provided doesn't already print. You may find extra messages useful during debugging, but they will confuse the grading scripts and thus lower your score.

3.3.3 Argument Passing

Currently, `process_execute()` does not support passing arguments to new processes. Implement this functionality, by extending `process_execute()` so that instead of simply taking a program file name as its argument, it divides it into words at spaces. The first word is the program name, the second word is the first argument, and so on. That is, `process_execute("grep foo bar")` should run `grep` passing two arguments `foo` and `bar`.

Within a command line, multiple spaces are equivalent to a single space, so that `process_execute("grep foo  bar")` is equivalent to our original example. You can impose a reasonable limit on the length of the command line arguments. For example, you could limit the arguments to those that will fit in a single page (4 kB). (There is an unrelated limit of 128 bytes on command-line arguments that the `pintos` utility can pass to the kernel.)

You can parse argument strings any way you like. If you're lost, look at `strtok_r()`, prototyped in '`lib/string.h`' and implemented with thorough comments in '`lib/string.c`'. You can find more about it by looking at the man page (run `man strtok_r` at the prompt).

See Section 3.5.1 [Program Startup Details], page 36, for information on exactly how you need to set up the stack.

3.3.4 System Calls

Implement the system call handler in '`userprog/syscall.c`'. The skeleton implementation we provide "handles" system calls by terminating the process. It will need to retrieve the system call number, then any system call arguments, and carry out appropriate actions.

Implement the following system calls. The prototypes listed are those seen by a user program that includes '`lib/user/syscall.h`'. (This header, and all others in '`lib/user`', are for use by user programs only.) System call numbers for each system call are defined in '`lib/syscall-nr.h`':

`void halt` (*void*) [System Call]

Terminates Pintos by calling `shutdown_power_off()` (declared in '`devices/shutdown.h`'). This should be seldom used, because you lose some information about possible deadlock situations, etc.

`void exit (`*int* `status``)` [System Call]

Terminates the current user program, returning *status* to the kernel. If the process's parent `wait`s for it (see below), this is the status that will be returned. Conventionally, a *status* of 0 indicates success and nonzero values indicate errors.

`pid_t exec (`*const char* `*cmd_line`)` [System Call]

Runs the executable whose name is given in *cmd_line*, passing any given arguments, and returns the new process's program id (pid). Must return pid -1, which otherwise should not be a valid pid, if the program cannot load or run for any reason. Thus, the parent process cannot return from the `exec` until it knows whether the child process successfully loaded its executable. You must use appropriate synchronization to ensure this.

`int wait (`*pid_t* `pid``)` [System Call]

Waits for a child process *pid* and retrieves the child's exit status.

If *pid* is still alive, waits until it terminates. Then, returns the status that *pid* passed to `exit`. If *pid* did not call `exit()`, but was terminated by the kernel (e.g. killed due to an exception), `wait(pid)` must return -1. It is perfectly legal for a parent process to wait for child processes that have already terminated by the time the parent calls `wait`, but the kernel must still allow the parent to retrieve its child's exit status, or learn that the child was terminated by the kernel.

`wait` must fail and return -1 immediately if any of the following conditions is true:

- *pid* does not refer to a direct child of the calling process. *pid* is a direct child of the calling process if and only if the calling process received *pid* as a return value from a successful call to `exec`.

  Note that children are not inherited: if *A* spawns child *B* and *B* spawns child process *C*, then *A* cannot wait for *C*, even if *B* is dead. A call to `wait(C)` by process *A* must fail. Similarly, orphaned processes are not assigned to a new parent if their parent process exits before they do.
- The process that calls `wait` has already called `wait` on *pid*. That is, a process may wait for any given child at most once.

Processes may spawn any number of children, wait for them in any order, and may even exit without having waited for some or all of their children. Your design should consider all the ways in which waits can occur. All of a process's resources, including its `struct thread`, must be freed whether its parent ever waits for it or not, and regardless of whether the child exits before or after its parent.

You must ensure that Pintos does not terminate until the initial process exits. The supplied Pintos code tries to do this by calling `process_wait()` (in '`userprog/process.c`') from `main()` (in '`threads/init.c`'). We suggest that you implement `process_wait()` according to the comment at the top of the function and then implement the `wait` system call in terms of `process_wait()`.

Implementing this system call requires considerably more work than any of the rest.

`bool create (`*const char* `*file`, *unsigned* `initial_size``)` [System Call]

Creates a new file called *file* initially *initial_size* bytes in size. Returns true if successful, false otherwise. Creating a new file does not open it: opening the new file is a separate operation which would require a `open` system call.

`bool remove (const char *file)` [System Call]

Deletes the file called *file*. Returns true if successful, false otherwise. A file may be removed regardless of whether it is open or closed, and removing an open file does not close it. See [Removing an Open File], page 35, for details.

`int open (const char *file)` [System Call]

Opens the file called *file*. Returns a nonnegative integer handle called a "file descriptor" (fd), or -1 if the file could not be opened.

File descriptors numbered 0 and 1 are reserved for the console: fd 0 (`STDIN_FILENO`) is standard input, fd 1 (`STDOUT_FILENO`) is standard output. The `open` system call will never return either of these file descriptors, which are valid as system call arguments only as explicitly described below.

Each process has an independent set of file descriptors. File descriptors are not inherited by child processes.

When a single file is opened more than once, whether by a single process or different processes, each `open` returns a new file descriptor. Different file descriptors for a single file are closed independently in separate calls to `close` and they do not share a file position.

`int filesize (int fd)` [System Call]

Returns the size, in bytes, of the file open as *fd*.

`int read (int fd, void *buffer, unsigned size)` [System Call]

Reads *size* bytes from the file open as *fd* into *buffer*. Returns the number of bytes actually read (0 at end of file), or -1 if the file could not be read (due to a condition other than end of file). Fd 0 reads from the keyboard using `input_getc()`.

`int write (int fd, const void *buffer, unsigned size)` [System Call]

Writes *size* bytes from *buffer* to the open file *fd*. Returns the number of bytes actually written, which may be less than *size* if some bytes could not be written.

Writing past end-of-file would normally extend the file, but file growth is not implemented by the basic file system. The expected behavior is to write as many bytes as possible up to end-of-file and return the actual number written, or 0 if no bytes could be written at all.

Fd 1 writes to the console. Your code to write to the console should write all of *buffer* in one call to `putbuf()`, at least as long as *size* is not bigger than a few hundred bytes. (It is reasonable to break up larger buffers.) Otherwise, lines of text output by different processes may end up interleaved on the console, confusing both human readers and our grading scripts.

`void seek (int fd, unsigned position)` [System Call]

Changes the next byte to be read or written in open file *fd* to *position*, expressed in bytes from the beginning of the file. (Thus, a *position* of 0 is the file's start.)

A seek past the current end of a file is not an error. A later read obtains 0 bytes, indicating end of file. A later write extends the file, filling any unwritten gap with zeros. (However, in Pintos files have a fixed length until project 4 is complete, so writes past end of file will return an error.) These semantics are implemented in the file system and do not require any special effort in system call implementation.

`unsigned tell (int fd)` [System Call]
: Returns the position of the next byte to be read or written in open file *fd*, expressed in bytes from the beginning of the file.

`void close (int fd)` [System Call]
: Closes file descriptor *fd*. Exiting or terminating a process implicitly closes all its open file descriptors, as if by calling this function for each one.

The file defines other syscalls. Ignore them for now. You will implement some of them in project 3 and the rest in project 4, so be sure to design your system with extensibility in mind.

To implement syscalls, you need to provide ways to read and write data in user virtual address space. You need this ability before you can even obtain the system call number, because the system call number is on the user's stack in the user's virtual address space. This can be a bit tricky: what if the user provides an invalid pointer, a pointer into kernel memory, or a block partially in one of those regions? You should handle these cases by terminating the user process. We recommend writing and testing this code before implementing any other system call functionality. See Section 3.1.5 [Accessing User Memory], page 27, for more information.

You must synchronize system calls so that any number of user processes can make them at once. In particular, it is not safe to call into the file system code provided in the '`filesys`' directory from multiple threads at once. Your system call implementation must treat the file system code as a critical section. Don't forget that `process_execute()` also accesses files. For now, we recommend against modifying code in the '`filesys`' directory.

We have provided you a user-level function for each system call in '`lib/user/syscall.c`'. These provide a way for user processes to invoke each system call from a C program. Each uses a little inline assembly code to invoke the system call and (if appropriate) returns the system call's return value.

When you're done with this part, and forevermore, Pintos should be bulletproof. Nothing that a user program can do should ever cause the OS to crash, panic, fail an assertion, or otherwise malfunction. It is important to emphasize this point: our tests will try to break your system calls in many, many ways. You need to think of all the corner cases and handle them. The sole way a user program should be able to cause the OS to halt is by invoking the `halt` system call.

If a system call is passed an invalid argument, acceptable options include returning an error value (for those calls that return a value), returning an undefined value, or terminating the process.

See Section 3.5.2 [System Call Details], page 37, for details on how system calls work.

3.3.5 Denying Writes to Executables

Add code to deny writes to files in use as executables. Many OSes do this because of the unpredictable results if a process tried to run code that was in the midst of being changed on disk. This is especially important once virtual memory is implemented in project 3, but it can't hurt even now.

You can use `file_deny_write()` to prevent writes to an open file. Calling `file_allow_write()` on the file will re-enable them (unless the file is denied writes by another opener).

Closing a file will also re-enable writes. Thus, to deny writes to a process's executable, you must keep it open as long as the process is still running.

3.4 FAQ

How much code will I need to write?

Here's a summary of our reference solution, produced by the `diffstat` program. The final row gives total lines inserted and deleted; a changed line counts as both an insertion and a deletion.

The reference solution represents just one possible solution. Many other solutions are also possible and many of those differ greatly from the reference solution. Some excellent solutions may not modify all the files modified by the reference solution, and some may modify files not modified by the reference solution.

```
threads/thread.c     |   13
threads/thread.h     |   26 +
userprog/exception.c |    8
userprog/process.c   |  247 +++++++++++++++--
userprog/syscall.c   |  468 ++++++++++++++++++++++++++++++++-
userprog/syscall.h   |    1
6 files changed, 725 insertions(+), 38 deletions(-)
```

The kernel always panics when I run `pintos -p` *`file`* `-- -q`.

Did you format the file system (with '`pintos -f`')?

Is your file name too long? The file system limits file names to 14 characters. A command like '`pintos -p ../../examples/echo -- -q`' will exceed the limit. Use '`pintos -p ../../examples/echo -a echo -- -q`' to put the file under the name '`echo`' instead.

Is the file system full?

Does the file system already contain 16 files? The base Pintos file system has a 16-file limit.

The file system may be so fragmented that there's not enough contiguous space for your file.

When I run `pintos -p ../file --`, '`file`' isn't copied.

Files are written under the name you refer to them, by default, so in this case the file copied in would be named '`../file`'. You probably want to run `pintos -p ../file -a file --` instead.

You can list the files in your file system with `pintos -q ls`.

All my user programs die with page faults.

This will happen if you haven't implemented argument passing (or haven't done so correctly). The basic C library for user programs tries to read *argc* and *argv* off the stack. If the stack isn't properly set up, this causes a page fault.

All my user programs die with `system call!`

You'll have to implement system calls before you see anything else. Every reasonable program tries to make at least one system call (`exit()`) and most

programs make more than that. Notably, `printf()` invokes the `write` system call. The default system call handler just prints '`system call!`' and terminates the program. Until then, you can use `hex_dump()` to convince yourself that argument passing is implemented correctly (see Section 3.5.1 [Program Startup Details], page 36).

How can I disassemble user programs?

The `objdump` (80x86) or `i386-elf-objdump` (SPARC) utility can disassemble entire user programs or object files. Invoke it as `objdump -d` *`file`*. You can use GDB's `disassemble` command to disassemble individual functions (see Section E.5 [GDB], page 105).

Why do many C include files not work in Pintos programs?

Can I use lib*foo* in my Pintos programs?

The C library we provide is very limited. It does not include many of the features that are expected of a real operating system's C library. The C library must be built specifically for the operating system (and architecture), since it must make system calls for I/O and memory allocation. (Not all functions do, of course, but usually the library is compiled as a unit.)

The chances are good that the library you want uses parts of the C library that Pintos doesn't implement. It will probably take at least some porting effort to make it work under Pintos. Notably, the Pintos user program C library does not have a `malloc()` implementation.

How do I compile new user programs?

Modify '`src/examples/Makefile`', then run `make`.

Can I run user programs under a debugger?

Yes, with some limitations. See Section E.5 [GDB], page 105.

What's the difference between `tid_t` and `pid_t`?

A `tid_t` identifies a kernel thread, which may have a user process running in it (if created with `process_execute()`) or not (if created with `thread_create()`). It is a data type used only in the kernel.

A `pid_t` identifies a user process. It is used by user processes and the kernel in the `exec` and `wait` system calls.

You can choose whatever suitable types you like for `tid_t` and `pid_t`. By default, they're both `int`. You can make them a one-to-one mapping, so that the same values in both identify the same process, or you can use a more complex mapping. It's up to you.

3.4.1 Argument Passing FAQ

Isn't the top of stack in kernel virtual memory?

The top of stack is at `PHYS_BASE`, typically `0xc0000000`, which is also where kernel virtual memory starts. But before the processor pushes data on the stack, it decrements the stack pointer. Thus, the first (4-byte) value pushed on the stack will be at address `0xbffffffc`.

Is `PHYS_BASE` fixed?

No. You should be able to support `PHYS_BASE` values that are any multiple of `0x10000000` from `0x80000000` to `0xf0000000`, simply via recompilation.

3.4.2 System Calls FAQ

Can I just cast a `struct file *` to get a file descriptor?
Can I just cast a `struct thread *` to a `pid_t`?

You will have to make these design decisions yourself. Most operating systems do distinguish between file descriptors (or pids) and the addresses of their kernel data structures. You might want to give some thought as to why they do so before committing yourself.

Can I set a maximum number of open files per process?

It is better not to set an arbitrary limit. You may impose a limit of 128 open files per process, if necessary.

What happens when an open file is removed?

You should implement the standard Unix semantics for files. That is, when a file is removed any process which has a file descriptor for that file may continue to use that descriptor. This means that they can read and write from the file. The file will not have a name, and no other processes will be able to open it, but it will continue to exist until all file descriptors referring to the file are closed or the machine shuts down.

How can I run user programs that need more than 4 kB stack space?

You may modify the stack setup code to allocate more than one page of stack space for each process. In the next project, you will implement a better solution.

What should happen if an `exec` fails midway through loading?

`exec` should return -1 if the child process fails to load for any reason. This includes the case where the load fails part of the way through the process (e.g. where it runs out of memory in the `multi-oom` test). Therefore, the parent process cannot return from the `exec` system call until it is established whether the load was successful or not. The child must communicate this information to its parent using appropriate synchronization, such as a semaphore (see Section A.3.2 [Semaphores], page 67), to ensure that the information is communicated without race conditions.

3.5 80x86 Calling Convention

This section summarizes important points of the convention used for normal function calls on 32-bit 80x86 implementations of Unix. Some details are omitted for brevity. If you do want all the details, refer to [SysV-i386].

The calling convention works like this:

1. The caller pushes each of the function's arguments on the stack one by one, normally using the `PUSH` assembly language instruction. Arguments are pushed in right-to-left order.

   The stack grows downward: each push decrements the stack pointer, then stores into the location it now points to, like the C expression '`*--sp = value`'.

2. The caller pushes the address of its next instruction (the *return address*) on the stack and jumps to the first instruction of the callee. A single 80*x*86 instruction, `CALL`, does both.
3. The callee executes. When it takes control, the stack pointer points to the return address, the first argument is just above it, the second argument is just above the first argument, and so on.
4. If the callee has a return value, it stores it into register `EAX`.
5. The callee returns by popping the return address from the stack and jumping to the location it specifies, using the 80*x*86 `RET` instruction.
6. The caller pops the arguments off the stack.

Consider a function `f()` that takes three `int` arguments. This diagram shows a sample stack frame as seen by the callee at the beginning of step 3 above, supposing that `f()` is invoked as `f(1, 2, 3)`. The initial stack address is arbitrary:

```
                              +----------------+
                   0xbffffe7c |        3       |
                   0xbffffe78 |        2       |
                   0xbffffe74 |        1       |
stack pointer --> 0xbffffe70 | return address |
                              +----------------+
```

3.5.1 Program Startup Details

The Pintos C library for user programs designates `_start()`, in '`lib/user/entry.c`', as the entry point for user programs. This function is a wrapper around `main()` that calls `exit()` if `main()` returns:

```
void
_start (int argc, char *argv[])
{
  exit (main (argc, argv));
}
```

The kernel must put the arguments for the initial function on the stack before it allows the user program to begin executing. The arguments are passed in the same way as the normal calling convention (see Section 3.5 [80x86 Calling Convention], page 35).

Consider how to handle arguments for the following example command: '`/bin/ls -l foo bar`'. First, break the command into words: '`/bin/ls`', '`-l`', '`foo`', '`bar`'. Place the words at the top of the stack. Order doesn't matter, because they will be referenced through pointers.

Then, push the address of each string plus a null pointer sentinel, on the stack, in right-to-left order. These are the elements of `argv`. The null pointer sentinel ensures that `argv[argc]` is a null pointer, as required by the C standard. The order ensures that `argv[0]` is at the lowest virtual address. Word-aligned accesses are faster than unaligned accesses, so for best performance round the stack pointer down to a multiple of 4 before the first push.

Then, push `argv` (the address of `argv[0]`) and `argc`, in that order. Finally, push a fake "return address": although the entry function will never return, its stack frame must have the same structure as any other.

The table below shows the state of the stack and the relevant registers right before the beginning of the user program, assuming `PHYS_BASE` is `0xc0000000`:

Address	Name	Data	Type
`0xbffffffc`	`argv[3][...]`	‘`bar\0`’	`char[4]`
`0xbffffff8`	`argv[2][...]`	‘`foo\0`’	`char[4]`
`0xbffffff5`	`argv[1][...]`	‘`-l\0`’	`char[3]`
`0xbfffffed`	`argv[0][...]`	‘`/bin/ls\0`’	`char[8]`
`0xbfffffec`	word-align	0	`uint8_t`
`0xbfffffe8`	`argv[4]`	0	`char *`
`0xbfffffe4`	`argv[3]`	`0xbffffffc`	`char *`
`0xbfffffe0`	`argv[2]`	`0xbffffff8`	`char *`
`0xbfffffdc`	`argv[1]`	`0xbffffff5`	`char *`
`0xbfffffd8`	`argv[0]`	`0xbfffffed`	`char *`
`0xbfffffd4`	`argv`	`0xbfffffd8`	`char **`
`0xbfffffd0`	`argc`	4	`int`
`0xbfffffcc`	return address	0	`void (*) ()`

In this example, the stack pointer would be initialized to `0xbfffffcc`.

As shown above, your code should start the stack at the very top of the user virtual address space, in the page just below virtual address `PHYS_BASE` (defined in ‘`threads/vaddr.h`’).

You may find the non-standard `hex_dump()` function, declared in ‘`<stdio.h>`’, useful for debugging your argument passing code. Here’s what it would show in the above example:

```
bffffc0                                          00 00 00 00 |            ....|
bffffd0  04 00 00 00 d8 ff ff bf-ed ff ff bf f5 ff ff bf |................|
bffffe0  f8 ff ff bf fc ff ff bf-00 00 00 00 00 2f 62 69 |............./bi|
bfffff0  6e 2f 6c 73 00 2d 6c 00-66 6f 6f 00 62 61 72 00 |n/ls.-l.foo.bar.|
```

3.5.2 System Call Details

The first project already dealt with one way that the operating system can regain control from a user program: interrupts from timers and I/O devices. These are “external” interrupts, because they are caused by entities outside the CPU (see Section A.4.3 [External Interrupt Handling], page 74).

The operating system also deals with software exceptions, which are events that occur in program code (see Section A.4.2 [Internal Interrupt Handling], page 73). These can be errors such as a page fault or division by zero. Exceptions are also the means by which a user program can request services (“system calls”) from the operating system.

In the 80x86 architecture, the ‘`int`’ instruction is the most commonly used means for invoking system calls. This instruction is handled in the same way as other software exceptions. In Pintos, user programs invoke ‘`int $0x30`’ to make a system call. The system call number and any additional arguments are expected to be pushed on the stack in the normal fashion before invoking the interrupt (see Section 3.5 [80x86 Calling Convention], page 35).

Thus, when the system call handler `syscall_handler()` gets control, the system call number is in the 32-bit word at the caller’s stack pointer, the first argument is in the 32-bit word at the next higher address, and so on. The caller’s stack pointer is accessible to

`syscall_handler()` as the '`esp`' member of the `struct intr_frame` passed to it. (`struct intr_frame` is on the kernel stack.)

The 80x86 convention for function return values is to place them in the `EAX` register. System calls that return a value can do so by modifying the '`eax`' member of `struct intr_frame`.

You should try to avoid writing large amounts of repetitive code for implementing system calls. Each system call argument, whether an integer or a pointer, takes up 4 bytes on the stack. You should be able to take advantage of this to avoid writing much near-identical code for retrieving each system call's arguments from the stack.

4 Project 3: Virtual Memory

By now you should have some familiarity with the inner workings of Pintos. Your OS can properly handle multiple threads of execution with proper synchronization, and can load multiple user programs at once. However, the number and size of programs that can run is limited by the machine's main memory size. In this assignment, you will remove that limitation.

You will build this assignment on top of the last one. Test programs from project 2 should also work with project 3. You should take care to fix any bugs in your project 2 submission before you start work on project 3, because those bugs will most likely cause the same problems in project 3.

You will continue to handle Pintos disks and file systems the same way you did in the previous assignment (see Section 3.1.2 [Using the File System], page 23).

4.1 Background

4.1.1 Source Files

You will work in the '`vm`' directory for this project. The '`vm`' directory contains only '`Makefile`'s. The only change from '`userprog`' is that this new '`Makefile`' turns on the setting '`-DVM`'. All code you write will be in new files or in files introduced in earlier projects.

You will probably be encountering just a few files for the first time:

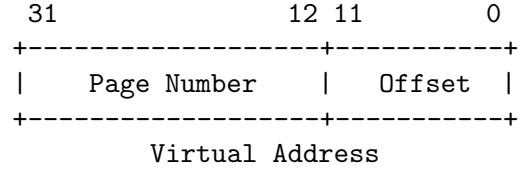
'`devices/block.h`'
'`devices/block.c`'
: Provides sector-based read and write access to block device. You will use this interface to access the swap partition as a block device.

4.1.2 Memory Terminology

Careful definitions are needed to keep discussion of virtual memory from being confusing. Thus, we begin by presenting some terminology for memory and storage. Some of these terms should be familiar from project 2 (see Section 3.1.4 [Virtual Memory Layout], page 25), but much of it is new.

4.1.2.1 Pages

A *page*, sometimes called a *virtual page*, is a continuous region of virtual memory 4,096 bytes (the *page size*) in length. A page must be *page-aligned*, that is, start on a virtual address evenly divisible by the page size. Thus, a 32-bit virtual address can be divided into a 20-bit *page number* and a 12-bit *page offset* (or just *offset*), like this:



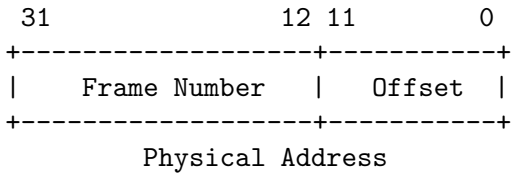
Each process has an independent set of *user (virtual) pages*, which are those pages below virtual address `PHYS_BASE`, typically `0xc0000000` (3 GB). The set of *kernel (virtual) pages*,

on the other hand, is global, remaining the same regardless of what thread or process is active. The kernel may access both user and kernel pages, but a user process may access only its own user pages. See Section 3.1.4 [Virtual Memory Layout], page 25, for more information.

Pintos provides several useful functions for working with virtual addresses. See Section A.6 [Virtual Addresses], page 77, for details.

4.1.2.2 Frames

A *frame*, sometimes called a *physical frame* or a *page frame*, is a continuous region of physical memory. Like pages, frames must be page-size and page-aligned. Thus, a 32-bit physical address can be divided into a 20-bit *frame number* and a 12-bit *frame offset* (or just *offset*), like this:



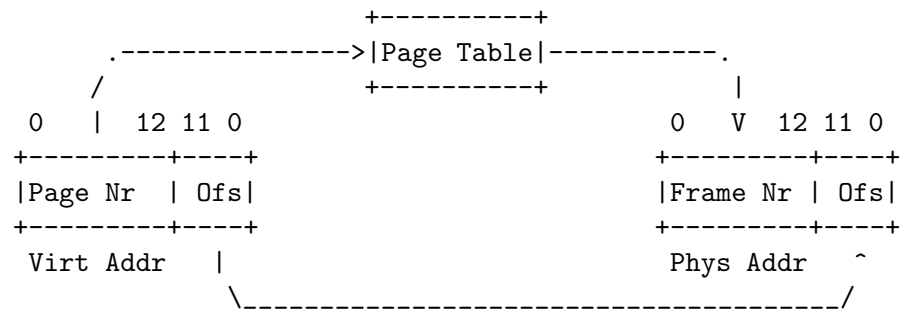
The 80x86 doesn't provide any way to directly access memory at a physical address. Pintos works around this by mapping kernel virtual memory directly to physical memory: the first page of kernel virtual memory is mapped to the first frame of physical memory, the second page to the second frame, and so on. Thus, frames can be accessed through kernel virtual memory.

Pintos provides functions for translating between physical addresses and kernel virtual addresses. See Section A.6 [Virtual Addresses], page 77, for details.

4.1.2.3 Page Tables

In Pintos, a *page table* is a data structure that the CPU uses to translate a virtual address to a physical address, that is, from a page to a frame. The page table format is dictated by the 80x86 architecture. Pintos provides page table management code in '`pagedir.c`' (see Section A.7 [Page Table], page 79).

The diagram below illustrates the relationship between pages and frames. The virtual address, on the left, consists of a page number and an offset. The page table translates the page number into a frame number, which is combined with the unmodified offset to obtain the physical address, on the right.



4.1.2.4 Swap Slots

A *swap slot* is a continuous, page-size region of disk space in the swap partition. Although hardware limitations dictating the placement of slots are looser than for pages and frames, swap slots should be page-aligned because there is no downside in doing so.

4.1.3 Resource Management Overview

You will need to design the following data structures:

Supplemental page table
: Enables page fault handling by supplementing the page table. See Section 4.1.4 [Managing the Supplemental Page Table], page 42.

Frame table
: Allows efficient implementation of eviction policy. See Section 4.1.5 [Managing the Frame Table], page 42.

Swap table
: Tracks usage of swap slots. See Section 4.1.6 [Managing the Swap Table], page 43.

Table of file mappings
: Processes may map files into their virtual memory space. You need a table to track which files are mapped into which pages.

You do not necessarily need to implement four completely distinct data structures: it may be convenient to wholly or partially merge related resources into a unified data structure.

For each data structure, you need to determine what information each element should contain. You also need to decide on the data structure's scope, either local (per-process) or global (applying to the whole system), and how many instances are required within its scope.

To simplify your design, you may store these data structures in non-pageable memory. That means that you can be sure that pointers among them will remain valid.

Possible choices of data structures include arrays, lists, bitmaps, and hash tables. An array is often the simplest approach, but a sparsely populated array wastes memory. Lists are also simple, but traversing a long list to find a particular position wastes time. Both arrays and lists can be resized, but lists more efficiently support insertion and deletion in the middle.

Pintos includes a bitmap data structure in '`lib/kernel/bitmap.c`' and '`lib/kernel/bitmap.h`'. A bitmap is an array of bits, each of which can be true or false. Bitmaps are typically used to track usage in a set of (identical) resources: if resource n is in use, then bit n of the bitmap is true. Pintos bitmaps are fixed in size, although you could extend their implementation to support resizing.

Pintos also includes a hash table data structure (see Section A.8 [Hash Table], page 84). Pintos hash tables efficiently support insertions and deletions over a wide range of table sizes.

Although more complex data structures may yield performance or other benefits, they may also needlessly complicate your implementation. Thus, we do not recommend implementing any advanced data structure (e.g. a balanced binary tree) as part of your design.

4.1.4 Managing the Supplemental Page Table

The *supplemental page table* supplements the page table with additional data about each page. It is needed because of the limitations imposed by the page table's format. Such a data structure is often called a "page table" also; we add the word "supplemental" to reduce confusion.

The supplemental page table is used for at least two purposes. Most importantly, on a page fault, the kernel looks up the virtual page that faulted in the supplemental page table to find out what data should be there. Second, the kernel consults the supplemental page table when a process terminates, to decide what resources to free.

You may organize the supplemental page table as you wish. There are at least two basic approaches to its organization: in terms of segments or in terms of pages. Optionally, you may use the page table itself as an index to track the members of the supplemental page table. You will have to modify the Pintos page table implementation in '`pagedir.c`' to do so. We recommend this approach for advanced students only. See Section A.7.4.2 [Page Table Entry Format], page 82, for more information.

The most important user of the supplemental page table is the page fault handler. In project 2, a page fault always indicated a bug in the kernel or a user program. In project 3, this is no longer true. Now, a page fault might only indicate that the page must be brought in from a file or swap. You will have to implement a more sophisticated page fault handler to handle these cases. Your page fault handler, which you should implement by modifying `page_fault()` in '`userprog/exception.c`', needs to do roughly the following:

1. Locate the page that faulted in the supplemental page table. If the memory reference is valid, use the supplemental page table entry to locate the data that goes in the page, which might be in the file system, or in a swap slot, or it might simply be an all-zero page. If you implement sharing, the page's data might even already be in a page frame, but not in the page table.

   If the supplemental page table indicates that the user process should not expect any data at the address it was trying to access, or if the page lies within kernel virtual memory, or if the access is an attempt to write to a read-only page, then the access is invalid. Any invalid access terminates the process and thereby frees all of its resources.

2. Obtain a frame to store the page. See Section 4.1.5 [Managing the Frame Table], page 42, for details.

   If you implement sharing, the data you need may already be in a frame, in which case you must be able to locate that frame.

3. Fetch the data into the frame, by reading it from the file system or swap, zeroing it, etc.

   If you implement sharing, the page you need may already be in a frame, in which case no action is necessary in this step.

4. Point the page table entry for the faulting virtual address to the physical page. You can use the functions in '`userprog/pagedir.c`'.

4.1.5 Managing the Frame Table

The *frame table* contains one entry for each frame that contains a user page. Each entry in the frame table contains a pointer to the page, if any, that currently occupies it, and other

data of your choice. The frame table allows Pintos to efficiently implement an eviction policy, by choosing a page to evict when no frames are free.

The frames used for user pages should be obtained from the "user pool," by calling `palloc_get_page(PAL_USER)`. You must use `PAL_USER` to avoid allocating from the "kernel pool," which could cause some test cases to fail unexpectedly (see [Why PAL_USER?], page 49). If you modify '`palloc.c`' as part of your frame table implementation, be sure to retain the distinction between the two pools.

The most important operation on the frame table is obtaining an unused frame. This is easy when a frame is free. When none is free, a frame must be made free by evicting some page from its frame.

If no frame can be evicted without allocating a swap slot, but swap is full, panic the kernel. Real OSes apply a wide range of policies to recover from or prevent such situations, but these policies are beyond the scope of this project.

The process of eviction comprises roughly the following steps:

1. Choose a frame to evict, using your page replacement algorithm. The "accessed" and "dirty" bits in the page table, described below, will come in handy.
2. Remove references to the frame from any page table that refers to it.

   Unless you have implemented sharing, only a single page should refer to a frame at any given time.
3. If necessary, write the page to the file system or to swap.

The evicted frame may then be used to store a different page.

4.1.5.1 Accessed and Dirty Bits

80x86 hardware provides some assistance for implementing page replacement algorithms, through a pair of bits in the page table entry (PTE) for each page. On any read or write to a page, the CPU sets the *accessed bit* to 1 in the page's PTE, and on any write, the CPU sets the *dirty bit* to 1. The CPU never resets these bits to 0, but the OS may do so.

You need to be aware of *aliases*, that is, two (or more) pages that refer to the same frame. When an aliased frame is accessed, the accessed and dirty bits are updated in only one page table entry (the one for the page used for access). The accessed and dirty bits for the other aliases are not updated.

In Pintos, every user virtual page is aliased to its kernel virtual page. You must manage these aliases somehow. For example, your code could check and update the accessed and dirty bits for both addresses. Alternatively, the kernel could avoid the problem by only accessing user data through the user virtual address.

Other aliases should only arise if you implement sharing for extra credit (see [VM Extra Credit], page 49), or if there is a bug in your code.

See Section A.7.3 [Page Table Accessed and Dirty Bits], page 80, for details of the functions to work with accessed and dirty bits.

4.1.6 Managing the Swap Table

The swap table tracks in-use and free swap slots. It should allow picking an unused swap slot for evicting a page from its frame to the swap partition. It should allow freeing a swap slot when its page is read back or the process whose page was swapped is terminated.

You may use the `BLOCK_SWAP` block device for swapping, obtaining the `struct block` that represents it by calling `block_get_role()`. From the '`vm/build`' directory, use the command `pintos-mkdisk swap.dsk --swap-size=`*n* to create an disk named '`swap.dsk`' that contains a *n*-MB swap partition. Afterward, '`swap.dsk`' will automatically be attached as an extra disk when you run `pintos`. Alternatively, you can tell `pintos` to use a temporary *n*-MB swap disk for a single run with '`--swap-size=`*n*'.

Swap slots should be allocated lazily, that is, only when they are actually required by eviction. Reading data pages from the executable and writing them to swap immediately at process startup is not lazy. Swap slots should not be reserved to store particular pages.

Free a swap slot when its contents are read back into a frame.

4.1.7 Managing Memory Mapped Files

The file system is most commonly accessed with `read` and `write` system calls. A secondary interface is to "map" the file into virtual pages, using the `mmap` system call. The program can then use memory instructions directly on the file data.

Suppose file '`foo`' is `0x1000` bytes (4 kB, or one page) long. If '`foo`' is mapped into memory starting at address `0x5000`, then any memory accesses to locations `0x5000...0x5fff` will access the corresponding bytes of '`foo`'.

Here's a program that uses `mmap` to print a file to the console. It opens the file specified on the command line, maps it at virtual address `0x10000000`, writes the mapped data to the console (fd 1), and unmaps the file.

```
#include <stdio.h>
#include <syscall.h>
int main (int argc UNUSED, char *argv[])
{
  void *data = (void *) 0x10000000;      /* Address at which to map. */

  int fd = open (argv[1]);               /* Open file. */
  mapid_t map = mmap (fd, data);         /* Map file. */
  write (1, data, filesize (fd));        /* Write file to console. */
  munmap (map);                          /* Unmap file (optional). */
  return 0;
}
```

A similar program with full error handling is included as '`mcat.c`' in the '`examples`' directory, which also contains '`mcp.c`' as a second example of `mmap`.

Your submission must be able to track what memory is used by memory mapped files. This is necessary to properly handle page faults in the mapped regions and to ensure that mapped files do not overlap any other segments within the process.

4.2 Suggested Order of Implementation

We suggest the following initial order of implementation:

1. Frame table (see Section 4.1.5 [Managing the Frame Table], page 42). Change '`process.c`' to use your frame table allocator.

   Do not implement swapping yet. If you run out of frames, fail the allocator or panic the kernel.

After this step, your kernel should still pass all the project 2 test cases.

2. Supplemental page table and page fault handler (see Section 4.1.4 [Managing the Supplemental Page Table], page 42). Change '`process.c`' to record the necessary information in the supplemental page table when loading an executable and setting up its stack. Implement loading of code and data segments in the page fault handler. For now, consider only valid accesses.

   After this step, your kernel should pass all of the project 2 functionality test cases, but only some of the robustness tests.

From here, you can implement stack growth, mapped files, and page reclamation on process exit in parallel.

The next step is to implement eviction (see Section 4.1.5 [Managing the Frame Table], page 42). Initially you could choose the page to evict randomly. At this point, you need to consider how to manage accessed and dirty bits and aliasing of user and kernel pages. Synchronization is also a concern: how do you deal with it if process A faults on a page whose frame process B is in the process of evicting? Finally, implement a eviction strategy such as the clock algorithm.

4.3 Requirements

This assignment is an open-ended design problem. We are going to say as little as possible about how to do things. Instead we will focus on what functionality we require your OS to support. We will expect you to come up with a design that makes sense. You will have the freedom to choose how to handle page faults, how to organize the swap partition, how to implement paging, etc.

4.3.1 Design Document

Before you turn in your project, you must copy the project 3 design document template into your source tree under the name '`pintos/src/vm/DESIGNDOC`' and fill it in. We recommend that you read the design document template before you start working on the project. See Appendix D [Project Documentation], page 99, for a sample design document that goes along with a fictitious project.

4.3.2 Paging

Implement paging for segments loaded from executables. All of these pages should be loaded lazily, that is, only as the kernel intercepts page faults for them. Upon eviction, pages modified since load (e.g. as indicated by the "dirty bit") should be written to swap. Unmodified pages, including read-only pages, should never be written to swap because they can always be read back from the executable.

Implement a global page replacement algorithm that approximates LRU. Your algorithm should perform at least as well as the simple variant of the "second chance" or "clock" algorithm.

Your design should allow for parallelism. If one page fault requires I/O, in the meantime processes that do not fault should continue executing and other page faults that do not require I/O should be able to complete. This will require some synchronization effort.

You'll need to modify the core of the program loader, which is the loop in `load_segment()` in '`userprog/process.c`'. Each time around the loop, `page_read_bytes` re-

ceives the number of bytes to read from the executable file and `page_zero_bytes` receives the number of bytes to initialize to zero following the bytes read. The two always sum to `PGSIZE` (4,096). The handling of a page depends on these variables' values:

- If `page_read_bytes` equals `PGSIZE`, the page should be demand paged from the underlying file on its first access.
- If `page_zero_bytes` equals `PGSIZE`, the page does not need to be read from disk at all because it is all zeroes. You should handle such pages by creating a new page consisting of all zeroes at the first page fault.
- Otherwise, neither `page_read_bytes` nor `page_zero_bytes` equals `PGSIZE`. In this case, an initial part of the page is to be read from the underlying file and the remainder zeroed.

4.3.3 Stack Growth

Implement stack growth. In project 2, the stack was a single page at the top of the user virtual address space, and programs were limited to that much stack. Now, if the stack grows past its current size, allocate additional pages as necessary.

Allocate additional pages only if they "appear" to be stack accesses. Devise a heuristic that attempts to distinguish stack accesses from other accesses.

User programs are buggy if they write to the stack below the stack pointer, because typical real OSes may interrupt a process at any time to deliver a "signal," which pushes data on the stack.[1] However, the 80*x*86 `PUSH` instruction checks access permissions before it adjusts the stack pointer, so it may cause a page fault 4 bytes below the stack pointer. (Otherwise, `PUSH` would not be restartable in a straightforward fashion.) Similarly, the `PUSHA` instruction pushes 32 bytes at once, so it can fault 32 bytes below the stack pointer.

You will need to be able to obtain the current value of the user program's stack pointer. Within a system call or a page fault generated by a user program, you can retrieve it from the `esp` member of the `struct intr_frame` passed to `syscall_handler()` or `page_fault()`, respectively. If you verify user pointers before accessing them (see Section 3.1.5 [Accessing User Memory], page 27), these are the only cases you need to handle. On the other hand, if you depend on page faults to detect invalid memory access, you will need to handle another case, where a page fault occurs in the kernel. Since the processor only saves the stack pointer when an exception causes a switch from user to kernel mode, reading `esp` out of the `struct intr_frame` passed to `page_fault()` would yield an undefined value, not the user stack pointer. You will need to arrange another way, such as saving `esp` into `struct thread` on the initial transition from user to kernel mode.

You should impose some absolute limit on stack size, as do most OSes. Some OSes make the limit user-adjustable, e.g. with the `ulimit` command on many Unix systems. On many GNU/Linux systems, the default limit is 8 MB.

The first stack page need not be allocated lazily. You can allocate and initialize it with the command line arguments at load time, with no need to wait for it to be faulted in.

All stack pages should be candidates for eviction. An evicted stack page should be written to swap.

[1] This rule is common but not universal. One modern exception is the *x*86-64 System V ABI (`http://www.x86-64.org/documentation/abi.pdf`), which designates 128 bytes below the stack pointer as a "red zone" that may not be modified by signal or interrupt handlers.

4.3.4 Memory Mapped Files

Implement memory mapped files, including the following system calls.

`mapid_t mmap (int fd, void *addr)` [System Call]

Maps the file open as *fd* into the process's virtual address space. The entire file is mapped into consecutive virtual pages starting at *addr*.

Your VM system must lazily load pages in `mmap` regions and use the `mmap`ed file itself as backing store for the mapping. That is, evicting a page mapped by `mmap` writes it back to the file it was mapped from.

If the file's length is not a multiple of `PGSIZE`, then some bytes in the final mapped page "stick out" beyond the end of the file. Set these bytes to zero when the page is faulted in from the file system, and discard them when the page is written back to disk.

If successful, this function returns a "mapping ID" that uniquely identifies the mapping within the process. On failure, it must return -1, which otherwise should not be a valid mapping id, and the process's mappings must be unchanged.

A call to `mmap` may fail if the file open as *fd* has a length of zero bytes. It must fail if *addr* is not page-aligned or if the range of pages mapped overlaps any existing set of mapped pages, including the stack or pages mapped at executable load time. It must also fail if *addr* is 0, because some Pintos code assumes virtual page 0 is not mapped. Finally, file descriptors 0 and 1, representing console input and output, are not mappable.

`void munmap (mapid_t mapping)` [System Call]

Unmaps the mapping designated by *mapping*, which must be a mapping ID returned by a previous call to `mmap` by the same process that has not yet been unmapped.

All mappings are implicitly unmapped when a process exits, whether via `exit` or by any other means. When a mapping is unmapped, whether implicitly or explicitly, all pages written to by the process are written back to the file, and pages not written must not be. The pages are then removed from the process's list of virtual pages.

Closing or removing a file does not unmap any of its mappings. Once created, a mapping is valid until `munmap` is called or the process exits, following the Unix convention. See [Removing an Open File], page 35, for more information. You should use the `file_reopen` function to obtain a separate and independent reference to the file for each of its mappings.

If two or more processes map the same file, there is no requirement that they see consistent data. Unix handles this by making the two mappings share the same physical page, but the `mmap` system call also has an argument allowing the client to specify whether the page is shared or private (i.e. copy-on-write).

4.3.5 Accessing User Memory

You will need to adapt your code to access user memory (see Section 3.1.5 [Accessing User Memory], page 27) while handling a system call. Just as user processes may access pages whose content is currently in a file or in swap space, so can they pass addresses that refer to such non-resident pages to system calls. Moreover, unless your kernel takes measures to

prevent this, a page may be evicted from its frame even while it is being accessed by kernel code. If kernel code accesses such non-resident user pages, a page fault will result.

While accessing user memory, your kernel must either be prepared to handle such page faults, or it must prevent them from occurring. The kernel must prevent such page faults while it is holding resources it would need to acquire to handle these faults. In Pintos, such resources include locks acquired by the device driver(s) that control the device(s) containing the file system and swap space. As a concrete example, you must not allow page faults to occur while a device driver accesses a user buffer passed to `file_read`, because you would not be able to invoke the driver while handling such faults.

Preventing such page faults requires cooperation between the code within which the access occurs and your page eviction code. For instance, you could extend your frame table to record when a page contained in a frame must not be evicted. (This is also referred to as "pinning" or "locking" the page in its frame.) Pinning restricts your page replacement algorithm's choices when looking for pages to evict, so be sure to pin pages no longer than necessary, and avoid pinning pages when it is not necessary.

4.4 FAQ

How much code will I need to write?

Here's a summary of our reference solution, produced by the `diffstat` program. The final row gives total lines inserted and deleted; a changed line counts as both an insertion and a deletion.

This summary is relative to the Pintos base code, but the reference solution for project 3 starts from the reference solution to project 2. See Section 3.4 [Project 2 FAQ], page 33, for the summary of project 2.

The reference solution represents just one possible solution. Many other solutions are also possible and many of those differ greatly from the reference solution. Some excellent solutions may not modify all the files modified by the reference solution, and some may modify files not modified by the reference solution.

```
Makefile.build       |    4
devices/timer.c      |   42 ++
threads/init.c       |    5
threads/interrupt.c  |    2
threads/thread.c     |   31 +
threads/thread.h     |   37 +-
userprog/exception.c |   12
userprog/pagedir.c   |   10
userprog/process.c   |  319 +++++++++++++++-----
userprog/syscall.c   |  545 ++++++++++++++++++++++++++++++++-
userprog/syscall.h   |    1
vm/frame.c           |  162 +++++++++
vm/frame.h           |   23 +
vm/page.c            |  297 ++++++++++++++++
vm/page.h            |   50 ++
vm/swap.c            |   85 ++++
```

```
vm/swap.h             |   11
17 files changed, 1532 insertions(+), 104 deletions(-)
```

Do we need a working Project 2 to implement Project 3?

Yes.

What extra credit is available?

You may implement sharing: when multiple processes are created that use the same executable file, share read-only pages among those processes instead of creating separate copies of read-only segments for each process. If you carefully designed your data structures, sharing of read-only pages should not make this part significantly harder.

How do we resume a process after we have handled a page fault?

Returning from `page_fault()` resumes the current user process (see Section A.4.2 [Internal Interrupt Handling], page 73). It will then retry the instruction to which the instruction pointer points.

Why do user processes sometimes fault above the stack pointer?

You might notice that, in the stack growth tests, the user program faults on an address that is above the user program's current stack pointer, even though the `PUSH` and `PUSHA` instructions would cause faults 4 and 32 bytes below the current stack pointer.

This is not unusual. The `PUSH` and `PUSHA` instructions are not the only instructions that can trigger user stack growth. For instance, a user program may allocate stack space by decrementing the stack pointer using a `SUB $n, %esp` instruction, and then use a `MOV ..., m(%esp)` instruction to write to a stack location within the allocated space that is *m* bytes above the current stack pointer. Such accesses are perfectly valid, and your kernel must grow the user program's stack to allow those accesses to succeed.

Does the virtual memory system need to support data segment growth?

No. The size of the data segment is determined by the linker. We still have no dynamic allocation in Pintos (although it is possible to "fake" it at the user level by using memory-mapped files). Supporting data segment growth should add little additional complexity to a well-designed system.

Why should I use `PAL_USER` for allocating page frames?

Passing `PAL_USER` to `palloc_get_page()` causes it to allocate memory from the user pool, instead of the main kernel pool. Running out of pages in the user pool just causes user programs to page, but running out of pages in the kernel pool will cause many failures because so many kernel functions need to obtain memory. You can layer some other allocator on top of `palloc_get_page()` if you like, but it should be the underlying mechanism.

Also, you can use the '`-ul`' kernel command-line option to limit the size of the user pool, which makes it easy to test your VM implementation with various user memory sizes.

5 Project 4: File Systems

In the previous two assignments, you made extensive use of a file system without actually worrying about how it was implemented underneath. For this last assignment, you will improve the implementation of the file system. You will be working primarily in the '`filesys`' directory.

You may build project 4 on top of project 2 or project 3. In either case, all of the functionality needed for project 2 must work in your filesys submission. If you build on project 3, then all of the project 3 functionality must work also, and you will need to edit '`filesys/Make.vars`' to enable VM functionality. You can receive up to 5% extra credit if you do enable VM.

5.1 Background

5.1.1 New Code

Here are some files that are probably new to you. These are in the '`filesys`' directory except where indicated:

'`fsutil.c`'
: Simple utilities for the file system that are accessible from the kernel command line.

'`filesys.h`'
'`filesys.c`'
: Top-level interface to the file system. See Section 3.1.2 [Using the File System], page 23, for an introduction.

'`directory.h`'
'`directory.c`'
: Translates file names to inodes. The directory data structure is stored as a file.

'`inode.h`'
'`inode.c`'
: Manages the data structure representing the layout of a file's data on disk.

'`file.h`'
'`file.c`'
: Translates file reads and writes to disk sector reads and writes.

'`lib/kernel/bitmap.h`'
'`lib/kernel/bitmap.c`'
: A bitmap data structure along with routines for reading and writing the bitmap to disk files.

Our file system has a Unix-like interface, so you may also wish to read the Unix man pages for `creat`, `open`, `close`, `read`, `write`, `lseek`, and `unlink`. Our file system has calls that are similar, but not identical, to these. The file system translates these calls into disk operations.

All the basic functionality is there in the code above, so that the file system is usable from the start, as you've seen in the previous two projects. However, it has severe limitations which you will remove.

While most of your work will be in '`filesys`', you should be prepared for interactions with all previous parts.

5.1.2 Testing File System Persistence

By now, you should be familiar with the basic process of running the Pintos tests. See Section 1.2.1 [Testing], page 5, for review, if necessary.

Until now, each test invoked Pintos just once. However, an important purpose of a file system is to ensure that data remains accessible from one boot to another. Thus, the tests that are part of the file system project invoke Pintos a second time. The second run combines all the files and directories in the file system into a single file, then copies that file out of the Pintos file system into the host (Unix) file system.

The grading scripts check the file system's correctness based on the contents of the file copied out in the second run. This means that your project will not pass any of the extended file system tests until the file system is implemented well enough to support `tar`, the Pintos user program that produces the file that is copied out. The `tar` program is fairly demanding (it requires both extensible file and subdirectory support), so this will take some work. Until then, you can ignore errors from `make check` regarding the extracted file system.

Incidentally, as you may have surmised, the file format used for copying out the file system contents is the standard Unix "tar" format. You can use the Unix `tar` program to examine them. The tar file for test *t* is named '`t.tar`'.

5.2 Suggested Order of Implementation

To make your job easier, we suggest implementing the parts of this project in the following order:

1. Buffer cache (see Section 5.3.4 [Buffer Cache], page 54). Implement the buffer cache and integrate it into the existing file system. At this point all the tests from project 2 (and project 3, if you're building on it) should still pass.
2. Extensible files (see Section 5.3.2 [Indexed and Extensible Files], page 52). After this step, your project should pass the file growth tests.
3. Subdirectories (see Section 5.3.3 [Subdirectories], page 52). Afterward, your project should pass the directory tests.
4. Remaining miscellaneous items.

You can implement extensible files and subdirectories in parallel if you temporarily make the number of entries in new directories fixed.

You should think about synchronization throughout.

5.3 Requirements

5.3.1 Design Document

Before you turn in your project, you must copy the project 4 design document template into your source tree under the name '`pintos/src/filesys/DESIGNDOC`' and fill it in. We recommend that you read the design document template before you start working on the project. See Appendix D [Project Documentation], page 99, for a sample design document that goes along with a fictitious project.

5.3.2 Indexed and Extensible Files

The basic file system allocates files as a single extent, making it vulnerable to external fragmentation, that is, it is possible that an n-block file cannot be allocated even though n blocks are free. Eliminate this problem by modifying the on-disk inode structure. In practice, this probably means using an index structure with direct, indirect, and doubly indirect blocks. You are welcome to choose a different scheme as long as you explain the rationale for it in your design documentation, and as long as it does not suffer from external fragmentation (as does the extent-based file system we provide).

You can assume that the file system partition will not be larger than 8 MB. You must support files as large as the partition (minus metadata). Each inode is stored in one disk sector, limiting the number of block pointers that it can contain. Supporting 8 MB files will require you to implement doubly-indirect blocks.

An extent-based file can only grow if it is followed by empty space, but indexed inodes make file growth possible whenever free space is available. Implement file growth. In the basic file system, the file size is specified when the file is created. In most modern file systems, a file is initially created with size 0 and is then expanded every time a write is made off the end of the file. Your file system must allow this.

There should be no predetermined limit on the size of a file, except that a file cannot exceed the size of the file system (minus metadata). This also applies to the root directory file, which should now be allowed to expand beyond its initial limit of 16 files.

User programs are allowed to seek beyond the current end-of-file (EOF). The seek itself does not extend the file. Writing at a position past EOF extends the file to the position being written, and any gap between the previous EOF and the start of the write must be filled with zeros. A read starting from a position past EOF returns no bytes.

Writing far beyond EOF can cause many blocks to be entirely zero. Some file systems allocate and write real data blocks for these implicitly zeroed blocks. Other file systems do not allocate these blocks at all until they are explicitly written. The latter file systems are said to support "sparse files." You may adopt either allocation strategy in your file system.

5.3.3 Subdirectories

Implement a hierarchical name space. In the basic file system, all files live in a single directory. Modify this to allow directory entries to point to files or to other directories.

Make sure that directories can expand beyond their original size just as any other file can.

The basic file system has a 14-character limit on file names. You may retain this limit for individual file name components, or may extend it, at your option. You must allow full path names to be much longer than 14 characters.

Maintain a separate current directory for each process. At startup, set the root as the initial process's current directory. When one process starts another with the `exec` system call, the child process inherits its parent's current directory. After that, the two processes' current directories are independent, so that either changing its own current directory has no effect on the other. (This is why, under Unix, the `cd` command is a shell built-in, not an external program.)

Update the existing system calls so that, anywhere a file name is provided by the caller, an absolute or relative path name may used. The directory separator character is forward

slash ('/'). You must also support special file names '.' and '..', which have the same meanings as they do in Unix.

Update the `open` system call so that it can also open directories. Of the existing system calls, only `close` needs to accept a file descriptor for a directory.

Update the `remove` system call so that it can delete empty directories (other than the root) in addition to regular files. Directories may only be deleted if they do not contain any files or subdirectories (other than '.' and '..'). You may decide whether to allow deletion of a directory that is open by a process or in use as a process's current working directory. If it is allowed, then attempts to open files (including '.' and '..') or create new files in a deleted directory must be disallowed.

Implement the following new system calls:

`bool chdir` (*const char* ***dir***) [System Call]

Changes the current working directory of the process to *dir*, which may be relative or absolute. Returns true if successful, false on failure.

`bool mkdir` (*const char* ***dir***) [System Call]

Creates the directory named *dir*, which may be relative or absolute. Returns true if successful, false on failure. Fails if *dir* already exists or if any directory name in *dir*, besides the last, does not already exist. That is, `mkdir("/a/b/c")` succeeds only if '`/a/b`' already exists and '`/a/b/c`' does not.

`bool readdir` (*int* ***fd***, *char* ***name***) [System Call]

Reads a directory entry from file descriptor *fd*, which must represent a directory. If successful, stores the null-terminated file name in *name*, which must have room for `READDIR_MAX_LEN + 1` bytes, and returns true. If no entries are left in the directory, returns false.

'.' and '..' should not be returned by `readdir`.

If the directory changes while it is open, then it is acceptable for some entries not to be read at all or to be read multiple times. Otherwise, each directory entry should be read once, in any order.

`READDIR_MAX_LEN` is defined in '`lib/user/syscall.h`'. If your file system supports longer file names than the basic file system, you should increase this value from the default of 14.

`bool isdir` (*int* ***fd***) [System Call]

Returns true if *fd* represents a directory, false if it represents an ordinary file.

`int inumber` (*int* ***fd***) [System Call]

Returns the *inode number* of the inode associated with *fd*, which may represent an ordinary file or a directory.

An inode number persistently identifies a file or directory. It is unique during the file's existence. In Pintos, the sector number of the inode is suitable for use as an inode number.

We have provided `ls` and `mkdir` user programs, which are straightforward once the above syscalls are implemented. We have also provided `pwd`, which is not so straightforward. The `shell` program implements `cd` internally.

The `pintos` '`extract`' and '`append`' commands should now accept full path names, assuming that the directories used in the paths have already been created. This should not require any significant extra effort on your part.

5.3.4 Buffer Cache

Modify the file system to keep a cache of file blocks. When a request is made to read or write a block, check to see if it is in the cache, and if so, use the cached data without going to disk. Otherwise, fetch the block from disk into the cache, evicting an older entry if necessary. You are limited to a cache no greater than 64 sectors in size.

You must implement a cache replacement algorithm that is at least as good as the "clock" algorithm. We encourage you to account for the generally greater value of meta-data compared to data. Experiment to see what combination of accessed, dirty, and other information results in the best performance, as measured by the number of disk accesses.

You can keep a cached copy of the free map permanently in memory if you like. It doesn't have to count against the cache size.

The provided inode code uses a "bounce buffer" allocated with `malloc()` to translate the disk's sector-by-sector interface into the system call interface's byte-by-byte interface. You should get rid of these bounce buffers. Instead, copy data into and out of sectors in the buffer cache directly.

Your cache should be *write-behind*, that is, keep dirty blocks in the cache, instead of immediately writing modified data to disk. Write dirty blocks to disk whenever they are evicted. Because write-behind makes your file system more fragile in the face of crashes, in addition you should periodically write all dirty, cached blocks back to disk. The cache should also be written back to disk in `filesys_done()`, so that halting Pintos flushes the cache.

If you have `timer_sleep()` from the first project working, write-behind is an excellent application. Otherwise, you may implement a less general facility, but make sure that it does not exhibit busy-waiting.

You should also implement *read-ahead*, that is, automatically fetch the next block of a file into the cache when one block of a file is read, in case that block is about to be read. Read-ahead is only really useful when done asynchronously. That means, if a process requests disk block 1 from the file, it should block until disk block 1 is read in, but once that read is complete, control should return to the process immediately. The read-ahead request for disk block 2 should be handled asynchronously, in the background.

We recommend integrating the cache into your design early. In the past, many groups have tried to tack the cache onto a design late in the design process. This is very difficult. These groups have often turned in projects that failed most or all of the tests.

5.3.5 Synchronization

The provided file system requires external synchronization, that is, callers must ensure that only one thread can be running in the file system code at once. Your submission must adopt a finer-grained synchronization strategy that does not require external synchronization. To the extent possible, operations on independent entities should be independent, so that they do not need to wait on each other.

Operations on different cache blocks must be independent. In particular, when I/O is required on a particular block, operations on other blocks that do not require I/O should proceed without having to wait for the I/O to complete.

Multiple processes must be able to access a single file at once. Multiple reads of a single file must be able to complete without waiting for one another. When writing to a file does not extend the file, multiple processes should also be able to write a single file at once. A read of a file by one process when the file is being written by another process is allowed to show that none, all, or part of the write has completed. (However, after the `write` system call returns to its caller, all subsequent readers must see the change.) Similarly, when two processes simultaneously write to the same part of a file, their data may be interleaved.

On the other hand, extending a file and writing data into the new section must be atomic. Suppose processes A and B both have a given file open and both are positioned at end-of-file. If A reads and B writes the file at the same time, A may read all, part, or none of what B writes. However, A may not read data other than what B writes, e.g. if B's data is all nonzero bytes, A is not allowed to see any zeros.

Operations on different directories should take place concurrently. Operations on the same directory may wait for one another.

Keep in mind that only data shared by multiple threads needs to be synchronized. In the base file system, `struct file` and `struct dir` are accessed only by a single thread.

5.4 FAQ

How much code will I need to write?

Here's a summary of our reference solution, produced by the `diffstat` program. The final row gives total lines inserted and deleted; a changed line counts as both an insertion and a deletion.

This summary is relative to the Pintos base code, but the reference solution for project 4 is based on the reference solution to project 3. Thus, the reference solution runs with virtual memory enabled. See Section 4.4 [Project 3 FAQ], page 48, for the summary of project 3.

The reference solution represents just one possible solution. Many other solutions are also possible and many of those differ greatly from the reference solution. Some excellent solutions may not modify all the files modified by the reference solution, and some may modify files not modified by the reference solution.

```
 Makefile.build       |    5
 devices/timer.c      |   42 ++
 filesys/Make.vars    |    6
 filesys/cache.c      |  473 ++++++++++++++++++++++++
 filesys/cache.h      |   23 +
 filesys/directory.c  |   99 ++++-
 filesys/directory.h  |    3
 filesys/file.c       |    4
 filesys/filesys.c    |  194 +++++++++-
 filesys/filesys.h    |    5
 filesys/free-map.c   |   45 +-
```

```
filesys/free-map.h   |    4
filesys/fsutil.c     |    8
filesys/inode.c      |  444 ++++++++++++++++++++-----
filesys/inode.h      |   11
threads/init.c       |    5
threads/interrupt.c  |    2
threads/thread.c     |   32 +
threads/thread.h     |   38 +-
userprog/exception.c |   12
userprog/pagedir.c   |   10
userprog/process.c   |  332 +++++++++++++----
userprog/syscall.c   |  582 ++++++++++++++++++++++++++++++-
userprog/syscall.h   |    1
vm/frame.c           |  161 ++++++++
vm/frame.h           |   23 +
vm/page.c            |  297 ++++++++++++++
vm/page.h            |   50 ++
vm/swap.c            |   85 ++++
vm/swap.h            |   11
30 files changed, 2721 insertions(+), 286 deletions(-)
```

Can `BLOCk_SECTOR_SIZE` change?

No, `BLOCK_SECTOR_SIZE` is fixed at 512. For IDE disks, this value is a fixed property of the hardware. Other disks do not necessarily have a 512-byte sector, but for simplicity Pintos only supports those that do.

5.4.1 Indexed Files FAQ

What is the largest file size that we are supposed to support?

The file system partition we create will be 8 MB or smaller. However, individual files will have to be smaller than the partition to accommodate the metadata. You'll need to consider this when deciding your inode organization.

5.4.2 Subdirectories FAQ

How should a file name like '`a//b`' be interpreted?

Multiple consecutive slashes are equivalent to a single slash, so this file name is the same as '`a/b`'.

How about a file name like '`/../x`'?

The root directory is its own parent, so it is equivalent to '`/x`'.

How should a file name that ends in '/' be treated?

Most Unix systems allow a slash at the end of the name for a directory, and reject other names that end in slashes. We will allow this behavior, as well as simply rejecting a name that ends in a slash.

5.4.3 Buffer Cache FAQ

Can we keep a `struct inode_disk` inside `struct inode`?

The goal of the 64-block limit is to bound the amount of cached file system data. If you keep a block of disk data—whether file data or metadata—anywhere in

kernel memory then you have to count it against the 64-block limit. The same rule applies to anything that's "similar" to a block of disk data, such as a `struct inode_disk` without the `length` or `sector_cnt` members.

That means you'll have to change the way the inode implementation accesses its corresponding on-disk inode right now, since it currently just embeds a `struct inode_disk` in `struct inode` and reads the corresponding sector from disk when it's created. Keeping extra copies of inodes would subvert the 64-block limitation that we place on your cache.

You can store a pointer to inode data in `struct inode`, but if you do so you should carefully make sure that this does not limit your OS to 64 simultaneously open files. You can also store other information to help you find the inode when you need it. Similarly, you may store some metadata along each of your 64 cache entries.

You can keep a cached copy of the free map permanently in memory if you like. It doesn't have to count against the cache size.

`byte_to_sector()` in '`filesys/inode.c`' uses the `struct inode_disk` directly, without first reading that sector from wherever it was in the storage hierarchy. This will no longer work. You will need to change `inode_byte_to_sector()` to obtain the `struct inode_disk` from the cache before using it.

Appendix A Reference Guide

This chapter is a reference for the Pintos code. The reference guide does not cover all of the code in Pintos, but it does cover those pieces that students most often find troublesome. You may find that you want to read each part of the reference guide as you work on the project where it becomes important.

We recommend using "tags" to follow along with references to function and variable names (see Section F.1 [Tags], page 113).

A.1 Loading

This section covers the Pintos loader and basic kernel initialization.

A.1.1 The Loader

The first part of Pintos that runs is the loader, in '`threads/loader.S`'. The PC BIOS loads the loader into memory. The loader, in turn, is responsible for finding the kernel on disk, loading it into memory, and then jumping to its start. It's not important to understand exactly how the loader works, but if you're interested, read on. You should probably read along with the loader's source. You should also understand the basics of the 80x86 architecture as described by chapter 3, "Basic Execution Environment," of [IA32-v1].

The PC BIOS loads the loader from the first sector of the first hard disk, called the *master boot record* (MBR). PC conventions reserve 64 bytes of the MBR for the partition table, and Pintos uses about 128 additional bytes for kernel command-line arguments. This leaves a little over 300 bytes for the loader's own code. This is a severe restriction that means, practically speaking, the loader must be written in assembly language.

The Pintos loader and kernel don't have to be on the same disk, nor does is the kernel required to be in any particular location on a given disk. The loader's first job, then, is to find the kernel by reading the partition table on each hard disk, looking for a bootable partition of the type used for a Pintos kernel.

When the loader finds a bootable kernel partition, it reads the partition's contents into memory at physical address 128 kB. The kernel is at the beginning of the partition, which might be larger than necessary due to partition boundary alignment conventions, so the loader reads no more than 512 kB (and the Pintos build process will refuse to produce kernels larger than that). Reading more data than this would cross into the region from 640 kB to 1 MB that the PC architecture reserves for hardware and the BIOS, and a standard PC BIOS does not provide any means to load the kernel above 1 MB.

The loader's final job is to extract the entry point from the loaded kernel image and transfer control to it. The entry point is not at a predictable location, but the kernel's ELF header contains a pointer to it. The loader extracts the pointer and jumps to the location it points to.

The Pintos kernel command line is stored in the boot loader. The `pintos` program actually modifies a copy of the boot loader on disk each time it runs the kernel, inserting whatever command-line arguments the user supplies to the kernel, and then the kernel at boot time reads those arguments out of the boot loader in memory. This is not an elegant solution, but it is simple and effective.

A.1.2 Low-Level Kernel Initialization

The loader's last action is to transfer control to the kernel's entry point, which is `start()` in '`threads/start.S`'. The job of this code is to switch the CPU from legacy 16-bit "real mode" into the 32-bit "protected mode" used by all modern 80*x*86 operating systems.

The startup code's first task is actually to obtain the machine's memory size, by asking the BIOS for the PC's memory size. The simplest BIOS function to do this can only detect up to 64 MB of RAM, so that's the practical limit that Pintos can support. The function stores the memory size, in pages, in global variable `init_ram_pages`.

The first part of CPU initialization is to enable the A20 line, that is, the CPU's address line numbered 20. For historical reasons, PCs boot with this address line fixed at 0, which means that attempts to access memory beyond the first 1 MB (2 raised to the 20th power) will fail. Pintos wants to access more memory than this, so we have to enable it.

Next, the loader creates a basic page table. This page table maps the 64 MB at the base of virtual memory (starting at virtual address 0) directly to the identical physical addresses. It also maps the same physical memory starting at virtual address `LOADER_PHYS_BASE`, which defaults to `0xc0000000` (3 GB). The Pintos kernel only wants the latter mapping, but there's a chicken-and-egg problem if we don't include the former: our current virtual address is roughly `0x20000`, the location where the loader put us, and we can't jump to `0xc0020000` until we turn on the page table, but if we turn on the page table without jumping there, then we've just pulled the rug out from under ourselves.

After the page table is initialized, we load the CPU's control registers to turn on protected mode and paging, and set up the segment registers. We aren't yet equipped to handle interrupts in protected mode, so we disable interrupts. The final step is to call `main()`.

A.1.3 High-Level Kernel Initialization

The kernel proper starts with the `main()` function. The `main()` function is written in C, as will be most of the code we encounter in Pintos from here on out.

When `main()` starts, the system is in a pretty raw state. We're in 32-bit protected mode with paging enabled, but hardly anything else is ready. Thus, the `main()` function consists primarily of calls into other Pintos modules' initialization functions. These are usually named *`module`*`_init()`, where *module* is the module's name, '*`module`*`.c`' is the module's source code, and '*`module`*`.h`' is the module's header.

The first step in `main()` is to call `bss_init()`, which clears out the kernel's "BSS", which is the traditional name for a segment that should be initialized to all zeros. In most C implementations, whenever you declare a variable outside a function without providing an initializer, that variable goes into the BSS. Because it's all zeros, the BSS isn't stored in the image that the loader brought into memory. We just use `memset()` to zero it out.

Next, `main()` calls `read_command_line()` to break the kernel command line into arguments, then `parse_options()` to read any options at the beginning of the command line. (Actions specified on the command line execute later.)

`thread_init()` initializes the thread system. We will defer full discussion to our discussion of Pintos threads below. It is called so early in initialization because a valid thread structure is a prerequisite for acquiring a lock, and lock acquisition in turn is important to other Pintos subsystems. Then we initialize the console and print a startup message to the console.

The next block of functions we call initializes the kernel's memory system. `palloc_init()` sets up the kernel page allocator, which doles out memory one or more pages at a time (see Section A.5.1 [Page Allocator], page 75). `malloc_init()` sets up the allocator that handles allocations of arbitrary-size blocks of memory (see Section A.5.2 [Block Allocator], page 76). `paging_init()` sets up a page table for the kernel (see Section A.7 [Page Table], page 79).

In projects 2 and later, `main()` also calls `tss_init()` and `gdt_init()`.

The next set of calls initializes the interrupt system. `intr_init()` sets up the CPU's *interrupt descriptor table* (IDT) to ready it for interrupt handling (see Section A.4.1 [Interrupt Infrastructure], page 72), then `timer_init()` and `kbd_init()` prepare for handling timer interrupts and keyboard interrupts, respectively. `input_init()` sets up to merge serial and keyboard input into one stream. In projects 2 and later, we also prepare to handle interrupts caused by user programs using `exception_init()` and `syscall_init()`.

Now that interrupts are set up, we can start the scheduler with `thread_start()`, which creates the idle thread and enables interrupts. With interrupts enabled, interrupt-driven serial port I/O becomes possible, so we use `serial_init_queue()` to switch to that mode. Finally, `timer_calibrate()` calibrates the timer for accurate short delays.

If the file system is compiled in, as it will starting in project 2, we initialize the IDE disks with `ide_init()`, then the file system with `filesys_init()`.

Boot is complete, so we print a message.

Function `run_actions()` now parses and executes actions specified on the kernel command line, such as `run` to run a test (in project 1) or a user program (in later projects).

Finally, if '`-q`' was specified on the kernel command line, we call `shutdown_power_off()` to terminate the machine simulator. Otherwise, `main()` calls `thread_exit()`, which allows any other running threads to continue running.

A.1.4 Physical Memory Map

Memory Range	Owner	Contents
00000000–000003ff	CPU	Real mode interrupt table.
00000400–000005ff	BIOS	Miscellaneous data area.
00000600–00007bff	—	—
00007c00–00007dff	Pintos	Loader.
0000e000–0000efff	Pintos	Stack for loader; kernel stack and `struct thread` for initial kernel thread.
0000f000–0000ffff	Pintos	Page directory for startup code.
00010000–00020000	Pintos	Page tables for startup code.
00020000–0009ffff	Pintos	Kernel code, data, and uninitialized data segments.
000a0000–000bffff	Video	VGA display memory.
000c0000–000effff	Hardware	Reserved for expansion card RAM and ROM.
000f0000–000fffff	BIOS	ROM BIOS.
00100000–03ffffff	Pintos	Dynamic memory allocation.

A.2 Threads

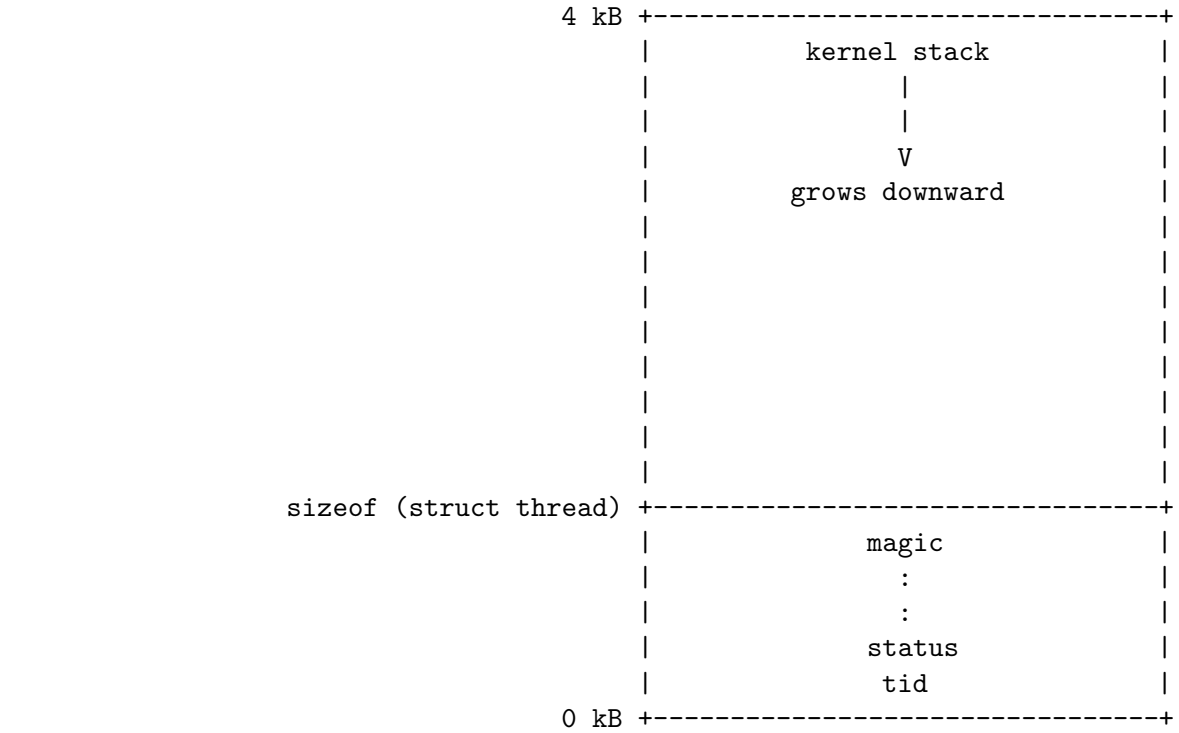
A.2.1 `struct thread`

The main Pintos data structure for threads is `struct thread`, declared in '`threads/thread.h`'.

`struct thread` [Structure]

Represents a thread or a user process. In the projects, you will have to add your own members to `struct thread`. You may also change or delete the definitions of existing members.

Every `struct thread` occupies the beginning of its own page of memory. The rest of the page is used for the thread's stack, which grows downward from the end of the page. It looks like this:



This has two consequences. First, `struct thread` must not be allowed to grow too big. If it does, then there will not be enough room for the kernel stack. The base `struct thread` is only a few bytes in size. It probably should stay well under 1 kB.

Second, kernel stacks must not be allowed to grow too large. If a stack overflows, it will corrupt the thread state. Thus, kernel functions should not allocate large structures or arrays as non-static local variables. Use dynamic allocation with `malloc()` or `palloc_get_page()` instead (see Section A.5 [Memory Allocation], page 75).

`tid_t tid` [Member of `struct thread`]

The thread's thread identifier or *tid*. Every thread must have a tid that is unique over the entire lifetime of the kernel. By default, `tid_t` is a `typedef` for `int` and each new thread receives the numerically next higher tid, starting from 1 for the initial process. You can change the type and the numbering scheme if you like.

`enum thread_status status` [Member of `struct thread`]

The thread's state, one of the following:

`THREAD_RUNNING` [Thread State]

The thread is running. Exactly one thread is running at a given time. `thread_current()` returns the running thread.

`THREAD_READY` [Thread State]

The thread is ready to run, but it's not running right now. The thread could be selected to run the next time the scheduler is invoked. Ready threads are kept in a doubly linked list called `ready_list`.

`THREAD_BLOCKED` [Thread State]

The thread is waiting for something, e.g. a lock to become available, an interrupt to be invoked. The thread won't be scheduled again until it transitions to the `THREAD_READY` state with a call to `thread_unblock()`. This is most conveniently done indirectly, using one of the Pintos synchronization primitives that block and unblock threads automatically (see Section A.3 [Synchronization], page 66).

There is no *a priori* way to tell what a blocked thread is waiting for, but a backtrace can help (see Section E.4 [Backtraces], page 103).

`THREAD_DYING` [Thread State]

The thread will be destroyed by the scheduler after switching to the next thread.

`char name[16]` [Member of `struct thread`]

The thread's name as a string, or at least the first few characters of it.

`uint8_t * stack` [Member of `struct thread`]

Every thread has its own stack to keep track of its state. When the thread is running, the CPU's stack pointer register tracks the top of the stack and this member is unused. But when the CPU switches to another thread, this member saves the thread's stack pointer. No other members are needed to save the thread's registers, because the other registers that must be saved are saved on the stack.

When an interrupt occurs, whether in the kernel or a user program, an `struct intr_frame` is pushed onto the stack. When the interrupt occurs in a user program, the `struct intr_frame` is always at the very top of the page. See Section A.4 [Interrupt Handling], page 71, for more information.

`int priority` [Member of `struct thread`]

A thread priority, ranging from `PRI_MIN` (0) to `PRI_MAX` (63). Lower numbers correspond to lower priorities, so that priority 0 is the lowest priority and priority 63 is the highest. Pintos as provided ignores thread priorities, but you will implement priority scheduling in project 1 (see Section 2.2.3 [Priority Scheduling], page 16).

`struct list_elem allelem` [Member of `struct thread`]

This "list element" is used to link the thread into the list of all threads. Each thread is inserted into this list when it is created and removed when it exits. The `thread_foreach()` function should be used to iterate over all threads.

`struct list_elem elem` [Member of `struct thread`]

A "list element" used to put the thread into doubly linked lists, either `ready_list` (the list of threads ready to run) or a list of threads waiting on a semaphore in `sema_down()`. It can do double duty because a thread waiting on a semaphore is not ready, and vice versa.

`uint32_t * pagedir` [Member of `struct thread`]

Only present in project 2 and later. See Section 4.1.2.3 [Page Tables], page 40.

`unsigned magic` [Member of `struct thread`]

Always set to `THREAD_MAGIC`, which is just an arbitrary number defined in '`threads/thread.c`', and used to detect stack overflow. `thread_current()` checks that the `magic` member of the running thread's `struct thread` is set to `THREAD_MAGIC`. Stack overflow tends to change this value, triggering the assertion. For greatest benefit, as you add members to `struct thread`, leave `magic` at the end.

A.2.2 Thread Functions

'`threads/thread.c`' implements several public functions for thread support. Let's take a look at the most useful:

`void thread_init (`*void*`)` [Function]

Called by `main()` to initialize the thread system. Its main purpose is to create a `struct thread` for Pintos's initial thread. This is possible because the Pintos loader puts the initial thread's stack at the top of a page, in the same position as any other Pintos thread.

Before `thread_init()` runs, `thread_current()` will fail because the running thread's `magic` value is incorrect. Lots of functions call `thread_current()` directly or indirectly, including `lock_acquire()` for locking a lock, so `thread_init()` is called early in Pintos initialization.

`void thread_start (`*void*`)` [Function]

Called by `main()` to start the scheduler. Creates the idle thread, that is, the thread that is scheduled when no other thread is ready. Then enables interrupts, which as a side effect enables the scheduler because the scheduler runs on return from the timer interrupt, using `intr_yield_on_return()` (see Section A.4.3 [External Interrupt Handling], page 74).

`void thread_tick (`*void*`)` [Function]

Called by the timer interrupt at each timer tick. It keeps track of thread statistics and triggers the scheduler when a time slice expires.

`void thread_print_stats (`*void*`)` [Function]

Called during Pintos shutdown to print thread statistics.

`tid_t thread_create (`*const char *`**`name`***`, int `**`priority`***`, thread_func *`**`func`***`, void *`**`aux`***`)` [Function]

Creates and starts a new thread named *name* with the given *priority*, returning the new thread's tid. The thread executes *func*, passing *aux* as the function's single argument.

`thread_create()` allocates a page for the thread's `struct thread` and stack and initializes its members, then it sets up a set of fake stack frames for it (see Section A.2.3 [Thread Switching], page 65). The thread is initialized in the blocked state, then unblocked just before returning, which allows the new thread to be scheduled (see [Thread States], page 62).

`void thread_func (void *aux)` [Type]
This is the type of the function passed to `thread_create()`, whose *aux* argument is passed along as the function's argument.

`void thread_block (void)` [Function]
Transitions the running thread from the running state to the blocked state (see [Thread States], page 62). The thread will not run again until `thread_unblock()` is called on it, so you'd better have some way arranged for that to happen. Because `thread_block()` is so low-level, you should prefer to use one of the synchronization primitives instead (see Section A.3 [Synchronization], page 66).

`void thread_unblock (struct thread *thread)` [Function]
Transitions *thread*, which must be in the blocked state, to the ready state, allowing it to resume running (see [Thread States], page 62). This is called when the event that the thread is waiting for occurs, e.g. when the lock that the thread is waiting on becomes available.

`struct thread * thread_current (void)` [Function]
Returns the running thread.

`tid_t thread_tid (void)` [Function]
Returns the running thread's thread id. Equivalent to `thread_current ()->tid`.

`const char * thread_name (void)` [Function]
Returns the running thread's name. Equivalent to `thread_current ()->name`.

`void thread_exit (void) NO_RETURN` [Function]
Causes the current thread to exit. Never returns, hence `NO_RETURN` (see Section E.3 [Function and Parameter Attributes], page 102).

`void thread_yield (void)` [Function]
Yields the CPU to the scheduler, which picks a new thread to run. The new thread might be the current thread, so you can't depend on this function to keep this thread from running for any particular length of time.

`void thread_foreach (thread_action_func *action, void *aux)` [Function]
Iterates over all threads t and invokes `action(t, aux)` on each. *action* must refer to a function that matches the signature given by `thread_action_func()`:

`void thread_action_func (struct thread *thread, void *aux)` [Type]
Performs some action on a thread, given *aux*.

`int thread_get_priority (void)` [Function]
`void thread_set_priority (int new_priority)` [Function]
Stub to set and get thread priority. See Section 2.2.3 [Priority Scheduling], page 16.

`int thread_get_nice` (*void*) [Function]
`void thread_set_nice` (*int* `new_nice`) [Function]
`int thread_get_recent_cpu` (*void*) [Function]
`int thread_get_load_avg` (*void*) [Function]
Stubs for the advanced scheduler. See Appendix B [4.4BSD Scheduler], page 91.

A.2.3 Thread Switching

`schedule()` is responsible for switching threads. It is internal to '`threads/thread.c`' and called only by the three public thread functions that need to switch threads: `thread_block()`, `thread_exit()`, and `thread_yield()`. Before any of these functions call `schedule()`, they disable interrupts (or ensure that they are already disabled) and then change the running thread's state to something other than running.

`schedule()` is short but tricky. It records the current thread in local variable *cur*, determines the next thread to run as local variable *next* (by calling `next_thread_to_run()`), and then calls `switch_threads()` to do the actual thread switch. The thread we switched to was also running inside `switch_threads()`, as are all the threads not currently running, so the new thread now returns out of `switch_threads()`, returning the previously running thread.

`switch_threads()` is an assembly language routine in '`threads/switch.S`'. It saves registers on the stack, saves the CPU's current stack pointer in the current `struct thread`'s `stack` member, restores the new thread's `stack` into the CPU's stack pointer, restores registers from the stack, and returns.

The rest of the scheduler is implemented in `thread_schedule_tail()`. It marks the new thread as running. If the thread we just switched from is in the dying state, then it also frees the page that contained the dying thread's `struct thread` and stack. These couldn't be freed prior to the thread switch because the switch needed to use it.

Running a thread for the first time is a special case. When `thread_create()` creates a new thread, it goes through a fair amount of trouble to get it started properly. In particular, the new thread hasn't started running yet, so there's no way for it to be running inside `switch_threads()` as the scheduler expects. To solve the problem, `thread_create()` creates some fake stack frames in the new thread's stack:

- The topmost fake stack frame is for `switch_threads()`, represented by `struct switch_threads_frame`. The important part of this frame is its `eip` member, the return address. We point `eip` to `switch_entry()`, indicating it to be the function that called `switch_entry()`.
- The next fake stack frame is for `switch_entry()`, an assembly language routine in '`threads/switch.S`' that adjusts the stack pointer,[1] calls `thread_schedule_tail()` (this special case is why `thread_schedule_tail()` is separate from `schedule()`), and returns. We fill in its stack frame so that it returns into `kernel_thread()`, a function in '`threads/thread.c`'.

[1] This is because `switch_threads()` takes arguments on the stack and the 80x86 SVR4 calling convention requires the caller, not the called function, to remove them when the call is complete. See [SysV-i386] chapter 3 for details.

- The final stack frame is for `kernel_thread()`, which enables interrupts and calls the thread's function (the function passed to `thread_create()`). If the thread's function returns, it calls `thread_exit()` to terminate the thread.

A.3 Synchronization

If sharing of resources between threads is not handled in a careful, controlled fashion, the result is usually a big mess. This is especially the case in operating system kernels, where faulty sharing can crash the entire machine. Pintos provides several synchronization primitives to help out.

A.3.1 Disabling Interrupts

The crudest way to do synchronization is to disable interrupts, that is, to temporarily prevent the CPU from responding to interrupts. If interrupts are off, no other thread will preempt the running thread, because thread preemption is driven by the timer interrupt. If interrupts are on, as they normally are, then the running thread may be preempted by another at any time, whether between two C statements or even within the execution of one.

Incidentally, this means that Pintos is a "preemptible kernel," that is, kernel threads can be preempted at any time. Traditional Unix systems are "nonpreemptible," that is, kernel threads can only be preempted at points where they explicitly call into the scheduler. (User programs can be preempted at any time in both models.) As you might imagine, preemptible kernels require more explicit synchronization.

You should have little need to set the interrupt state directly. Most of the time you should use the other synchronization primitives described in the following sections. The main reason to disable interrupts is to synchronize kernel threads with external interrupt handlers, which cannot sleep and thus cannot use most other forms of synchronization (see Section A.4.3 [External Interrupt Handling], page 74).

Some external interrupts cannot be postponed, even by disabling interrupts. These interrupts, called *non-maskable interrupts* (NMIs), are supposed to be used only in emergencies, e.g. when the computer is on fire. Pintos does not handle non-maskable interrupts.

Types and functions for disabling and enabling interrupts are in '`threads/interrupt.h`'.

`enum intr_level` [Type]
One of `INTR_OFF` or `INTR_ON`, denoting that interrupts are disabled or enabled, respectively.

`enum intr_level intr_get_level (`*void*`)` [Function]
Returns the current interrupt state.

`enum intr_level intr_set_level (`*enum intr_level* `level`*`)`* [Function]
Turns interrupts on or off according to *level*. Returns the previous interrupt state.

`enum intr_level intr_enable (`*void*`)` [Function]
Turns interrupts on. Returns the previous interrupt state.

`enum intr_level intr_disable (`*void*`)` [Function]
Turns interrupts off. Returns the previous interrupt state.

A.3.2 Semaphores

A *semaphore* is a nonnegative integer together with two operators that manipulate it atomically, which are:

- "Down" or "P": wait for the value to become positive, then decrement it.
- "Up" or "V": increment the value (and wake up one waiting thread, if any).

A semaphore initialized to 0 may be used to wait for an event that will happen exactly once. For example, suppose thread A starts another thread B and wants to wait for B to signal that some activity is complete. A can create a semaphore initialized to 0, pass it to B as it starts it, and then "down" the semaphore. When B finishes its activity, it "ups" the semaphore. This works regardless of whether A "downs" the semaphore or B "ups" it first.

A semaphore initialized to 1 is typically used for controlling access to a resource. Before a block of code starts using the resource, it "downs" the semaphore, then after it is done with the resource it "ups" the resource. In such a case a lock, described below, may be more appropriate.

Semaphores can also be initialized to values larger than 1. These are rarely used.

Semaphores were invented by Edsger Dijkstra and first used in the THE operating system ([Dijkstra]).

Pintos' semaphore type and operations are declared in '`threads/synch.h`'.

`struct semaphore` [Type]
Represents a semaphore.

`void sema_init` (*struct semaphore* `*sema`, *unsigned* `value`) [Function]
Initializes *sema* as a new semaphore with the given initial *value*.

`void sema_down` (*struct semaphore* `*sema`) [Function]
Executes the "down" or "P" operation on *sema*, waiting for its value to become positive and then decrementing it by one.

`bool sema_try_down` (*struct semaphore* `*sema`) [Function]
Tries to execute the "down" or "P" operation on *sema*, without waiting. Returns true if *sema* was successfully decremented, or false if it was already zero and thus could not be decremented without waiting. Calling this function in a tight loop wastes CPU time, so use `sema_down()` or find a different approach instead.

`void sema_up` (*struct semaphore* `*sema`) [Function]
Executes the "up" or "V" operation on *sema*, incrementing its value. If any threads are waiting on *sema*, wakes one of them up.

Unlike most synchronization primitives, `sema_up()` may be called inside an external interrupt handler (see Section A.4.3 [External Interrupt Handling], page 74).

Semaphores are internally built out of disabling interrupt (see Section A.3.1 [Disabling Interrupts], page 66) and thread blocking and unblocking (`thread_block()` and `thread_unblock()`). Each semaphore maintains a list of waiting threads, using the linked list implementation in '`lib/kernel/list.c`'.

A.3.3 Locks

A *lock* is like a semaphore with an initial value of 1 (see Section A.3.2 [Semaphores], page 67). A lock's equivalent of "up" is called "release", and the "down" operation is called "acquire".

Compared to a semaphore, a lock has one added restriction: only the thread that acquires a lock, called the lock's "owner", is allowed to release it. If this restriction is a problem, it's a good sign that a semaphore should be used, instead of a lock.

Locks in Pintos are not "recursive," that is, it is an error for the thread currently holding a lock to try to acquire that lock.

Lock types and functions are declared in '`threads/synch.h`'.

`struct lock` [Type]
Represents a lock.

`void lock_init (`*struct lock *`lock`*`)` [Function]
Initializes *lock* as a new lock. The lock is not initially owned by any thread.

`void lock_acquire (`*struct lock *`lock`*`)` [Function]
Acquires *lock* for the current thread, first waiting for any current owner to release it if necessary.

`bool lock_try_acquire (`*struct lock *`lock`*`)` [Function]
Tries to acquire *lock* for use by the current thread, without waiting. Returns true if successful, false if the lock is already owned. Calling this function in a tight loop is a bad idea because it wastes CPU time, so use `lock_acquire()` instead.

`void lock_release (`*struct lock *`lock`*`)` [Function]
Releases *lock*, which the current thread must own.

`bool lock_held_by_current_thread (`*const struct lock *`lock`*`)` [Function]
Returns true if the running thread owns *lock*, false otherwise. There is no function to test whether an arbitrary thread owns a lock, because the answer could change before the caller could act on it.

A.3.4 Monitors

A *monitor* is a higher-level form of synchronization than a semaphore or a lock. A monitor consists of data being synchronized, plus a lock, called the *monitor lock*, and one or more *condition variables*. Before it accesses the protected data, a thread first acquires the monitor lock. It is then said to be "in the monitor". While in the monitor, the thread has control over all the protected data, which it may freely examine or modify. When access to the protected data is complete, it releases the monitor lock.

Condition variables allow code in the monitor to wait for a condition to become true. Each condition variable is associated with an abstract condition, e.g. "some data has arrived for processing" or "over 10 seconds has passed since the user's last keystroke". When code in the monitor needs to wait for a condition to become true, it "waits" on the associated condition variable, which releases the lock and waits for the condition to be signaled. If, on the other hand, it has caused one of these conditions to become true, it "signals" the condition to wake up one waiter, or "broadcasts" the condition to wake all of them.

The theoretical framework for monitors was laid out by C. A. R. Hoare ([Hoare]). Their practical usage was later elaborated in a paper on the Mesa operating system ([Lampson]).

Condition variable types and functions are declared in '`threads/synch.h`'.

`struct condition` [Type]
Represents a condition variable.

`void cond_init (`*struct condition* `*cond`*`)` [Function]
Initializes *cond* as a new condition variable.

`void cond_wait (`*struct condition* `*cond`*, *struct lock* `*lock`*`)` [Function]
Atomically releases *lock* (the monitor lock) and waits for *cond* to be signaled by some other piece of code. After *cond* is signaled, reacquires *lock* before returning. *lock* must be held before calling this function.

Sending a signal and waking up from a wait are not an atomic operation. Thus, typically `cond_wait()`'s caller must recheck the condition after the wait completes and, if necessary, wait again. See the next section for an example.

`void cond_signal (`*struct condition* `*cond`*, *struct lock* `*lock`*`)` [Function]
If any threads are waiting on *cond* (protected by monitor lock *lock*), then this function wakes up one of them. If no threads are waiting, returns without performing any action. *lock* must be held before calling this function.

`void cond_broadcast (`*struct condition* `*cond`*, *struct lock* `*lock`*`)` [Function]
Wakes up all threads, if any, waiting on *cond* (protected by monitor lock *lock*). *lock* must be held before calling this function.

A.3.4.1 Monitor Example

The classical example of a monitor is handling a buffer into which one or more "producer" threads write characters and out of which one or more "consumer" threads read characters. To implement this we need, besides the monitor lock, two condition variables which we will call *not_full* and *not_empty*:

```
char buf[BUF_SIZE];      /* Buffer. */
size_t n = 0;            /* 0 <= n <= BUF_SIZE: # of characters in buffer. */
size_t head = 0;         /* buf index of next char to write (mod BUF_SIZE). */
size_t tail = 0;         /* buf index of next char to read (mod BUF_SIZE). */
struct lock lock;        /* Monitor lock. */
struct condition not_empty; /* Signaled when the buffer is not empty. */
struct condition not_full; /* Signaled when the buffer is not full. */

...initialize the locks and condition variables...

void put (char ch) {
  lock_acquire (&lock);
  while (n == BUF_SIZE)             /* Can't add to buf as long as it's full. */
    cond_wait (&not_full, &lock);
  buf[head++ % BUF_SIZE] = ch;      /* Add ch to buf. */
  n++;
```

```
  cond_signal (&not_empty, &lock); /* buf can't be empty anymore. */
  lock_release (&lock);
}

char get (void) {
  char ch;
  lock_acquire (&lock);
  while (n == 0)                   /* Can't read buf as long as it's empty. */
    cond_wait (&not_empty, &lock);
  ch = buf[tail++ % BUF_SIZE];     /* Get ch from buf. */
  n--;
  cond_signal (&not_full, &lock); /* buf can't be full anymore. */
  lock_release (&lock);
}
```

Note that `BUF_SIZE` must divide evenly into `SIZE_MAX + 1` for the above code to be completely correct. Otherwise, it will fail the first time `head` wraps around to 0. In practice, `BUF_SIZE` would ordinarily be a power of 2.

A.3.5 Optimization Barriers

An *optimization barrier* is a special statement that prevents the compiler from making assumptions about the state of memory across the barrier. The compiler will not reorder reads or writes of variables across the barrier or assume that a variable's value is unmodified across the barrier, except for local variables whose address is never taken. In Pintos, '`threads/synch.h`' defines the `barrier()` macro as an optimization barrier.

One reason to use an optimization barrier is when data can change asynchronously, without the compiler's knowledge, e.g. by another thread or an interrupt handler. The `too_many_loops()` function in '`devices/timer.c`' is an example. This function starts out by busy-waiting in a loop until a timer tick occurs:

```
/* Wait for a timer tick. */
int64_t start = ticks;
while (ticks == start)
  barrier ();
```

Without an optimization barrier in the loop, the compiler could conclude that the loop would never terminate, because `start` and `ticks` start out equal and the loop itself never changes them. It could then "optimize" the function into an infinite loop, which would definitely be undesirable.

Optimization barriers can be used to avoid other compiler optimizations. The `busy_wait()` function, also in '`devices/timer.c`', is an example. It contains this loop:

```
while (loops-- > 0)
  barrier ();
```

The goal of this loop is to busy-wait by counting `loops` down from its original value to 0. Without the barrier, the compiler could delete the loop entirely, because it produces no useful output and has no side effects. The barrier forces the compiler to pretend that the loop body has an important effect.

Finally, optimization barriers can be used to force the ordering of memory reads or writes. For example, suppose we add a "feature" that, whenever a timer interrupt occurs, the character in global variable `timer_put_char` is printed on the console, but only if global Boolean variable `timer_do_put` is true. The best way to set up '`x`' to be printed is then to use an optimization barrier, like this:

```
timer_put_char = 'x';
barrier ();
timer_do_put = true;
```

Without the barrier, the code is buggy because the compiler is free to reorder operations when it doesn't see a reason to keep them in the same order. In this case, the compiler doesn't know that the order of assignments is important, so its optimizer is permitted to exchange their order. There's no telling whether it will actually do this, and it is possible that passing the compiler different optimization flags or using a different version of the compiler will produce different behavior.

Another solution is to disable interrupts around the assignments. This does not prevent reordering, but it prevents the interrupt handler from intervening between the assignments. It also has the extra runtime cost of disabling and re-enabling interrupts:

```
enum intr_level old_level = intr_disable ();
timer_put_char = 'x';
timer_do_put = true;
intr_set_level (old_level);
```

A second solution is to mark the declarations of `timer_put_char` and `timer_do_put` as '`volatile`'. This keyword tells the compiler that the variables are externally observable and restricts its latitude for optimization. However, the semantics of '`volatile`' are not well-defined, so it is not a good general solution. The base Pintos code does not use '`volatile`' at all.

The following is *not* a solution, because locks neither prevent interrupts nor prevent the compiler from reordering the code within the region where the lock is held:

```
lock_acquire (&timer_lock);     /* INCORRECT CODE */
timer_put_char = 'x';
timer_do_put = true;
lock_release (&timer_lock);
```

The compiler treats invocation of any function defined externally, that is, in another source file, as a limited form of optimization barrier. Specifically, the compiler assumes that any externally defined function may access any statically or dynamically allocated data and any local variable whose address is taken. This often means that explicit barriers can be omitted. It is one reason that Pintos contains few explicit barriers.

A function defined in the same source file, or in a header included by the source file, cannot be relied upon as a optimization barrier. This applies even to invocation of a function before its definition, because the compiler may read and parse the entire source file before performing optimization.

A.4 Interrupt Handling

An *interrupt* notifies the CPU of some event. Much of the work of an operating system relates to interrupts in one way or another. For our purposes, we classify interrupts into two broad categories:

- *Internal interrupts*, that is, interrupts caused directly by CPU instructions. System calls, attempts at invalid memory access (*page faults*), and attempts to divide by zero are some activities that cause internal interrupts. Because they are caused by CPU instructions, internal interrupts are *synchronous* or synchronized with CPU instructions. `intr_disable()` does not disable internal interrupts.
- *External interrupts*, that is, interrupts originating outside the CPU. These interrupts come from hardware devices such as the system timer, keyboard, serial ports, and disks. External interrupts are *asynchronous*, meaning that their delivery is not synchronized with instruction execution. Handling of external interrupts can be postponed with `intr_disable()` and related functions (see Section A.3.1 [Disabling Interrupts], page 66).

The CPU treats both classes of interrupts largely the same way, so Pintos has common infrastructure to handle both classes. The following section describes this common infrastructure. The sections after that give the specifics of external and internal interrupts.

If you haven't already read chapter 3, "Basic Execution Environment," in [IA32-v1], it is recommended that you do so now. You might also want to skim chapter 5, "Interrupt and Exception Handling," in [IA32-v3a].

A.4.1 Interrupt Infrastructure

When an interrupt occurs, the CPU saves its most essential state on a stack and jumps to an interrupt handler routine. The 80*x*86 architecture supports 256 interrupts, numbered 0 through 255, each with an independent handler defined in an array called the *interrupt descriptor table* or IDT.

In Pintos, `intr_init()` in '`threads/interrupt.c`' sets up the IDT so that each entry points to a unique entry point in '`threads/intr-stubs.S`' named `intr`*NN*`_stub()`, where *NN* is the interrupt number in hexadecimal. Because the CPU doesn't give us any other way to find out the interrupt number, this entry point pushes the interrupt number on the stack. Then it jumps to `intr_entry()`, which pushes all the registers that the processor didn't already push for us, and then calls `intr_handler()`, which brings us back into C in '`threads/interrupt.c`'.

The main job of `intr_handler()` is to call the function registered for handling the particular interrupt. (If no function is registered, it dumps some information to the console and panics.) It also does some extra processing for external interrupts (see Section A.4.3 [External Interrupt Handling], page 74).

When `intr_handler()` returns, the assembly code in '`threads/intr-stubs.S`' restores all the CPU registers saved earlier and directs the CPU to return from the interrupt.

The following types and functions are common to all interrupts.

`void intr_handler_func (struct intr_frame *frame)` [Type]
This is how an interrupt handler function must be declared. Its *frame* argument (see below) allows it to determine the cause of the interrupt and the state of the thread that was interrupted.

`struct intr_frame` [Type]
The stack frame of an interrupt handler, as saved by the CPU, the interrupt stubs, and `intr_entry()`. Its most interesting members are described below.

`uint32_t edi` [Member of `struct intr_frame`]
`uint32_t esi` [Member of `struct intr_frame`]
`uint32_t ebp` [Member of `struct intr_frame`]
`uint32_t esp_dummy` [Member of `struct intr_frame`]
`uint32_t ebx` [Member of `struct intr_frame`]
`uint32_t edx` [Member of `struct intr_frame`]
`uint32_t ecx` [Member of `struct intr_frame`]
`uint32_t eax` [Member of `struct intr_frame`]
`uint16_t es` [Member of `struct intr_frame`]
`uint16_t ds` [Member of `struct intr_frame`]
Register values in the interrupted thread, pushed by `intr_entry()`. The `esp_dummy` value isn't actually used (refer to the description of `PUSHA` in [IA32-v2b] for details).

`uint32_t vec_no` [Member of `struct intr_frame`]
The interrupt vector number, ranging from 0 to 255.

`uint32_t error_code` [Member of `struct intr_frame`]
The "error code" pushed on the stack by the CPU for some internal interrupts.

`void (*eip) (void)` [Member of `struct intr_frame`]
The address of the next instruction to be executed by the interrupted thread.

`void * esp` [Member of `struct intr_frame`]
The interrupted thread's stack pointer.

`const char * intr_name (uint8_t vec)` [Function]
Returns the name of the interrupt numbered *vec*, or `"unknown"` if the interrupt has no registered name.

A.4.2 Internal Interrupt Handling

Internal interrupts are caused directly by CPU instructions executed by the running kernel thread or user process (from project 2 onward). An internal interrupt is therefore said to arise in a "process context."

In an internal interrupt's handler, it can make sense to examine the `struct intr_frame` passed to the interrupt handler, or even to modify it. When the interrupt returns, modifications in `struct intr_frame` become changes to the calling thread or process's state. For example, the Pintos system call handler returns a value to the user program by modifying the saved EAX register (see Section 3.5.2 [System Call Details], page 37).

There are no special restrictions on what an internal interrupt handler can or can't do. Generally they should run with interrupts enabled, just like other code, and so they can be

preempted by other kernel threads. Thus, they do need to synchronize with other threads on shared data and other resources (see Section A.3 [Synchronization], page 66).

Internal interrupt handlers can be invoked recursively. For example, the system call handler might cause a page fault while attempting to read user memory. Deep recursion would risk overflowing the limited kernel stack (see Section A.2.1 [struct thread], page 61), but should be unnecessary.

`void intr_register_int` (*uint8_t* `vec`, *int* `dpl`, *enum intr_level* `level`, *intr_handler_func* *`handler`, *const char* *`name`) [Function]

Registers *handler* to be called when internal interrupt numbered *vec* is triggered. Names the interrupt *name* for debugging purposes.

If *level* is `INTR_ON`, external interrupts will be processed normally during the interrupt handler's execution, which is normally desirable. Specifying `INTR_OFF` will cause the CPU to disable external interrupts when it invokes the interrupt handler. The effect is slightly different from calling `intr_disable()` inside the handler, because that leaves a window of one or more CPU instructions in which external interrupts are still enabled. This is important for the page fault handler; refer to the comments in '`userprog/exception.c`' for details.

dpl determines how the interrupt can be invoked. If *dpl* is 0, then the interrupt can be invoked only by kernel threads. Otherwise *dpl* should be 3, which allows user processes to invoke the interrupt with an explicit INT instruction. The value of *dpl* doesn't affect user processes' ability to invoke the interrupt indirectly, e.g. an invalid memory reference will cause a page fault regardless of *dpl*.

A.4.3 External Interrupt Handling

External interrupts are caused by events outside the CPU. They are asynchronous, so they can be invoked at any time that interrupts have not been disabled. We say that an external interrupt runs in an "interrupt context."

In an external interrupt, the `struct intr_frame` passed to the handler is not very meaningful. It describes the state of the thread or process that was interrupted, but there is no way to predict which one that is. It is possible, although rarely useful, to examine it, but modifying it is a recipe for disaster.

Only one external interrupt may be processed at a time. Neither internal nor external interrupt may nest within an external interrupt handler. Thus, an external interrupt's handler must run with interrupts disabled (see Section A.3.1 [Disabling Interrupts], page 66).

An external interrupt handler must not sleep or yield, which rules out calling `lock_acquire()`, `thread_yield()`, and many other functions. Sleeping in interrupt context would effectively put the interrupted thread to sleep, too, until the interrupt handler was again scheduled and returned. This would be unfair to the unlucky thread, and it would deadlock if the handler were waiting for the sleeping thread to, e.g., release a lock.

An external interrupt handler effectively monopolizes the machine and delays all other activities. Therefore, external interrupt handlers should complete as quickly as they can. Anything that require much CPU time should instead run in a kernel thread, possibly one that the interrupt triggers using a synchronization primitive.

External interrupts are controlled by a pair of devices outside the CPU called *programmable interrupt controllers*, *PICs* for short. When `intr_init()` sets up the CPU's

IDT, it also initializes the PICs for interrupt handling. The PICs also must be "acknowledged" at the end of processing for each external interrupt. `intr_handler()` takes care of that by calling `pic_end_of_interrupt()`, which properly signals the PICs.

The following functions relate to external interrupts.

`void intr_register_ext (`*uint8_t* `vec`*, intr_handler_func* `*handler`*, `const char *name)` [Function]

Registers *handler* to be called when external interrupt numbered *vec* is triggered. Names the interrupt *name* for debugging purposes. The handler will run with interrupts disabled.

`bool intr_context (`*void*`)` [Function]

Returns true if we are running in an interrupt context, otherwise false. Mainly used in functions that might sleep or that otherwise should not be called from interrupt context, in this form:

```
ASSERT (!intr_context ());
```

`void intr_yield_on_return (`*void*`)` [Function]

When called in an interrupt context, causes `thread_yield()` to be called just before the interrupt returns. Used in the timer interrupt handler when a thread's time slice expires, to cause a new thread to be scheduled.

A.5 Memory Allocation

Pintos contains two memory allocators, one that allocates memory in units of a page, and one that can allocate blocks of any size.

A.5.1 Page Allocator

The page allocator declared in '`threads/palloc.h`' allocates memory in units of a page. It is most often used to allocate memory one page at a time, but it can also allocate multiple contiguous pages at once.

The page allocator divides the memory it allocates into two pools, called the kernel and user pools. By default, each pool gets half of system memory above 1 MB, but the division can be changed with the '`-ul`' kernel command line option (see [Why PAL_USER?], page 49). An allocation request draws from one pool or the other. If one pool becomes empty, the other may still have free pages. The user pool should be used for allocating memory for user processes and the kernel pool for all other allocations. This will only become important starting with project 3. Until then, all allocations should be made from the kernel pool.

Each pool's usage is tracked with a bitmap, one bit per page in the pool. A request to allocate *n* pages scans the bitmap for *n* consecutive bits set to false, indicating that those pages are free, and then sets those bits to true to mark them as used. This is a "first fit" allocation strategy (see [Wilson], page 118).

The page allocator is subject to fragmentation. That is, it may not be possible to allocate *n* contiguous pages even though *n* or more pages are free, because the free pages are separated by used pages. In fact, in pathological cases it may be impossible to allocate 2 contiguous pages even though half of the pool's pages are free. Single-page requests can't

fail due to fragmentation, so requests for multiple contiguous pages should be limited as much as possible.

Pages may not be allocated from interrupt context, but they may be freed.

When a page is freed, all of its bytes are cleared to `0xcc`, as a debugging aid (see Section E.8 [Debugging Tips], page 112).

Page allocator types and functions are described below.

`void * palloc_get_page (`*enum palloc_flags* `flags``)` [Function]
`void * palloc_get_multiple (`*enum palloc_flags* `flags`, *size_t* `page_cnt``)` [Function]

Obtains and returns one page, or *page_cnt* contiguous pages, respectively. Returns a null pointer if the pages cannot be allocated.

The *flags* argument may be any combination of the following flags:

`PAL_ASSERT` [Page Allocator Flag]

If the pages cannot be allocated, panic the kernel. This is only appropriate during kernel initialization. User processes should never be permitted to panic the kernel.

`PAL_ZERO` [Page Allocator Flag]

Zero all the bytes in the allocated pages before returning them. If not set, the contents of newly allocated pages are unpredictable.

`PAL_USER` [Page Allocator Flag]

Obtain the pages from the user pool. If not set, pages are allocated from the kernel pool.

`void palloc_free_page (`*void *page*`)` [Function]
`void palloc_free_multiple (`*void *pages*, *size_t* `page_cnt``)` [Function]

Frees one page, or *page_cnt* contiguous pages, respectively, starting at *pages*. All of the pages must have been obtained using `palloc_get_page()` or `palloc_get_multiple()`.

A.5.2 Block Allocator

The block allocator, declared in '`threads/malloc.h`', can allocate blocks of any size. It is layered on top of the page allocator described in the previous section. Blocks returned by the block allocator are obtained from the kernel pool.

The block allocator uses two different strategies for allocating memory. The first strategy applies to blocks that are 1 kB or smaller (one-fourth of the page size). These allocations are rounded up to the nearest power of 2, or 16 bytes, whichever is larger. Then they are grouped into a page used only for allocations of that size.

The second strategy applies to blocks larger than 1 kB. These allocations (plus a small amount of overhead) are rounded up to the nearest page in size, and then the block allocator requests that number of contiguous pages from the page allocator.

In either case, the difference between the allocation requested size and the actual block size is wasted. A real operating system would carefully tune its allocator to minimize this waste, but this is unimportant in an instructional system like Pintos.

As long as a page can be obtained from the page allocator, small allocations always succeed. Most small allocations do not require a new page from the page allocator at all, because they are satisfied using part of a page already allocated. However, large allocations always require calling into the page allocator, and any allocation that needs more than one contiguous page can fail due to fragmentation, as already discussed in the previous section. Thus, you should minimize the number of large allocations in your code, especially those over approximately 4 kB each.

When a block is freed, all of its bytes are cleared to `0xcc`, as a debugging aid (see Section E.8 [Debugging Tips], page 112).

The block allocator may not be called from interrupt context.

The block allocator functions are described below. Their interfaces are the same as the standard C library functions of the same names.

`void * malloc` (*size_t* `size`) [Function]
: Obtains and returns a new block, from the kernel pool, at least *size* bytes long. Returns a null pointer if *size* is zero or if memory is not available.

`void * calloc` (*size_t* `a`, *size_t* `b`) [Function]
: Obtains a returns a new block, from the kernel pool, at least `a * b` bytes long. The block's contents will be cleared to zeros. Returns a null pointer if *a* or *b* is zero or if insufficient memory is available.

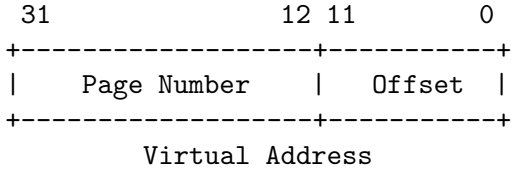
`void * realloc` (*void* `*block`, *size_t* `new_size`) [Function]
: Attempts to resize *block* to *new_size* bytes, possibly moving it in the process. If successful, returns the new block, in which case the old block must no longer be accessed. On failure, returns a null pointer, and the old block remains valid.

  A call with *block* null is equivalent to `malloc()`. A call with *new_size* zero is equivalent to `free()`.

`void free` (*void* `*block`) [Function]
: Frees *block*, which must have been previously returned by `malloc()`, `calloc()`, or `realloc()` (and not yet freed).

A.6 Virtual Addresses

A 32-bit virtual address can be divided into a 20-bit *page number* and a 12-bit *page offset* (or just *offset*), like this:



Header '`threads/vaddr.h`' defines these functions and macros for working with virtual addresses:

`PGSHIFT` [Macro]
`PGBITS` [Macro]
: The bit index (0) and number of bits (12) of the offset part of a virtual address, respectively.

`PGMASK` [Macro]
A bit mask with the bits in the page offset set to 1, the rest set to 0 (`0xfff`).

`PGSIZE` [Macro]
The page size in bytes (4,096).

`unsigned pg_ofs (const void *va)` [Function]
Extracts and returns the page offset in virtual address *va*.

`uintptr_t pg_no (const void *va)` [Function]
Extracts and returns the page number in virtual address *va*.

`void * pg_round_down (const void *va)` [Function]
Returns the start of the virtual page that *va* points within, that is, *va* with the page offset set to 0.

`void * pg_round_up (const void *va)` [Function]
Returns *va* rounded up to the nearest page boundary.

Virtual memory in Pintos is divided into two regions: user virtual memory and kernel virtual memory (see Section 3.1.4 [Virtual Memory Layout], page 25). The boundary between them is `PHYS_BASE`:

`PHYS_BASE` [Macro]
Base address of kernel virtual memory. It defaults to `0xc0000000` (3 GB), but it may be changed to any multiple of `0x10000000` from `0x80000000` to `0xf0000000`.

User virtual memory ranges from virtual address 0 up to `PHYS_BASE`. Kernel virtual memory occupies the rest of the virtual address space, from `PHYS_BASE` up to 4 GB.

`bool is_user_vaddr (const void *va)` [Function]
`bool is_kernel_vaddr (const void *va)` [Function]
Returns true if *va* is a user or kernel virtual address, respectively, false otherwise.

The 80*x*86 doesn't provide any way to directly access memory given a physical address. This ability is often necessary in an operating system kernel, so Pintos works around it by mapping kernel virtual memory one-to-one to physical memory. That is, virtual address `PHYS_BASE` accesses physical address 0, virtual address `PHYS_BASE + 0x1234` accesses physical address `0x1234`, and so on up to the size of the machine's physical memory. Thus, adding `PHYS_BASE` to a physical address obtains a kernel virtual address that accesses that address; conversely, subtracting `PHYS_BASE` from a kernel virtual address obtains the corresponding physical address. Header '`threads/vaddr.h`' provides a pair of functions to do these translations:

`void * ptov (uintptr_t pa)` [Function]
Returns the kernel virtual address corresponding to physical address *pa*, which should be between 0 and the number of bytes of physical memory.

`uintptr_t vtop (void *va)` [Function]
Returns the physical address corresponding to *va*, which must be a kernel virtual address.

A.7 Page Table

The code in '`pagedir.c`' is an abstract interface to the 80x86 hardware page table, also called a "page directory" by Intel processor documentation. The page table interface uses a `uint32_t *` to represent a page table because this is convenient for accessing their internal structure.

The sections below describe the page table interface and internals.

A.7.1 Creation, Destruction, and Activation

These functions create, destroy, and activate page tables. The base Pintos code already calls these functions where necessary, so it should not be necessary to call them yourself.

`uint32_t * pagedir_create (`*void*`)` [Function]
Creates and returns a new page table. The new page table contains Pintos's normal kernel virtual page mappings, but no user virtual mappings.

Returns a null pointer if memory cannot be obtained.

`void pagedir_destroy (`*uint32_t *pd*`)` [Function]
Frees all of the resources held by *pd*, including the page table itself and the frames that it maps.

`void pagedir_activate (`*uint32_t *pd*`)` [Function]
Activates *pd*. The active page table is the one used by the CPU to translate memory references.

A.7.2 Inspection and Updates

These functions examine or update the mappings from pages to frames encapsulated by a page table. They work on both active and inactive page tables (that is, those for running and suspended processes), flushing the TLB as necessary.

`bool pagedir_set_page (`*uint32_t *pd, void *upage, void *kpage, bool writable*`)` [Function]
Adds to *pd* a mapping from user page *upage* to the frame identified by kernel virtual address *kpage*. If *writable* is true, the page is mapped read/write; otherwise, it is mapped read-only.

User page *upage* must not already be mapped in *pd*.

Kernel page *kpage* should be a kernel virtual address obtained from the user pool with `palloc_get_page(PAL_USER)` (see [Why PAL_USER?], page 49).

Returns true if successful, false on failure. Failure will occur if additional memory required for the page table cannot be obtained.

`void * pagedir_get_page (`*uint32_t *pd, const void *uaddr*`)` [Function]
Looks up the frame mapped to *uaddr* in *pd*. Returns the kernel virtual address for that frame, if *uaddr* is mapped, or a null pointer if it is not.

`void pagedir_clear_page (`*uint32_t *pd, void *page*`)` [Function]
Marks *page* "not present" in *pd*. Later accesses to the page will fault.

Other bits in the page table for *page* are preserved, permitting the accessed and dirty bits (see the next section) to be checked.

This function has no effect if *page* is not mapped.

A.7.3 Accessed and Dirty Bits

80x86 hardware provides some assistance for implementing page replacement algorithms, through a pair of bits in the page table entry (PTE) for each page. On any read or write to a page, the CPU sets the *accessed bit* to 1 in the page's PTE, and on any write, the CPU sets the *dirty bit* to 1. The CPU never resets these bits to 0, but the OS may do so.

Proper interpretation of these bits requires understanding of *aliases*, that is, two (or more) pages that refer to the same frame. When an aliased frame is accessed, the accessed and dirty bits are updated in only one page table entry (the one for the page used for access). The accessed and dirty bits for the other aliases are not updated.

See Section 4.1.5.1 [Accessed and Dirty Bits], page 43, on applying these bits in implementing page replacement algorithms.

`bool pagedir_is_dirty (`*uint32_t *pd, const void *page*`)` [Function]
`bool pagedir_is_accessed (`*uint32_t *pd, const void *page*`)` [Function]
Returns true if page directory *pd* contains a page table entry for *page* that is marked dirty (or accessed). Otherwise, returns false.

`void pagedir_set_dirty (`*uint32_t *pd, const void *page, bool* `value`*)* [Function]
`void pagedir_set_accessed (`*uint32_t *pd, const void *page, bool* `value`*)* [Function]
If page directory *pd* has a page table entry for *page*, then its dirty (or accessed) bit is set to *value*.

A.7.4 Page Table Details

The functions provided with Pintos are sufficient to implement the projects. However, you may still find it worthwhile to understand the hardware page table format, so we'll go into a little detail in this section.

A.7.4.1 Structure

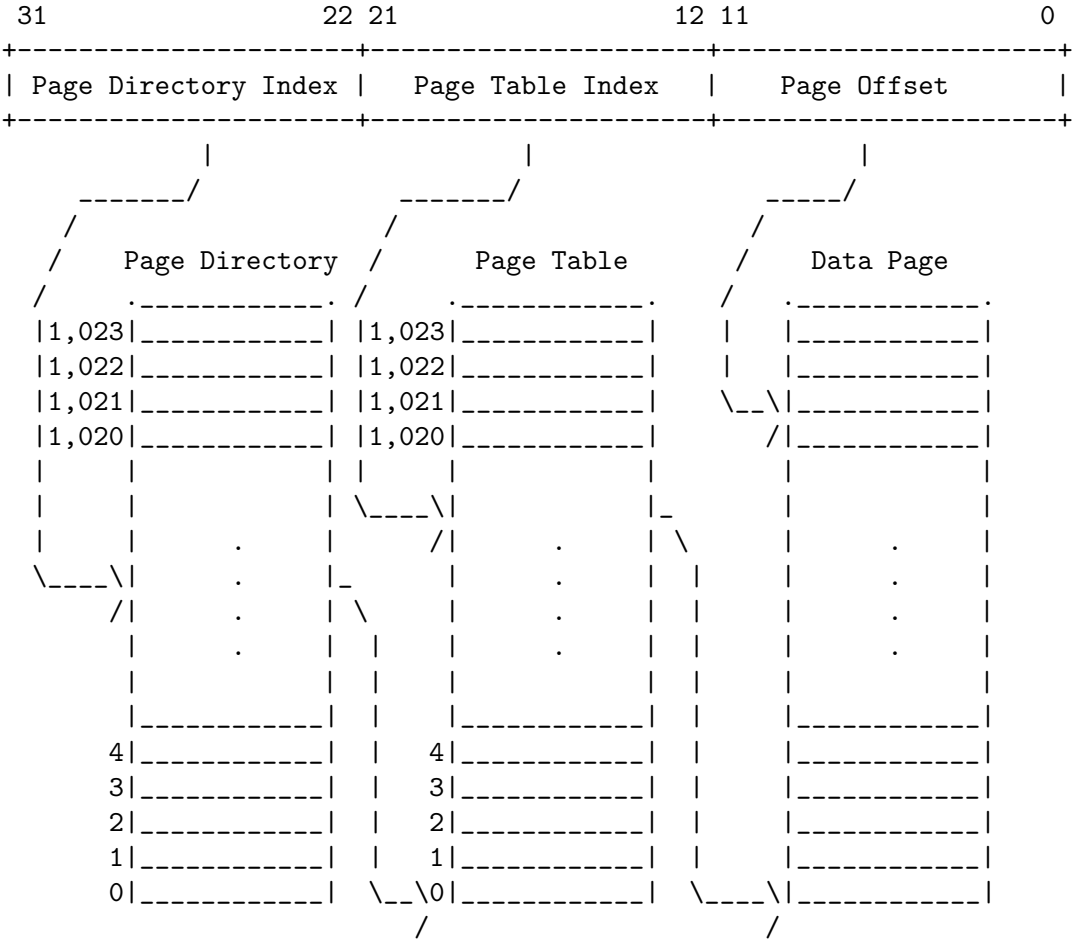
The top-level paging data structure is a page called the "page directory" (PD) arranged as an array of 1,024 32-bit page directory entries (PDEs), each of which represents 4 MB of virtual memory. Each PDE may point to the physical address of another page called a "page table" (PT) arranged, similarly, as an array of 1,024 32-bit page table entries (PTEs), each of which translates a single 4 kB virtual page to a physical page.

Translation of a virtual address into a physical address follows the three-step process illustrated in the diagram below:[2]

1. The most-significant 10 bits of the virtual address (bits 22...31) index the page directory. If the PDE is marked "present," the physical address of a page table is read from the PDE thus obtained. If the PDE is marked "not present" then a page fault occurs.

[2] Actually, virtual to physical translation on the 80x86 architecture occurs via an intermediate "linear address," but Pintos (and most modern 80x86 OSes) set up the CPU so that linear and virtual addresses are one and the same. Thus, you can effectively ignore this CPU feature.

2. The next 10 bits of the virtual address (bits 12...21) index the page table. If the PTE is marked "present," the physical address of a data page is read from the PTE thus obtained. If the PTE is marked "not present" then a page fault occurs.
3. The least-significant 12 bits of the virtual address (bits 0...11) are added to the data page's physical base address, yielding the final physical address.



Pintos provides some macros and functions that are useful for working with raw page tables:

`PTSHIFT` [Macro]
`PTBITS` [Macro]

The starting bit index (12) and number of bits (10), respectively, in a page table index.

`PTMASK` [Macro]

A bit mask with the bits in the page table index set to 1 and the rest set to 0 (`0x3ff000`).

`PTSPAN` [Macro]

The number of bytes of virtual address space that a single page table page covers (4,194,304 bytes, or 4 MB).

`PDSHIFT` [Macro]
`PDBITS` [Macro]
The starting bit index (22) and number of bits (10), respectively, in a page directory index.

`PDMASK` [Macro]
A bit mask with the bits in the page directory index set to 1 and other bits set to 0 (`0xffc00000`).

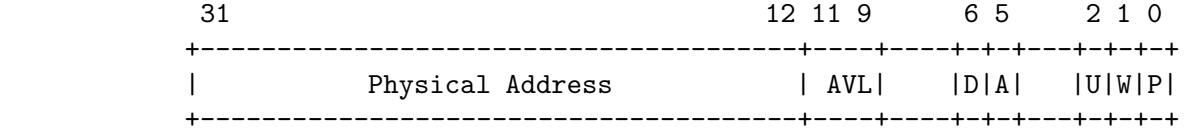
`uintptr_t pd_no (const void *va)` [Function]
`uintptr_t pt_no (const void *va)` [Function]
Returns the page directory index or page table index, respectively, for virtual address *va*. These functions are defined in '`threads/pte.h`'.

`unsigned pg_ofs (const void *va)` [Function]
Returns the page offset for virtual address *va*. This function is defined in '`threads/vaddr.h`'.

A.7.4.2 Page Table Entry Format

You do not need to understand the PTE format to do the Pintos projects, unless you wish to incorporate the page table into your supplemental page table (see Section 4.1.4 [Managing the Supplemental Page Table], page 42).

The actual format of a page table entry is summarized below. For complete information, refer to section 3.7, "Page Translation Using 32-Bit Physical Addressing," in [IA32-v3a].



Some more information on each bit is given below. The names are '`threads/pte.h`' macros that represent the bits' values:

`PTE_P` [Macro]
Bit 0, the "present" bit. When this bit is 1, the other bits are interpreted as described below. When this bit is 0, any attempt to access the page will page fault. The remaining bits are then not used by the CPU and may be used by the OS for any purpose.

`PTE_W` [Macro]
Bit 1, the "read/write" bit. When it is 1, the page is writable. When it is 0, write attempts will page fault.

`PTE_U` [Macro]
Bit 2, the "user/supervisor" bit. When it is 1, user processes may access the page. When it is 0, only the kernel may access the page (user accesses will page fault).

Pintos clears this bit in PTEs for kernel virtual memory, to prevent user processes from accessing them.

`PTE_A` [Macro]
Bit 5, the "accessed" bit. See Section A.7.3 [Page Table Accessed and Dirty Bits], page 80.

`PTE_D` [Macro]
Bit 6, the "dirty" bit. See Section A.7.3 [Page Table Accessed and Dirty Bits], page 80.

`PTE_AVL` [Macro]
Bits 9...11, available for operating system use. Pintos, as provided, does not use them and sets them to 0.

`PTE_ADDR` [Macro]
Bits 12...31, the top 20 bits of the physical address of a frame. The low 12 bits of the frame's address are always 0.

Other bits are either reserved or uninteresting in a Pintos context and should be set to 0.

Header '`threads/pte.h`' defines three functions for working with page table entries:

`uint32_t pte_create_kernel (`*uint32_t* `*page`, *bool* `writable`) [Function]
Returns a page table entry that points to *page*, which should be a kernel virtual address. The PTE's present bit will be set. It will be marked for kernel-only access. If *writable* is true, the PTE will also be marked read/write; otherwise, it will be read-only.

`uint32_t pte_create_user (`*uint32_t* `*page`, *bool* `writable`) [Function]
Returns a page table entry that points to *page*, which should be the kernel virtual address of a frame in the user pool (see [Why PAL_USER?], page 49). The PTE's present bit will be set and it will be marked to allow user-mode access. If *writable* is true, the PTE will also be marked read/write; otherwise, it will be read-only.

`void * pte_get_page (`*uint32_t* `pte`) [Function]
Returns the kernel virtual address for the frame that *pte* points to. The *pte* may be present or not-present; if it is not-present then the pointer returned is only meaningful if the address bits in the PTE actually represent a physical address.

A.7.4.3 Page Directory Entry Format

Page directory entries have the same format as PTEs, except that the physical address points to a page table page instead of a frame. Header '`threads/pte.h`' defines two functions for working with page directory entries:

`uint32_t pde_create (`*uint32_t* `*pt`) [Function]
Returns a page directory that points to *page*, which should be the kernel virtual address of a page table page. The PDE's present bit will be set, it will be marked to allow user-mode access, and it will be marked read/write.

`uint32_t * pde_get_pt (`*uint32_t* `pde`) [Function]
Returns the kernel virtual address for the page table page that *pde*, which must be marked present, points to.

A.8 Hash Table

Pintos provides a hash table data structure in '`lib/kernel/hash.c`'. To use it you will need to include its header file, '`lib/kernel/hash.h`', with `#include <hash.h>`. No code provided with Pintos uses the hash table, which means that you are free to use it as is, modify its implementation for your own purposes, or ignore it, as you wish.

Most implementations of the virtual memory project use a hash table to translate pages to frames. You may find other uses for hash tables as well.

A.8.1 Data Types

A hash table is represented by `struct hash`.

`struct hash` [Type]
: Represents an entire hash table. The actual members of `struct hash` are "opaque." That is, code that uses a hash table should not access `struct hash` members directly, nor should it need to. Instead, use hash table functions and macros.

The hash table operates on elements of type `struct hash_elem`.

`struct hash_elem` [Type]
: Embed a `struct hash_elem` member in the structure you want to include in a hash table. Like `struct hash`, `struct hash_elem` is opaque. All functions for operating on hash table elements actually take and return pointers to `struct hash_elem`, not pointers to your hash table's real element type.

You will often need to obtain a `struct hash_elem` given a real element of the hash table, and vice versa. Given a real element of the hash table, you may use the '`&`' operator to obtain a pointer to its `struct hash_elem`. Use the `hash_entry()` macro to go the other direction.

type `* hash_entry` (*struct hash_elem *elem*, *type*, *member*) [Macro]
: Returns a pointer to the structure that *elem*, a pointer to a `struct hash_elem`, is embedded within. You must provide *type*, the name of the structure that *elem* is inside, and *member*, the name of the member in *type* that *elem* points to.

  For example, suppose `h` is a `struct hash_elem *` variable that points to a `struct thread` member (of type `struct hash_elem`) named `h_elem`. Then, `hash_entry (h, struct thread, h_elem)` yields the address of the `struct thread` that `h` points within.

See Section A.8.5 [Hash Table Example], page 88, for an example.

Each hash table element must contain a key, that is, data that identifies and distinguishes elements, which must be unique among elements in the hash table. (Elements may also contain non-key data that need not be unique.) While an element is in a hash table, its key data must not be changed. Instead, if need be, remove the element from the hash table, modify its key, then reinsert the element.

For each hash table, you must write two functions that act on keys: a hash function and a comparison function. These functions must match the following prototypes:

`unsigned hash_hash_func (const struct hash_elem *element, void *aux)` [Type]

Returns a hash of *element*'s data, as a value anywhere in the range of `unsigned int`. The hash of an element should be a pseudo-random function of the element's key. It must not depend on non-key data in the element or on any non-constant data other than the key. Pintos provides the following functions as a suitable basis for hash functions.

`unsigned hash_bytes (const void *buf, size_t *size)` [Function]

Returns a hash of the *size* bytes starting at *buf*. The implementation is the general-purpose Fowler-Noll-Vo hash (`http://en.wikipedia.org/wiki/Fowler_Noll_Vo_hash`) for 32-bit words.

`unsigned hash_string (const char *s)` [Function]

Returns a hash of null-terminated string *s*.

`unsigned hash_int (int i)` [Function]

Returns a hash of integer *i*.

If your key is a single piece of data of an appropriate type, it is sensible for your hash function to directly return the output of one of these functions. For multiple pieces of data, you may wish to combine the output of more than one call to them using, e.g., the '^' (exclusive or) operator. Finally, you may entirely ignore these functions and write your own hash function from scratch, but remember that your goal is to build an operating system kernel, not to design a hash function.

See Section A.8.6 [Hash Auxiliary Data], page 89, for an explanation of *aux*.

`bool hash_less_func (const struct hash_elem *a, const struct hash_elem *b, void *aux)` [Type]

Compares the keys stored in elements *a* and *b*. Returns true if *a* is less than *b*, false if *a* is greater than or equal to *b*.

If two elements compare equal, then they must hash to equal values.

See Section A.8.6 [Hash Auxiliary Data], page 89, for an explanation of *aux*.

See Section A.8.5 [Hash Table Example], page 88, for hash and comparison function examples.

A few functions accept a pointer to a third kind of function as an argument:

`void hash_action_func (struct hash_elem *element, void *aux)` [Type]

Performs some kind of action, chosen by the caller, on *element*.

See Section A.8.6 [Hash Auxiliary Data], page 89, for an explanation of *aux*.

A.8.2 Basic Functions

These functions create, destroy, and inspect hash tables.

`bool hash_init (struct hash *hash, hash_hash_func *hash_func, hash_less_func *less_func, void *aux)` [Function]

Initializes *hash* as a hash table with *hash_func* as hash function, *less_func* as comparison function, and *aux* as auxiliary data. Returns true if successful, false on failure. `hash_init()` calls `malloc()` and fails if memory cannot be allocated.

See Section A.8.6 [Hash Auxiliary Data], page 89, for an explanation of *aux*, which is most often a null pointer.

`void hash_clear` (*struct hash* **hash*, *hash_action_func* **action*) [Function]

Removes all the elements from *hash*, which must have been previously initialized with `hash_init()`.

If *action* is non-null, then it is called once for each element in the hash table, which gives the caller an opportunity to deallocate any memory or other resources used by the element. For example, if the hash table elements are dynamically allocated using `malloc()`, then *action* could `free()` the element. This is safe because `hash_clear()` will not access the memory in a given hash element after calling *action* on it. However, *action* must not call any function that may modify the hash table, such as `hash_insert()` or `hash_delete()`.

`void hash_destroy` (*struct hash* **hash*, *hash_action_func* **action*) [Function]

If *action* is non-null, calls it for each element in the hash, with the same semantics as a call to `hash_clear()`. Then, frees the memory held by *hash*. Afterward, *hash* must not be passed to any hash table function, absent an intervening call to `hash_init()`.

`size_t hash_size` (*struct hash* **hash*) [Function]

Returns the number of elements currently stored in *hash*.

`bool hash_empty` (*struct hash* **hash*) [Function]

Returns true if *hash* currently contains no elements, false if *hash* contains at least one element.

A.8.3 Search Functions

Each of these functions searches a hash table for an element that compares equal to one provided. Based on the success of the search, they perform some action, such as inserting a new element into the hash table, or simply return the result of the search.

`struct hash_elem * hash_insert` (*struct hash* **hash*, *struct hash_elem* **element*) [Function]

Searches *hash* for an element equal to *element*. If none is found, inserts *element* into *hash* and returns a null pointer. If the table already contains an element equal to *element*, it is returned without modifying *hash*.

`struct hash_elem * hash_replace` (*struct hash* **hash*, *struct hash_elem* **element*) [Function]

Inserts *element* into *hash*. Any element equal to *element* already in *hash* is removed. Returns the element removed, or a null pointer if *hash* did not contain an element equal to *element*.

The caller is responsible for deallocating any resources associated with the returned element, as appropriate. For example, if the hash table elements are dynamically allocated using `malloc()`, then the caller must `free()` the element after it is no longer needed.

The element passed to the following functions is only used for hashing and comparison purposes. It is never actually inserted into the hash table. Thus, only key data in the

element needs to be initialized, and other data in the element will not be used. It often makes sense to declare an instance of the element type as a local variable, initialize the key data, and then pass the address of its `struct hash_elem` to `hash_find()` or `hash_delete()`. See Section A.8.5 [Hash Table Example], page 88, for an example. (Large structures should not be allocated as local variables. See Section A.2.1 [struct thread], page 61, for more information.)

`struct hash_elem * hash_find` (*struct hash *`hash`, struct hash_elem *`element`*) [Function]

Searches *hash* for an element equal to *element*. Returns the element found, if any, or a null pointer otherwise.

`struct hash_elem * hash_delete` (*struct hash *`hash`, struct hash_elem *`element`*) [Function]

Searches *hash* for an element equal to *element*. If one is found, it is removed from *hash* and returned. Otherwise, a null pointer is returned and *hash* is unchanged.

The caller is responsible for deallocating any resources associated with the returned element, as appropriate. For example, if the hash table elements are dynamically allocated using `malloc()`, then the caller must `free()` the element after it is no longer needed.

A.8.4 Iteration Functions

These functions allow iterating through the elements in a hash table. Two interfaces are supplied. The first requires writing and supplying a *hash_action_func* to act on each element (see Section A.8.1 [Hash Data Types], page 84).

`void hash_apply` (*struct hash *`hash`, hash_action_func *`action`*) [Function]

Calls *action* once for each element in *hash*, in arbitrary order. *action* must not call any function that may modify the hash table, such as `hash_insert()` or `hash_delete()`. *action* must not modify key data in elements, although it may modify any other data.

The second interface is based on an "iterator" data type. Idiomatically, iterators are used as follows:

```
struct hash_iterator i;

hash_first (&i, h);
while (hash_next (&i))
  {
    struct foo *f = hash_entry (hash_cur (&i), struct foo, elem);
    ...do something with f...
  }
```

`struct hash_iterator` [Type]

Represents a position within a hash table. Calling any function that may modify a hash table, such as `hash_insert()` or `hash_delete()`, invalidates all iterators within that hash table.

Like `struct hash` and `struct hash_elem`, `struct hash_elem` is opaque.

`void hash_first` (*struct hash_iterator* *`iterator`, *struct hash* *`hash`) [Function]
Initializes *iterator* to just before the first element in *hash*.

`struct hash_elem * hash_next` (*struct hash_iterator* *`iterator`) [Function]
Advances *iterator* to the next element in *hash*, and returns that element. Returns a null pointer if no elements remain. After `hash_next()` returns null for *iterator*, calling it again yields undefined behavior.

`struct hash_elem * hash_cur` (*struct hash_iterator* *`iterator`) [Function]
Returns the value most recently returned by `hash_next()` for *iterator*. Yields undefined behavior after `hash_first()` has been called on *iterator* but before `hash_next()` has been called for the first time.

A.8.5 Hash Table Example

Suppose you have a structure, called `struct page`, that you want to put into a hash table. First, define `struct page` to include a `struct hash_elem` member:

```
struct page
  {
    struct hash_elem hash_elem; /* Hash table element. */
    void *addr;                 /* Virtual address. */
    /* ...other members... */
  };
```

We write a hash function and a comparison function using *addr* as the key. A pointer can be hashed based on its bytes, and the '`<`' operator works fine for comparing pointers:

```
/* Returns a hash value for page p. */
unsigned
page_hash (const struct hash_elem *p_, void *aux UNUSED)
{
  const struct page *p = hash_entry (p_, struct page, hash_elem);
  return hash_bytes (&p->addr, sizeof p->addr);
}

/* Returns true if page a precedes page b. */
bool
page_less (const struct hash_elem *a_, const struct hash_elem *b_,
           void *aux UNUSED)
{
  const struct page *a = hash_entry (a_, struct page, hash_elem);
  const struct page *b = hash_entry (b_, struct page, hash_elem);

  return a->addr < b->addr;
}
```

(The use of `UNUSED` in these functions' prototypes suppresses a warning that *aux* is unused. See Section E.3 [Function and Parameter Attributes], page 102, for information about `UNUSED`. See Section A.8.6 [Hash Auxiliary Data], page 89, for an explanation of *aux*.)

Then, we can create a hash table like this:

```
struct hash pages;

hash_init (&pages, page_hash, page_less, NULL);
```

Now we can manipulate the hash table we've created. If *p* is a pointer to a `struct page`, we can insert it into the hash table with:

```
hash_insert (&pages, &p->hash_elem);
```

If there's a chance that *pages* might already contain a page with the same *addr*, then we should check `hash_insert()`'s return value.

To search for an element in the hash table, use `hash_find()`. This takes a little setup, because `hash_find()` takes an element to compare against. Here's a function that will find and return a page based on a virtual address, assuming that *pages* is defined at file scope:

```
/* Returns the page containing the given virtual address,
   or a null pointer if no such page exists. */
struct page *
page_lookup (const void *address)
{
  struct page p;
  struct hash_elem *e;

  p.addr = address;
  e = hash_find (&pages, &p.hash_elem);
  return e != NULL ? hash_entry (e, struct page, hash_elem) : NULL;
}
```

`struct page` is allocated as a local variable here on the assumption that it is fairly small. Large structures should not be allocated as local variables. See Section A.2.1 [struct thread], page 61, for more information.

A similar function could delete a page by address using `hash_delete()`.

A.8.6 Auxiliary Data

In simple cases like the example above, there's no need for the *aux* parameters. In these cases, just pass a null pointer to `hash_init()` for *aux* and ignore the values passed to the hash function and comparison functions. (You'll get a compiler warning if you don't use the *aux* parameter, but you can turn that off with the `UNUSED` macro, as shown in the example, or you can just ignore it.)

aux is useful when you have some property of the data in the hash table is both constant and needed for hashing or comparison, but not stored in the data items themselves. For example, if the items in a hash table are fixed-length strings, but the items themselves don't indicate what that fixed length is, you could pass the length as an *aux* parameter.

A.8.7 Synchronization

The hash table does not do any internal synchronization. It is the caller's responsibility to synchronize calls to hash table functions. In general, any number of functions that examine but do not modify the hash table, such as `hash_find()` or `hash_next()`, may execute simultaneously. However, these function cannot safely execute at the same time as any

function that may modify a given hash table, such as `hash_insert()` or `hash_delete()`, nor may more than one function that can modify a given hash table execute safely at once.

It is also the caller's responsibility to synchronize access to data in hash table elements. How to synchronize access to this data depends on how it is designed and organized, as with any other data structure.

Appendix B 4.4BSD Scheduler

The goal of a general-purpose scheduler is to balance threads' different scheduling needs. Threads that perform a lot of I/O require a fast response time to keep input and output devices busy, but need little CPU time. On the other hand, compute-bound threads need to receive a lot of CPU time to finish their work, but have no requirement for fast response time. Other threads lie somewhere in between, with periods of I/O punctuated by periods of computation, and thus have requirements that vary over time. A well-designed scheduler can often accommodate threads with all these requirements simultaneously.

For project 1, you must implement the scheduler described in this appendix. Our scheduler resembles the one described in [McKusick], which is one example of a *multilevel feedback queue* scheduler. This type of scheduler maintains several queues of ready-to-run threads, where each queue holds threads with a different priority. At any given time, the scheduler chooses a thread from the highest-priority non-empty queue. If the highest-priority queue contains multiple threads, then they run in "round robin" order.

Multiple facets of the scheduler require data to be updated after a certain number of timer ticks. In every case, these updates should occur before any ordinary kernel thread has a chance to run, so that there is no chance that a kernel thread could see a newly increased `timer_ticks()` value but old scheduler data values.

The 4.4BSD scheduler does not include priority donation.

B.1 Niceness

Thread priority is dynamically determined by the scheduler using a formula given below. However, each thread also has an integer *nice* value that determines how "nice" the thread should be to other threads. A *nice* of zero does not affect thread priority. A positive *nice*, to the maximum of 20, decreases the priority of a thread and causes it to give up some CPU time it would otherwise receive. On the other hand, a negative *nice*, to the minimum of -20, tends to take away CPU time from other threads.

The initial thread starts with a *nice* value of zero. Other threads start with a *nice* value inherited from their parent thread. You must implement the functions described below, which are for use by test programs. We have provided skeleton definitions for them in '`threads/thread.c`'.

`int thread_get_nice (`*void*`)` [Function]
Returns the current thread's *nice* value.

`void thread_set_nice (`*int* *new_nice*`)` [Function]
Sets the current thread's *nice* value to *new_nice* and recalculates the thread's priority based on the new value (see Section B.2 [Calculating Priority], page 91). If the running thread no longer has the highest priority, yields.

B.2 Calculating Priority

Our scheduler has 64 priorities and thus 64 ready queues, numbered 0 (`PRI_MIN`) through 63 (`PRI_MAX`). Lower numbers correspond to lower priorities, so that priority 0 is the lowest priority and priority 63 is the highest. Thread priority is calculated initially at thread

initialization. It is also recalculated once every fourth clock tick, for every thread. In either case, it is determined by the formula

priority = PRI_MAX - (*recent_cpu* / 4) - (*nice* * 2),

where *recent_cpu* is an estimate of the CPU time the thread has used recently (see below) and *nice* is the thread's *nice* value. The result should be rounded down to the nearest integer (truncated). The coefficients 1/4 and 2 on *recent_cpu* and *nice*, respectively, have been found to work well in practice but lack deeper meaning. The calculated *priority* is always adjusted to lie in the valid range PRI_MIN to PRI_MAX.

This formula gives a thread that has received CPU time recently lower priority for being reassigned the CPU the next time the scheduler runs. This is key to preventing starvation: a thread that has not received any CPU time recently will have a *recent_cpu* of 0, which barring a high *nice* value should ensure that it receives CPU time soon.

B.3 Calculating *recent_cpu*

We wish *recent_cpu* to measure how much CPU time each process has received "recently." Furthermore, as a refinement, more recent CPU time should be weighted more heavily than less recent CPU time. One approach would use an array of n elements to track the CPU time received in each of the last n seconds. However, this approach requires $O(n)$ space per thread and $O(n)$ time per calculation of a new weighted average.

Instead, we use a *exponentially weighted moving average*, which takes this general form:

$$x(0) = f(0),$$
$$x(t) = ax(t-1) + (1-a)f(t),$$
$$a = k/(k+1),$$

where $x(t)$ is the moving average at integer time $t \geq 0$, $f(t)$ is the function being averaged, and $k > 0$ controls the rate of decay. We can iterate the formula over a few steps as follows:

$$x(1) = f(1),$$
$$x(2) = af(1) + f(2),$$
$$\vdots$$
$$x(5) = a^4 f(1) + a^3 f(2) + a^2 f(3) + af(4) + f(5).$$

The value of $f(t)$ has a weight of 1 at time t, a weight of a at time $t+1$, a^2 at time $t+2$, and so on. We can also relate $x(t)$ to k: $f(t)$ has a weight of approximately $1/e$ at time $t+k$, approximately $1/e^2$ at time $t+2k$, and so on. From the opposite direction, $f(t)$ decays to weight w at time $t + \log_a w$.

The initial value of *recent_cpu* is 0 in the first thread created, or the parent's value in other new threads. Each time a timer interrupt occurs, *recent_cpu* is incremented by 1 for the running thread only, unless the idle thread is running. In addition, once per second the value of *recent_cpu* is recalculated for every thread (whether running, ready, or blocked), using this formula:

recent_cpu = (2**load_avg*)/(2**load_avg* + 1) * *recent_cpu* + *nice*,

where *load_avg* is a moving average of the number of threads ready to run (see below). If *load_avg* is 1, indicating that a single thread, on average, is competing for the CPU, then the current value of *recent_cpu* decays to a weight of .1 in $\log_{2/3} .1 \approx 6$ seconds; if *load_avg* is 2, then decay to a weight of .1 takes $\log_{3/4} .1 \approx 8$ seconds. The effect is that *recent_cpu* estimates the amount of CPU time the thread has received "recently," with the rate of decay inversely proportional to the number of threads competing for the CPU.

Assumptions made by some of the tests require that these recalculations of *recent_cpu* be made exactly when the system tick counter reaches a multiple of a second, that is, when `timer_ticks () % TIMER_FREQ == 0`, and not at any other time.

The value of *recent_cpu* can be negative for a thread with a negative *nice* value. Do not clamp negative *recent_cpu* to 0.

You may need to think about the order of calculations in this formula. We recommend computing the coefficient of *recent_cpu* first, then multiplying. Some students have reported that multiplying *load_avg* by *recent_cpu* directly can cause overflow.

You must implement `thread_get_recent_cpu()`, for which there is a skeleton in '`threads/thread.c`'.

`int thread_get_recent_cpu (`*void*`)` [Function]
Returns 100 times the current thread's *recent_cpu* value, rounded to the nearest integer.

B.4 Calculating *load_avg*

Finally, *load_avg*, often known as the system load average, estimates the average number of threads ready to run over the past minute. Like *recent_cpu*, it is an exponentially weighted moving average. Unlike *priority* and *recent_cpu*, *load_avg* is system-wide, not thread-specific. At system boot, it is initialized to 0. Once per second thereafter, it is updated according to the following formula:

$$load\_avg = (59/60) * load\_avg + (1/60) * ready\_threads,$$

where *ready_threads* is the number of threads that are either running or ready to run at time of update (not including the idle thread).

Because of assumptions made by some of the tests, *load_avg* must be updated exactly when the system tick counter reaches a multiple of a second, that is, when `timer_ticks () % TIMER_FREQ == 0`, and not at any other time.

You must implement `thread_get_load_avg()`, for which there is a skeleton in '`threads/thread.c`'.

`int thread_get_load_avg (`*void*`)` [Function]
Returns 100 times the current system load average, rounded to the nearest integer.

B.5 Summary

The following formulas summarize the calculations required to implement the scheduler. They are not a complete description of scheduler requirements.

Every thread has a *nice* value between -20 and 20 directly under its control. Each thread also has a priority, between 0 (`PRI_MIN`) through 63 (`PRI_MAX`), which is recalculated using the following formula every fourth tick:

$$priority = PRI\_MAX - (recent\_cpu / 4) - (nice * 2).$$

recent_cpu measures the amount of CPU time a thread has received "recently." On each timer tick, the running thread's *recent_cpu* is incremented by 1. Once per second, every thread's *recent_cpu* is updated this way:

$$recent\_cpu = (2 * load\_avg)/(2 * load\_avg + 1) * recent\_cpu + nice.$$

load_avg estimates the average number of threads ready to run over the past minute. It is initialized to 0 at boot and recalculated once per second as follows:

```
load_avg = (59/60)*load_avg + (1/60)*ready_threads.
```

where *ready_threads* is the number of threads that are either running or ready to run at time of update (not including the idle thread).

B.6 Fixed-Point Real Arithmetic

In the formulas above, *priority*, *nice*, and *ready_threads* are integers, but *recent_cpu* and *load_avg* are real numbers. Unfortunately, Pintos does not support floating-point arithmetic in the kernel, because it would complicate and slow the kernel. Real kernels often have the same limitation, for the same reason. This means that calculations on real quantities must be simulated using integers. This is not difficult, but many students do not know how to do it. This section explains the basics.

The fundamental idea is to treat the rightmost bits of an integer as representing a fraction. For example, we can designate the lowest 14 bits of a signed 32-bit integer as fractional bits, so that an integer x represents the real number $x/2^{14}$. This is called a 17.14 fixed-point number representation, because there are 17 bits before the decimal point, 14 bits after it, and one sign bit.[1] A number in 17.14 format represents, at maximum, a value of $(2^{31} - 1)/2^{14} \approx 131{,}071.999$.

Suppose that we are using a $p.q$ fixed-point format, and let $f = 2^q$. By the definition above, we can convert an integer or real number into $p.q$ format by multiplying with f. For example, in 17.14 format the fraction 59/60 used in the calculation of *load_avg*, above, is $(59/60)2^{14} = 16{,}110$. To convert a fixed-point value back to an integer, divide by f. (The normal '`/`' operator in C rounds toward zero, that is, it rounds positive numbers down and negative numbers up. To round to nearest, add $f/2$ to a positive number, or subtract it from a negative number, before dividing.)

Many operations on fixed-point numbers are straightforward. Let `x` and `y` be fixed-point numbers, and let `n` be an integer. Then the sum of `x` and `y` is `x + y` and their difference is `x - y`. The sum of `x` and `n` is `x + n * f`; difference, `x - n * f`; product, `x * n`; quotient, `x / n`.

Multiplying two fixed-point values has two complications. First, the decimal point of the result is q bits too far to the left. Consider that $(59/60)(59/60)$ should be slightly less than 1, but $16{,}111 \times 16{,}111 = 259{,}564{,}321$ is much greater than $2^{14} = 16{,}384$. Shifting q bits right, we get $259{,}564{,}321/2^{14} = 15{,}842$, or about 0.97, the correct answer. Second, the multiplication can overflow even though the answer is representable. For example, 64 in 17.14 format is $64 \times 2^{14} = 1{,}048{,}576$ and its square $64^2 = 4{,}096$ is well within the 17.14 range, but $1{,}048{,}576^2 = 2^{40}$, greater than the maximum signed 32-bit integer value $2^{31} - 1$. An easy solution is to do the multiplication as a 64-bit operation. The product of `x` and `y` is then `((int64_t) x) * y / f`.

Dividing two fixed-point values has opposite issues. The decimal point will be too far to the right, which we fix by shifting the dividend q bits to the left before the division. The left shift discards the top q bits of the dividend, which we can again fix by doing the division in 64 bits. Thus, the quotient when `x` is divided by `y` is `((int64_t) x) * f / y`.

[1] Because we are working in binary, the "decimal" point might more correctly be called the "binary" point, but the meaning should be clear.

This section has consistently used multiplication or division by f, instead of q-bit shifts, for two reasons. First, multiplication and division do not have the surprising operator precedence of the C shift operators. Second, multiplication and division are well-defined on negative operands, but the C shift operators are not. Take care with these issues in your implementation.

The following table summarizes how fixed-point arithmetic operations can be implemented in C. In the table, `x` and `y` are fixed-point numbers, `n` is an integer, fixed-point numbers are in signed $p.q$ format where $p + q = 31$, and `f` is `1 << q`:

Convert `n` to fixed point:	`n * f`
Convert `x` to integer (rounding toward zero):	`x / f`
Convert `x` to integer (rounding to nearest):	`(x + f / 2) / f` if `x >= 0`, `(x - f / 2) / f` if `x <= 0`.
Add `x` and `y`:	`x + y`
Subtract `y` from `x`:	`x - y`
Add `x` and `n`:	`x + n * f`
Subtract `n` from `x`:	`x - n * f`
Multiply `x` by `y`:	`((int64_t) x) * y / f`
Multiply `x` by `n`:	`x * n`
Divide `x` by `y`:	`((int64_t) x) * f / y`
Divide `x` by `n`:	`x / n`

Appendix C Coding Standards

All of you should have taken a class like CS 220, so we expect you to be familiar C programming, concurrency, and parallel programming. Your code should be consistent with the existing Pintos coding style.

Our standards for coding are most important for grading. We want to stress that aside from the fact that we are explicitly basing part of your grade on these things, good coding practices will improve the quality of your code. This makes it easier for your partners to interact with it, and ultimately, will improve your chances of having a good working program. That said once, the rest of this document will discuss only the ways in which our coding standards will affect our grading.

C.1 Style

Style, for the purposes of our grading, refers to how readable your code is. At minimum, this means that your code is well formatted, your variable names are descriptive and your functions are decomposed and well commented. Any other factors which make it hard (or easy) for us to read or use your code will be reflected in your style grade.

The existing Pintos code is written in the GNU style and largely follows the GNU Coding Standards. We encourage you to follow the applicable parts of them too, especially chapter 5, "Making the Best Use of C." Using a different style won't cause actual problems, but it's ugly to see gratuitous differences in style from one function to another. If your code is too ugly, it will cost you points.

Please limit C source file lines to at most 79 characters long.

Pintos comments sometimes refer to external standards or specifications by writing a name inside square brackets, like this: `[IA32-v3a]`. These names refer to the reference names used in this documentation (see [Bibliography], page 117).

If you remove existing Pintos code, please delete it from your source file entirely. Don't just put it into a comment or a conditional compilation directive, because that makes the resulting code hard to read.

We're only going to do a compile in the directory for the project being submitted. You don't need to make sure that the previous projects also compile.

Project code should be written so that all of the subproblems for the project function together, that is, without the need to rebuild with different macros defined, etc. If you do extra credit work that changes normal Pintos behavior so as to interfere with grading, then you must implement it so that it only acts that way when given a special command-line option of the form '`-`*`name`*', where *name* is a name of your choice. You can add such an option by modifying `parse_options()` in '`threads/init.c`'.

The introduction describes additional coding style requirements (see Section 1.2.2 [Design], page 5).

C.2 C99

The Pintos source code uses a few features of the "C99" standard library that were not in the original 1989 standard for C. Many programmers are unaware of these feature, so we will describe them. The new features used in Pintos are mostly in new headers:

‘<stdbool.h>’
: Defines macros `bool`, a 1-bit type that takes on only the values 0 and 1, `true`, which expands to 1, and `false`, which expands to 0.

‘<stdint.h>’
: On systems that support them, this header defines types `intn_t` and `uintn_t` for n = 8, 16, 32, 64, and possibly other values. These are 2's complement signed and unsigned types, respectively, with the given number of bits.

  On systems where it is possible, this header also defines types `intptr_t` and `uintptr_t`, which are integer types big enough to hold a pointer.

  On all systems, this header defines types `intmax_t` and `uintmax_t`, which are the system's signed and unsigned integer types with the widest ranges.

  For every signed integer type *type*`_t` defined here, as well as for `ptrdiff_t` defined in ‘<stddef.h>’, this header also defines macros *TYPE*`_MAX` and *TYPE*`_MIN` that give the type's range. Similarly, for every unsigned integer type *type*`_t` defined here, as well as for `size_t` defined in ‘<stddef.h>’, this header defines a *TYPE*`_MAX` macro giving its maximum value.

‘<inttypes.h>’
: ‘<stdint.h>’ provides no straightforward way to format the types it defines with `printf()` and related functions. This header provides macros to help with that. For every `intn_t` defined by ‘<stdint.h>’, it provides macros `PRIdn` and `PRIin` for formatting values of that type with `"%d"` and `"%i"`. Similarly, for every `uintn_t`, it provides `PRIon`, `PRIun`, `PRIux`, and `PRIuX`.

  You use these something like this, taking advantage of the fact that the C compiler concatenates adjacent string literals:

```
#include <inttypes.h>
...
int32_t value = ...;
printf ("value=%08"PRId32"\n", value);
```

  The ‘%’ is not supplied by the `PRI` macros. As shown above, you supply it yourself and follow it by any flags, field width, etc.

‘<stdio.h>’
: The `printf()` function has some new type modifiers for printing standard types:

  ‘j’ For `intmax_t` (e.g. ‘%jd’) or `uintmax_t` (e.g. ‘%ju’).

  ‘z’ For `size_t` (e.g. ‘%zu’).

  ‘t’ For `ptrdiff_t` (e.g. ‘%td’).

  Pintos `printf()` also implements a nonstandard ‘’’ flag that groups large numbers with commas to make them easier to read.

C.3 Unsafe String Functions

A few of the string functions declared in the standard ‘<string.h>’ and ‘<stdio.h>’ headers are notoriously unsafe. The worst offenders are intentionally not included in the Pintos C library:

`strcpy()` When used carelessly this function can overflow the buffer reserved for its output string. Use `strlcpy()` instead. Refer to comments in its source code in `lib/string.c` for documentation.

`strncpy()`
This function can leave its destination buffer without a null string terminator. It also has performance problems. Again, use `strlcpy()`.

`strcat()` Same issue as `strcpy()`. Use `strlcat()` instead. Again, refer to comments in its source code in `lib/string.c` for documentation.

`strncat()`
The meaning of its buffer size argument is surprising. Again, use `strlcat()`.

`strtok()` Uses global data, so it is unsafe in threaded programs such as kernels. Use `strtok_r()` instead, and see its source code in `lib/string.c` for documentation and an example.

`sprintf()`
Same issue as `strcpy()`. Use `snprintf()` instead. Refer to comments in `lib/stdio.h` for documentation.

`vsprintf()`
Same issue as `strcpy()`. Use `vsnprintf()` instead.

If you try to use any of these functions, the error message will give you a hint by referring to an identifier like `dont_use_sprintf_use_snprintf`.

Appendix D Project Documentation

This chapter presents a sample assignment and a filled-in design document for one possible implementation. Its purpose is to give you an idea of what we expect to see in your own design documents.

D.1 Sample Assignment

Implement `thread_join()`.

`void thread_join (`*tid_t* `tid)` [Function]

Blocks the current thread until thread *tid* exits. If *A* is the running thread and *B* is the argument, then we say that "*A* joins *B*."

Incidentally, the argument is a thread id, instead of a thread pointer, because a thread pointer is not unique over time. That is, when a thread dies, its memory may be, whether immediately or much later, reused for another thread. If thread *A* over time had two children *B* and *C* that were stored at the same address, then `thread_join(B)` and `thread_join(C)` would be ambiguous.

A thread may only join its immediate children. Calling `thread_join()` on a thread that is not the caller's child should cause the caller to return immediately. Children are not "inherited," that is, if *A* has child *B* and *B* has child *C*, then *A* always returns immediately should it try to join *C*, even if *B* is dead.

A thread need not ever be joined. Your solution should properly free all of a thread's resources, including its `struct thread`, whether it is ever joined or not, and regardless of whether the child exits before or after its parent. That is, a thread should be freed exactly once in all cases.

Joining a given thread is idempotent. That is, joining a thread multiple times is equivalent to joining it once, because it has already exited at the time of the later joins. Thus, joins on a given thread after the first should return immediately.

You must handle all the ways a join can occur: nested joins (*A* joins *B*, then *B* joins *C*), multiple joins (*A* joins *B*, then *A* joins *C*), and so on.

D.2 Sample Design Document

```
                        +------------------+
                        |      CS 326      |
                        |  SAMPLE PROJECT  |
                        | DESIGN DOCUMENT  |
                        +------------------+

---- GROUP ----

Ben Pfaff <blp@stanford.edu>

---- PRELIMINARIES ----
```

```
>> If you have any preliminary comments on your submission, notes for
>> the TAs, or extra credit, please give them here.

(This is a sample design document.)

>> Please cite any offline or online sources you consulted while
>> preparing your submission, other than the Pintos documentation,
>> course text, and lecture notes.

None.

                                JOIN
                                ====

---- DATA STRUCTURES ----

>> Copy here the declaration of each new or changed ‘struct’ or ‘struct’
>> member, global or static variable, ‘typedef’, or enumeration.
>> Identify the purpose of each in 25 words or less.

A "latch" is a new synchronization primitive.  Acquires block
until the first release.  Afterward, all ongoing and future
acquires pass immediately.

    /* Latch. */
    struct latch
      {
        bool released;              /* Released yet? */
        struct lock monitor_lock;   /* Monitor lock. */
        struct condition rel_cond;  /* Signaled when released. */
      };

Added to struct thread:

    /* Members for implementing thread_join(). */
    struct latch ready_to_die;   /* Release when thread about to die. */
    struct semaphore can_die;    /* Up when thread allowed to die. */
    struct list children;        /* List of child threads. */
    list_elem children_elem;     /* Element of ‘children’ list. */

---- ALGORITHMS ----

>> Briefly describe your implementation of thread_join() and how it
>> interacts with thread termination.

thread_join() finds the joined child on the thread's list of
children and waits for the child to exit by acquiring the child's
```

```
ready_to_die latch.  When thread_exit() is called, the thread
releases its ready_to_die latch, allowing the parent to continue.

---- SYNCHRONIZATION ----

>> Consider parent thread P with child thread C.  How do you ensure
>> proper synchronization and avoid race conditions when P calls wait(C)
>> before C exits?  After C exits?  How do you ensure that all resources
>> are freed in each case?  How about when P terminates without waiting,
>> before C exits?  After C exits?  Are there any special cases?

C waits in thread_exit() for P to die before it finishes its own
exit, using the can_die semaphore "down"ed by C and "up"ed by P as
it exits.  Regardless of whether whether C has terminated, there
is no race on wait(C), because C waits for P's permission before
it frees itself.

Regardless of whether P waits for C, P still "up"s C's can_die
semaphore when P dies, so C will always be freed.  (However,
freeing C's resources is delayed until P's death.)

The initial thread is a special case because it has no parent to
wait for it or to "up" its can_die semaphore.  Therefore, its
can_die semaphore is initialized to 1.

---- RATIONALE ----

>> Critique your design, pointing out advantages and disadvantages in
>> your design choices.

This design has the advantage of simplicity.  Encapsulating most
of the synchronization logic into a new "latch" structure
abstracts what little complexity there is into a separate layer,
making the design easier to reason about.  Also, all the new data
members are in 'struct thread', with no need for any extra dynamic
allocation, etc., that would require extra management code.

On the other hand, this design is wasteful in that a child thread
cannot free itself before its parent has terminated.  A parent
thread that creates a large number of short-lived child threads
could unnecessarily exhaust kernel memory.  This is probably
acceptable for implementing kernel threads, but it may be a bad
idea for use with user processes because of the larger number of
resources that user processes tend to own.
```

Appendix E Debugging Tools

Many tools lie at your disposal for debugging Pintos. This appendix introduces you to a few of them.

E.1 `printf()`

Don't underestimate the value of `printf()`. The way `printf()` is implemented in Pintos, you can call it from practically anywhere in the kernel, whether it's in a kernel thread or an interrupt handler, almost regardless of what locks are held.

`printf()` is useful for more than just examining data. It can also help figure out when and where something goes wrong, even when the kernel crashes or panics without a useful error message. The strategy is to sprinkle calls to `printf()` with different strings (e.g. `"<1>"`, `"<2>"`, ...) throughout the pieces of code you suspect are failing. If you don't even see `<1>` printed, then something bad happened before that point, if you see `<1>` but not `<2>`, then something bad happened between those two points, and so on. Based on what you learn, you can then insert more `printf()` calls in the new, smaller region of code you suspect. Eventually you can narrow the problem down to a single statement. See Section E.6 [Triple Faults], page 111, for a related technique.

E.2 `ASSERT`

Assertions are useful because they can catch problems early, before they'd otherwise be noticed. Ideally, each function should begin with a set of assertions that check its arguments for validity. (Initializers for functions' local variables are evaluated before assertions are checked, so be careful not to assume that an argument is valid in an initializer.) You can also sprinkle assertions throughout the body of functions in places where you suspect things are likely to go wrong. They are especially useful for checking loop invariants.

Pintos provides the `ASSERT` macro, defined in '`<debug.h>`', for checking assertions.

`ASSERT` (*expression*) [Macro]

Tests the value of *expression*. If it evaluates to zero (false), the kernel panics. The panic message includes the expression that failed, its file and line number, and a backtrace, which should help you to find the problem. See Section E.4 [Backtraces], page 103, for more information.

E.3 Function and Parameter Attributes

These macros defined in '`<debug.h>`' tell the compiler special attributes of a function or function parameter. Their expansions are GCC-specific.

`UNUSED` [Macro]

Appended to a function parameter to tell the compiler that the parameter might not be used within the function. It suppresses the warning that would otherwise appear.

`NO_RETURN` [Macro]

Appended to a function prototype to tell the compiler that the function never returns. It allows the compiler to fine-tune its warnings and its code generation.

`NO_INLINE` [Macro]

Appended to a function prototype to tell the compiler to never emit the function in-line. Occasionally useful to improve the quality of backtraces (see below).

`PRINTF_FORMAT (`*`format`*`, `*`first`*`)` [Macro]

Appended to a function prototype to tell the compiler that the function takes a `printf()`-like format string as the argument numbered *format* (starting from 1) and that the corresponding value arguments start at the argument numbered *first*. This lets the compiler tell you if you pass the wrong argument types.

E.4 Backtraces

When the kernel panics, it prints a "backtrace," that is, a summary of how your program got where it is, as a list of addresses inside the functions that were running at the time of the panic. You can also insert a call to `debug_backtrace()`, prototyped in '`<debug.h>`', to print a backtrace at any point in your code. `debug_backtrace_all()`, also declared in '`<debug.h>`', prints backtraces of all threads.

The addresses in a backtrace are listed as raw hexadecimal numbers, which are difficult to interpret. We provide a tool called `backtrace` to translate these into function names and source file line numbers. Give it the name of your '`kernel.o`' as the first argument and the hexadecimal numbers composing the backtrace (including the '`0x`' prefixes) as the remaining arguments. It outputs the function name and source file line numbers that correspond to each address.

If the translated form of a backtrace is garbled, or doesn't make sense (e.g. function A is listed above function B, but B doesn't call A), then it's a good sign that you're corrupting a kernel thread's stack, because the backtrace is extracted from the stack. Alternatively, it could be that the '`kernel.o`' you passed to `backtrace` is not the same kernel that produced the backtrace.

Sometimes backtraces can be confusing without any corruption. Compiler optimizations can cause surprising behavior. When a function has called another function as its final action (a *tail call*), the calling function may not appear in a backtrace at all. Similarly, when function A calls another function B that never returns, the compiler may optimize such that an unrelated function C appears in the backtrace instead of A. Function C is simply the function that happens to be in memory just after A. In the threads project, this is commonly seen in backtraces for test failures; see [`pass()` Fails], page 18, for more information.

E.4.1 Example

Here's an example. Suppose that Pintos printed out this following call stack, which is taken from an actual Pintos submission for the file system project:

```
Call stack: 0xc0106eff 0xc01102fb 0xc010dc22 0xc010cf67 0xc0102319
0xc010325a 0x804812c 0x8048a96 0x8048ac8.
```

You would then invoke the `backtrace` utility like shown below, cutting and pasting the backtrace information into the command line. This assumes that '`kernel.o`' is in the current directory. You would of course enter all of the following on a single shell command line, even though that would overflow our margins here:

```
backtrace kernel.o 0xc0106eff 0xc01102fb 0xc010dc22 0xc010cf67
0xc0102319 0xc010325a 0x804812c 0x8048a96 0x8048ac8
```

The backtrace output would then look something like this:

```
0xc0106eff: debug_panic (lib/debug.c:86)
0xc01102fb: file_seek (filesys/file.c:405)
0xc010dc22: seek (userprog/syscall.c:744)
0xc010cf67: syscall_handler (userprog/syscall.c:444)
0xc0102319: intr_handler (threads/interrupt.c:334)
0xc010325a: intr_entry (threads/intr-stubs.S:38)
0x0804812c: (unknown)
0x08048a96: (unknown)
0x08048ac8: (unknown)
```

(You will probably not see exactly the same addresses if you run the command above on your own kernel binary, because the source code you compiled and the compiler you used are probably different.)

The first line in the backtrace refers to `debug_panic()`, the function that implements kernel panics. Because backtraces commonly result from kernel panics, `debug_panic()` will often be the first function shown in a backtrace.

The second line shows `file_seek()` as the function that panicked, in this case as the result of an assertion failure. In the source code tree used for this example, line 405 of '`filesys/file.c`' is the assertion

```
ASSERT (file_ofs >= 0);
```

(This line was also cited in the assertion failure message.) Thus, `file_seek()` panicked because it passed a negative file offset argument.

The third line indicates that `seek()` called `file_seek()`, presumably without validating the offset argument. In this submission, `seek()` implements the `seek` system call.

The fourth line shows that `syscall_handler()`, the system call handler, invoked `seek()`.

The fifth and sixth lines are the interrupt handler entry path.

The remaining lines are for addresses below `PHYS_BASE`. This means that they refer to addresses in the user program, not in the kernel. If you know what user program was running when the kernel panicked, you can re-run `backtrace` on the user program, like so: (typing the command on a single line, of course):

```
backtrace tests/filesys/extended/grow-too-big 0xc0106eff 0xc01102fb
0xc010dc22 0xc010cf67 0xc0102319 0xc010325a 0x804812c 0x8048a96
0x8048ac8
```

The results look like this:

```
0xc0106eff: (unknown)
0xc01102fb: (unknown)
0xc010dc22: (unknown)
0xc010cf67: (unknown)
0xc0102319: (unknown)
0xc010325a: (unknown)
0x0804812c: test_main (...xtended/grow-too-big.c:20)
0x08048a96: main (tests/main.c:10)
```

```
0x08048ac8: _start (lib/user/entry.c:9)
```

You can even specify both the kernel and the user program names on the command line, like so:

```
backtrace kernel.o tests/filesys/extended/grow-too-big 0xc0106eff
0xc01102fb 0xc010dc22 0xc010cf67 0xc0102319 0xc010325a 0x804812c
0x8048a96 0x8048ac8
```

The result is a combined backtrace:

```
In kernel.o:
0xc0106eff: debug_panic (lib/debug.c:86)
0xc01102fb: file_seek (filesys/file.c:405)
0xc010dc22: seek (userprog/syscall.c:744)
0xc010cf67: syscall_handler (userprog/syscall.c:444)
0xc0102319: intr_handler (threads/interrupt.c:334)
0xc010325a: intr_entry (threads/intr-stubs.S:38)
In tests/filesys/extended/grow-too-big:
0x0804812c: test_main (...xtended/grow-too-big.c:20)
0x08048a96: main (tests/main.c:10)
0x08048ac8: _start (lib/user/entry.c:9)
```

Here's an extra tip for anyone who read this far: `backtrace` is smart enough to strip the `Call stack:` header and '`.`' trailer from the command line if you include them. This can save you a little bit of trouble in cutting and pasting. Thus, the following command prints the same output as the first one we used:

```
backtrace kernel.o Call stack: 0xc0106eff 0xc01102fb 0xc010dc22
0xc010cf67 0xc0102319 0xc010325a 0x804812c 0x8048a96 0x8048ac8.
```

E.5 GDB

You can run Pintos under the supervision of the GDB debugger. First, start Pintos with the '`--gdb`' option, e.g. `pintos --gdb -- run mytest`. Second, open a second terminal on the same machine and use `pintos-gdb` to invoke GDB on '`kernel.o`':[1]

```
pintos-gdb kernel.o
```

and issue the following GDB command:

```
target remote localhost:1234
```

Now GDB is connected to the simulator over a local network connection. You can now issue any normal GDB commands. If you issue the '`c`' command, the simulated BIOS will take control, load Pintos, and then Pintos will run in the usual way. You can pause the process at any point with ⟨Ctrl+C⟩.

E.5.1 Using GDB

You can read the GDB manual by typing `info gdb` at a terminal command prompt. Here's a few commonly useful GDB commands:

[1] `pintos-gdb` is a wrapper around `gdb` (80*x*86) or `i386-elf-gdb` (SPARC) that loads the Pintos macros at startup.

`c` [GDB Command]

Continues execution until ⟨Ctrl+C⟩ or the next breakpoint.

`break` *function* [GDB Command]
`break` *file:line* [GDB Command]
`break` **address* [GDB Command]

Sets a breakpoint at *function*, at *line* within *file*, or *address*. (Use a '`0x`' prefix to specify an address in hex.)

Use `break main` to make GDB stop when Pintos starts running.

`p` *expression* [GDB Command]

Evaluates the given *expression* and prints its value. If the expression contains a function call, that function will actually be executed.

`l` **address* [GDB Command]

Lists a few lines of code around *address*. (Use a '`0x`' prefix to specify an address in hex.)

`bt` [GDB Command]

Prints a stack backtrace similar to that output by the `backtrace` program described above.

`p/a` *address* [GDB Command]

Prints the name of the function or variable that occupies *address*. (Use a '`0x`' prefix to specify an address in hex.)

`diassemble` *function* [GDB Command]

Disassembles *function*.

We also provide a set of macros specialized for debugging Pintos, written by Godmar Back `gback@cs.vt.edu`. You can type `help user-defined` for basic help with the macros. Here is an overview of their functionality, based on Godmar's documentation:

`debugpintos` [GDB Macro]

Attach debugger to a waiting pintos process on the same machine. Shorthand for `target remote localhost:1234`.

`dumplist` *list type element* [GDB Macro]

Prints the elements of *list*, which should be a `struct` list that contains elements of the given *type* (without the word `struct`) in which *element* is the `struct list_elem` member that links the elements.

Example: `dumplist all_list thread allelem` prints all elements of `struct thread` that are linked in `struct list all_list` using the `struct list_elem allelem` which is part of `struct thread`.

`btthread` *thread* [GDB Macro]

Shows the backtrace of *thread*, which is a pointer to the `struct thread` of the thread whose backtrace it should show. For the current thread, this is identical to the `bt` (backtrace) command. It also works for any thread suspended in `schedule()`, provided you know where its kernel stack page is located.

`btthreadlist` *list element* [GDB Macro]

Shows the backtraces of all threads in *list*, the `struct list` in which the threads are kept. Specify *element* as the `struct list_elem` field used inside `struct thread` to link the threads together.

Example: `btthreadlist all_list allelem` shows the backtraces of all threads contained in `struct list all_list`, linked together by `allelem`. This command is useful to determine where your threads are stuck when a deadlock occurs. Please see the example scenario below.

`btthreadall` [GDB Macro]

Short-hand for `btthreadlist all_list allelem`.

`btpagefault` [GDB Macro]

Print a backtrace of the current thread after a page fault exception. Normally, when a page fault exception occurs, GDB will stop with a message that might say:[2]

```
Program received signal 0, Signal 0.
0xc0102320 in intr0e_stub ()
```

In that case, the `bt` command might not give a useful backtrace. Use `btpagefault` instead.

You may also use `btpagefault` for page faults that occur in a user process. In this case, you may wish to also load the user program's symbol table using the `loadusersymbols` macro, as described above.

`hook-stop` [GDB Macro]

GDB invokes this macro every time the simulation stops, which Bochs will do for every processor exception, among other reasons. If the simulation stops due to a page fault, `hook-stop` will print a message that says and explains further whether the page fault occurred in the kernel or in user code.

If the exception occurred from user code, `hook-stop` will say:

```
pintos-debug: a page fault exception occurred in user mode
pintos-debug: hit 'c' to continue, or 's' to step to intr_handler
```

In Project 2, a page fault in a user process leads to the termination of the process. You should expect those page faults to occur in the robustness tests where we test that your kernel properly terminates processes that try to access invalid addresses. To debug those, set a break point in `page_fault()` in '`exception.c`', which you will need to modify accordingly.

In Project 3, a page fault in a user process no longer automatically leads to the termination of a process. Instead, it may require reading in data for the page the process was trying to access, either because it was swapped out or because this is the first time it's accessed. In either case, you will reach `page_fault()` and need to take the appropriate action there.

If the page fault did not occur in user mode while executing a user process, then it occurred in kernel mode while executing kernel code. In this case, `hook-stop` will print this message:

[2] To be precise, GDB will stop only when running under Bochs. When running under QEMU, you must set a breakpoint in the `page_fault` function to stop execution when a page fault occurs. In that case, the `btpagefault` macro is unnecessary.

```
pintos-debug: a page fault occurred in kernel mode
```

followed by the output of the `btpagefault` command.

Before Project 3, a page fault exception in kernel code is always a bug in your kernel, because your kernel should never crash. Starting with Project 3, the situation will change if you use the `get_user()` and `put_user()` strategy to verify user memory accesses (see Section 3.1.5 [Accessing User Memory], page 27).

E.5.2 Example GDB Session

This section narrates a sample GDB session, provided by Godmar Back. This example illustrates how one might debug a Project 1 solution in which occasionally a thread that calls `timer_sleep()` is not woken up. With this bug, tests such as `mlfqs_load_1` get stuck.

This session was captured with a slightly older version of Bochs and the GDB macros for Pintos, so it looks slightly different than it would now. Program output is shown in normal type, user input in **strong** type.

First, I start Pintos:

```
$ pintos -v –gdb – -q -mlfqs run mlfqs-load-1
Writing command line to /tmp/gDAlqTB5Uf.dsk...
bochs -q
========================================================================
                       Bochs x86 Emulator 2.2.5
             Build from CVS snapshot on December 30, 2005
========================================================================
00000000000i[     ] reading configuration from bochsrc.txt
00000000000i[     ] Enabled gdbstub
00000000000i[     ] installing nogui module as the Bochs GUI
00000000000i[     ] using log file bochsout.txt
Waiting for gdb connection on localhost:1234
```

Then, I open a second window on the same machine and start GDB:

```
$ pintos-gdb kernel.o
GNU gdb Red Hat Linux (6.3.0.0-1.84rh)
Copyright 2004 Free Software Foundation, Inc.
GDB is free software, covered by the GNU General Public License, and you are
welcome to change it and/or distribute copies of it under certain conditions.
Type "show copying" to see the conditions.
There is absolutely no warranty for GDB.  Type "show warranty" for details.
This GDB was configured as "i386-redhat-linux-gnu"...
Using host libthread_db library "/lib/libthread_db.so.1".
```

Then, I tell GDB to attach to the waiting Pintos emulator:

```
(gdb) debugpintos
Remote debugging using localhost:1234
0x0000fff0 in ?? ()
Reply contains invalid hex digit 78
```

Now I tell Pintos to run by executing `c` (short for `continue`) twice:

```
(gdb) c
Continuing.
Reply contains invalid hex digit 78
(gdb) c
Continuing.
```

Now Pintos will continue and output:

```
Pintos booting with 4,096 kB RAM...
Kernel command line: -q -mlfqs run mlfqs-load-1
374 pages available in kernel pool.
373 pages available in user pool.
Calibrating timer...  102,400 loops/s.
Boot complete.
Executing 'mlfqs-load-1':
(mlfqs-load-1) begin
(mlfqs-load-1) spinning for up to 45 seconds, please wait...
(mlfqs-load-1) load average rose to 0.5 after 42 seconds
(mlfqs-load-1) sleeping for another 10 seconds, please wait...
```

. . . until it gets stuck because of the bug I had introduced. I hit ⟨Ctrl+C⟩ in the debugger window:

```
Program received signal 0, Signal 0.
0xc010168c in next_thread_to_run () at ../../threads/thread.c:649
649   while (i <= PRI_MAX && list_empty (&ready_list[i]))
(gdb)
```

The thread that was running when I interrupted Pintos was the idle thread. If I run `backtrace`, it shows this backtrace:

```
(gdb) bt
#0  0xc010168c in next_thread_to_run () at ../../threads/thread.c:649
#1  0xc0101778 in schedule () at ../../threads/thread.c:714
#2  0xc0100f8f in thread_block () at ../../threads/thread.c:324
#3  0xc0101419 in idle (aux=0x0) at ../../threads/thread.c:551
#4  0xc010145a in kernel_thread (function=0xc01013ff , aux=0x0)
    at ../../threads/thread.c:575
#5  0x00000000 in ?? ()
```

Not terribly useful. What I really like to know is what's up with the other thread (or threads). Since I keep all threads in a linked list called `all_list`, linked together by a `struct list_elem` member named `allelem`, I can use the `btthreadlist` macro from the macro library I wrote. `btthreadlist` iterates through the list of threads and prints the backtrace for each thread:

```
(gdb) btthreadlist all_list allelem
pintos-debug: dumping backtrace of thread 'main' @0xc002f000
#0  0xc0101820 in schedule () at ../../threads/thread.c:722
#1  0xc0100f8f in thread_block () at ../../threads/thread.c:324
#2  0xc0104755 in timer_sleep (ticks=1000) at ../../devices/timer.c:141
#3  0xc010bf7c in test_mlfqs_load_1 () at ../../tests/threads/mlfqs-load-1.c:49
#4  0xc010aabb in run_test (name=0xc0007d8c "mlfqs-load-1")
    at ../../tests/threads/tests.c:50
#5  0xc0100647 in run_task (argv=0xc0110d28) at ../../threads/init.c:281
#6  0xc0100721 in run_actions (argv=0xc0110d28) at ../../threads/init.c:331
#7  0xc01000c7 in main () at ../../threads/init.c:140

pintos-debug: dumping backtrace of thread 'idle' @0xc0116000
#0  0xc010168c in next_thread_to_run () at ../../threads/thread.c:649
#1  0xc0101778 in schedule () at ../../threads/thread.c:714
#2  0xc0100f8f in thread_block () at ../../threads/thread.c:324
#3  0xc0101419 in idle (aux=0x0) at ../../threads/thread.c:551
#4  0xc010145a in kernel_thread (function=0xc01013ff , aux=0x0)
    at ../../threads/thread.c:575
#5  0x00000000 in ?? ()
```

In this case, there are only two threads, the idle thread and the main thread. The kernel stack pages (to which the `struct thread` points) are at `0xc0116000` and `0xc002f000`, respectively. The main thread is stuck in `timer_sleep()`, called from `test_mlfqs_load_1`.

Knowing where threads are stuck can be tremendously useful, for instance when diagnosing deadlocks or unexplained hangs.

`loadusersymbols` [GDB Macro]

You can also use GDB to debug a user program running under Pintos. To do that, use the `loadusersymbols` macro to load the program's symbol table:

```
loadusersymbols program
```

where *program* is the name of the program's executable (in the host file system, not in the Pintos file system). For example, you may issue:

```
(gdb) loadusersymbols tests/userprog/exec-multiple
add symbol table from file "tests/userprog/exec-multiple" at
    .text_addr = 0x80480a0
(gdb)
```

After this, you should be able to debug the user program the same way you would the kernel, by placing breakpoints, inspecting data, etc. Your actions apply to every user program running in Pintos, not just to the one you want to debug, so be careful in interpreting the results: GDB does not know which process is currently active (because that is an abstraction the Pintos kernel creates). Also, a name that appears in both the kernel and the user program will actually refer to the kernel name. (The latter problem can be avoided by giving the user executable name on the GDB command line, instead of '`kernel.o`', and then using `loadusersymbols` to load '`kernel.o`'.) `loadusersymbols` is implemented via GDB's `add-symbol-file` command.

E.5.3 FAQ

GDB can't connect to Bochs.

If the `target remote` command fails, then make sure that both GDB and `pintos` are running on the same machine by running `hostname` in each terminal. If the names printed differ, then you need to open a new terminal for GDB on the machine running `pintos`.

GDB doesn't recognize any of the macros.

If you start GDB with `pintos-gdb`, it should load the Pintos macros automatically. If you start GDB some other way, then you must issue the command `source pintosdir/src/misc/gdb-macros`, where *pintosdir* is the root of your Pintos directory, before you can use them.

Can I debug Pintos with DDD?

Yes, you can. DDD invokes GDB as a subprocess, so you'll need to tell it to invokes `pintos-gdb` instead:

```
ddd --gdb --debugger pintos-gdb
```

Can I use GDB inside Emacs?

Yes, you can. Emacs has special support for running GDB as a subprocess. Type *M-x gdb* and enter your `pintos-gdb` command at the prompt. The Emacs manual has information on how to use its debugging features in a section titled "Debuggers."

GDB is doing something weird.

> If you notice strange behavior while using GDB, there are three possibilities: a bug in your modified Pintos, a bug in Bochs's interface to GDB or in GDB itself, or a bug in the original Pintos code. The first and second are quite likely, and you should seriously consider both. We hope that the third is less likely, but it is also possible.

E.6 Triple Faults

When a CPU exception handler, such as a page fault handler, cannot be invoked because it is missing or defective, the CPU will try to invoke the "double fault" handler. If the double fault handler is itself missing or defective, that's called a "triple fault." A triple fault causes an immediate CPU reset.

Thus, if you get yourself into a situation where the machine reboots in a loop, that's probably a "triple fault." In a triple fault situation, you might not be able to use `printf()` for debugging, because the reboots might be happening even before everything needed for `printf()` is initialized.

There are at least two ways to debug triple faults. First, you can run Pintos in Bochs under GDB (see Section E.5 [GDB], page 105). If Bochs has been built properly for Pintos, a triple fault under GDB will cause it to print the message "Triple fault: stopping for gdb" on the console and break into the debugger. (If Bochs is not running under GDB, a triple fault will still cause it to reboot.) You can then inspect where Pintos stopped, which is where the triple fault occurred.

Another option is what I call "debugging by infinite loop." Pick a place in the Pintos code, insert the infinite loop `for (;;);` there, and recompile and run. There are two likely possibilities:

- The machine hangs without rebooting. If this happens, you know that the infinite loop is running. That means that whatever caused the reboot must be *after* the place you inserted the infinite loop. Now move the infinite loop later in the code sequence.
- The machine reboots in a loop. If this happens, you know that the machine didn't make it to the infinite loop. Thus, whatever caused the reboot must be *before* the place you inserted the infinite loop. Now move the infinite loop earlier in the code sequence.

If you move around the infinite loop in a "binary search" fashion, you can use this technique to pin down the exact spot that everything goes wrong. It should only take a few minutes at most.

E.7 Modifying Bochs

An advanced debugging technique is to modify and recompile the simulator. This proves useful when the simulated hardware has more information than it makes available to the OS. For example, page faults have a long list of potential causes, but the hardware does not report to the OS exactly which one is the particular cause. Furthermore, a bug in the kernel's handling of page faults can easily lead to recursive faults, but a "triple fault" will cause the CPU to reset itself, which is hardly conducive to debugging.

In a case like this, you might appreciate being able to make Bochs print out more debug information, such as the exact type of fault that occurred. It's

not very hard. You start by retrieving the source code for Bochs 2.2.6 from `http://bochs.sourceforge.net` and saving the file '`bochs-2.2.6.tar.gz`' into a directory. The script '`pintos/src/misc/bochs-2.2.6-build.sh`' applies a number of patches contained in '`pintos/src/misc`' to the Bochs tree, then builds Bochs and installs it in a directory of your choice. Run this script without arguments to learn usage instructions. To use your '`bochs`' binary with `pintos`, put it in your `PATH`, and make sure that it is earlier than '`/home/web/benson/cs326/pintos/bin/bochs`'.

Of course, to get any good out of this you'll have to actually modify Bochs. Instructions for doing this are firmly out of the scope of this document. However, if you want to debug page faults as suggested above, a good place to start adding `printf()`s is `BX_CPU_C::dtranslate_linear()` in '`cpu/paging.cc`'.

E.8 Tips

The page allocator in '`threads/palloc.c`' and the block allocator in '`threads/malloc.c`' clear all the bytes in memory to `0xcc` at time of free. Thus, if you see an attempt to dereference a pointer like `0xcccccccc`, or some other reference to `0xcc`, there's a good chance you're trying to reuse a page that's already been freed. Also, byte `0xcc` is the CPU opcode for "invoke interrupt 3," so if you see an error like `Interrupt 0x03 (#BP Breakpoint Exception)`, then Pintos tried to execute code in a freed page or block.

An assertion failure on the expression `sec_no < d->capacity` indicates that Pintos tried to access a file through an inode that has been closed and freed. Freeing an inode clears its starting sector number to `0xcccccccc`, which is not a valid sector number for disks smaller than about 1.6 TB.

Appendix F Development Tools

Here are some tools that you might find useful while developing code.

F.1 Tags

Tags are an index to the functions and global variables declared in a program. Many editors, including Emacs and `vi`, can use them. The '`Makefile`' in '`pintos/src`' produces Emacs-style tags with the command `make TAGS` or `vi`-style tags with `make tags`.

In Emacs, use *`M-.`* to follow a tag in the current window, *`C-x 4 .`* in a new window, or *`C-x 5 .`* in a new frame. If your cursor is on a symbol name for any of those commands, it becomes the default target. If a tag name has multiple definitions, *`M-0 M-.`* jumps to the next one. To jump back to where you were before you followed the last tag, use *`M-*`*.

F.2 cscope

The `cscope` program also provides an index to functions and variables declared in a program. It has some features that tag facilities lack. Most notably, it can find all the points in a program at which a given function is called.

The '`Makefile`' in '`pintos/src`' produces `cscope` indexes when it is invoked as `make cscope`. Once the index has been generated, run `cscope` from a shell command line; no command-line arguments are normally necessary. Then use the arrow keys to choose one of the search criteria listed near the bottom of the terminal, type in an identifier, and hit ⟨Enter⟩. `cscope` will then display the matches in the upper part of the terminal. You may use the arrow keys to choose a particular match; if you then hit ⟨Enter⟩, `cscope` will invoke the default system editor[1] and position the cursor on that match. To start a new search, type ⟨Tab⟩. To exit `cscope`, type *`Ctrl-d`*.

Emacs and some versions of `vi` have their own interfaces to `cscope`. For information on how to use these interface, visit the `cscope` home page (`http://cscope.sourceforge.net`).

F.3 Git

Git is a version-control system. That is, you can use it to keep track of multiple versions of files. The idea is that you do some work on your code and test it, then check it into the version-control system. If you decide that the work you've done since your last check-in is no good, you can easily revert to the last checked-in version. Furthermore, you can retrieve any old version of your code as of some given day and time. The version control logs tell you who made changes and when.

For more information, visit the Git home page.

F.4 VNC

VNC stands for Virtual Network Computing. It is, in essence, a remote display system which allows you to view a computing "desktop" environment not only on the machine where it is running, but from anywhere on the Internet and from a wide variety of machine architectures. It is already installed on the lab machines. For more information, look at the VNC Home Page.

[1] This is typically `vi`. To exit `vi`, type *`: q`* ⟨Enter⟩.

Appendix G Installing Pintos

This chapter explains how to install a Pintos development environment on your own machine. If you are using a Pintos development environment that has been set up by someone else, you do not need to read this chapter or follow these instructions.

The Pintos development environment is targeted at Unix-like systems. It has been most extensively tested on GNU/Linux, in particular the Debian and Ubuntu distributions, and Solaris. It is not designed to install under any form of Windows.

Prerequisites for installing a Pintos development environment include the following, on top of standard Unix utilities:

- Required: GCC (`http://gcc.gnu.org/`). Version 4.0 or later is preferred. Version 3.3 or later should work. If the host machine has an 80*x*86 processor, then GCC should be available as `gcc`; otherwise, an 80*x*86 cross-compiler should be available as `i386-elf-gcc`. A sample set of commands for installing GCC 3.3.6 as a cross-compiler are included in '`src/misc/gcc-3.3.6-cross-howto`'.
- Required: GNU binutils (`http://www.gnu.org/software/binutils/`). Pintos uses `addr2line`, `ar`, `ld`, `objcopy`, and `ranlib`. If the host machine is not an 80*x*86, versions targeting 80*x*86 should be available with an '`i386-elf-`' prefix.
- Required: Perl (`http://www.perl.org`). Version 5.8.0 or later is preferred. Version 5.6.1 or later should work.
- Required: GNU make (`http://www.gnu.org/software/make/`), version 3.80 or later.
- Recommended: QEMU (`http://fabrice.bellard.free.fr/qemu/`), version 0.11.0 or later. If QEMU is not available, Bochs can be used, but its slowness is frustrating.
- Recommended: GDB (`http://www.gnu.org/software/gdb/`). GDB is helpful in debugging (see Section E.5 [GDB], page 105). If the host machine is not an 80*x*86, a version of GDB targeting 80*x*86 should be available as '`i386-elf-gdb`'.
- Recommended: X (`http://www.x.org/`). Being able to use an X server makes the virtual machine feel more like a physical machine, but it is not strictly necessary.
- Optional: Texinfo (`http://www.gnu.org/software/texinfo/`), version 4.5 or later. Texinfo is required to build the PDF version of the documentation.
- Optional: TEX (`http://www.tug.org/`). Also required to build the PDF version of the documentation.
- Optional: VMware Player (`http://www.vmware.com/`). This is a third platform that can also be used to test Pintos.

Once these prerequisites are available, follow these instructions to install Pintos:

1. Install Bochs (`http://bochs.sourceforge.net/`), version 2.2.6, as described below (see Section G.1 [Building Bochs for Pintos], page 115).
2. Install scripts from '`src/utils`'. Copy '`backtrace`', '`pintos`', '`pintos-gdb`', '`pintos-mkdisk`', '`pintos-set-cmdline`', and '`Pintos.pm`' into the default `PATH`.
3. Install '`src/misc/gdb-macros`' in a public location. Then use a text editor to edit the installed copy of '`pintos-gdb`', changing the definition of `GDBMACROS` to point to where you installed '`gdb-macros`'. Test the installation by running `pintos-gdb` without any arguments. If it does not complain about missing '`gdb-macros`', it is installed correctly.

4. Compile the remaining Pintos utilities by typing `make` in '`src/utils`'. Install '`squish-pty`' somewhere in `PATH`. To support VMware Player, install '`squish-unix`'. If your Perl is older than version 5.8.0, also install '`setitimer-helper`'; otherwise, it is unneeded.
5. Pintos should now be ready for use. If you have the Pintos reference solutions, which are provided only to faculty and their teaching assistants, then you may test your installation by running `make check` in the top-level '`tests`' directory. The tests take between 20 minutes and 1 hour to run, depending on the speed of your hardware.
6. Optional: Build the documentation, by running `make dist` in the top-level '`doc`' directory. This creates a '`WWW`' subdirectory within '`doc`' that contains HTML and PDF versions of the documentation, plus the design document templates and various hardware specifications referenced by the documentation. Building the PDF version of the manual requires Texinfo and TEX (see above). You may install '`WWW`' wherever you find most useful.

   The '`doc`' directory is not included in the '`.tar.gz`' distributed for Pintos. It is in the Pintos CVS tree available via `:pserver:anonymous@footstool.stanford.edu:/var/lib/cvs`, in the `pintos` module. The CVS tree is *not* the authoritative source for Stanford course materials, which should be obtained from the course website.

G.1 Building Bochs for Pintos

Upstream Bochs has bugs and warts that should be fixed when used with Pintos. Thus, Bochs should be installed manually for use with Pintos, instead of using the packaged version of Bochs included with an operating system distribution.

Two different Bochs binaries should be installed. One, named simply `bochs`, should have the GDB stub enabled, by passing '`--enable-gdb-stub`' to the Bochs `configure` script. The other, named `bochs-dbg`, should have the internal debugger enabled, by passing '`--enable-debugger`' to `configure`. (The `pintos` script selects a binary based on the options passed to it.) In each case, the X, terminal, and "no GUI" interfaces should be configured, by passing '`--with-x --with-x11 --with-term --with-nogui`' to `configure`.

This version of Pintos is designed for use with Bochs 2.2.6. A number of patches for this version of Bochs are included in '`src/misc`':

'`bochs-2.2.6-big-endian.patch`'
: Makes the GDB stubs work on big-endian systems such as Solaris/Sparc, by doing proper byteswapping. It should be harmless elsewhere.

'`bochs-2.2.6-jitter.patch`'
: Adds the "jitter" feature, in which timer interrupts are delivered at random intervals (see Section 1.1.4 [Debugging versus Testing], page 4).

'`bochs-2.2.6-triple-fault.patch`'
: Causes Bochs to break to GDB when a triple fault occurs and the GDB stub is active (see Section E.6 [Triple Faults], page 111).

'`bochs-2.2.6-ms-extensions.patch`'
: Needed for Bochs to compile with GCC on some hosts. Probably harmless elsewhere.

‘`bochs-2.2.6-solaris-tty.patch`’
: Needed for Bochs to compile in terminal support on Solaris hosts. Probably harmless elsewhere.

‘`bochs-2.2.6-page-fault-segv.patch`’
: Makes the GDB stub report a SIGSEGV to the debugger when a page-fault exception occurs, instead of “signal 0.” The former can be ignored with `handle SIGSEGV nostop` but the latter cannot.

‘`bochs-2.2.6-paranoia.patch`’
: Fixes compile error with modern versions of GCC.

‘`bochs-2.2.6-solaris-link.patch`’
: Needed on Solaris hosts. Do not apply it elsewhere.

To apply all the patches, `cd` into the Bochs directory, then type:

```
patch -p1 < $PINTOSDIR/src/misc/bochs-2.2.6-big-endian.patch
patch -p1 < $PINTOSDIR/src/misc/bochs-2.2.6-jitter.patch
patch -p1 < $PINTOSDIR/src/misc/bochs-2.2.6-triple-fault.patch
patch -p1 < $PINTOSDIR/src/misc/bochs-2.2.6-ms-extensions.patch
patch -p1 < $PINTOSDIR/src/misc/bochs-2.2.6-solaris-tty.patch
patch -p1 < $PINTOSDIR/src/misc/bochs-2.2.6-page-fault-segv.patch
patch -p1 < $PINTOSDIR/src/misc/bochs-2.2.6-paranoia.patch
patch -p1 < $PINTOSDIR/src/misc/bochs-2.2.6-solaris-link.patch
```

You will have to supply the proper `$PINTOSDIR`, of course. You can use `patch`’s ‘`--dry-run`’ option if you want to test whether the patches would apply cleanly before trying to apply them.

Sample commands to build and install Bochs for Pintos are supplied in ‘`src/misc/bochs-2.2.6-build.sh`’.

Bibliography

Hardware References

[IA32-v1]. IA-32 Intel Architecture Software Developer's Manual Volume 1: Basic Architecture. Basic 80x86 architecture and programming environment. Available via `developer.intel.com`. Section numbers in this document refer to revision 18.

[IA32-v2a]. IA-32 Intel Architecture Software Developer's Manual Volume 2A: Instruction Set Reference A-M. 80x86 instructions whose names begin with A through M. Available via `developer.intel.com`. Section numbers in this document refer to revision 18.

[IA32-v2b]. IA-32 Intel Architecture Software Developer's Manual Volume 2B: Instruction Set Reference N-Z. 80x86 instructions whose names begin with N through Z. Available via `developer.intel.com`. Section numbers in this document refer to revision 18.

[IA32-v3a]. IA-32 Intel Architecture Software Developer's Manual Volume 3A: System Programming Guide. Operating system support, including segmentation, paging, tasks, interrupt and exception handling. Available via `developer.intel.com`. Section numbers in this document refer to revision 18.

[FreeVGA]. FreeVGA Project. Documents the VGA video hardware used in PCs.

[kbd]. Keyboard scancodes. Documents PC keyboard interface.

[ATA-3]. AT Attachment-3 Interface (ATA-3) Working Draft. Draft of an old version of the ATA aka IDE interface for the disks used in most desktop PCs.

[PC16550D]. National Semiconductor PC16550D Universal Asynchronous Receiver/Transmitter with FIFOs. Datasheet for a chip used for PC serial ports.

[8254]. Intel 8254 Programmable Interval Timer. Datasheet for PC timer chip.

[8259A]. Intel 8259A Programmable Interrupt Controller (8259A/8259A-2). Datasheet for PC interrupt controller chip.

[MC146818A]. Motorola MC146818A Real Time Clock Plus Ram (RTC). Datasheet for PC real-time clock chip.

Software References

[ELF1]. Tool Interface Standard (TIS) Executable and Linking Format (ELF) Specification Version 1.2 Book I: Executable and Linking Format. The ubiquitous format for executables in modern Unix systems.

[ELF2]. Tool Interface Standard (TIS) Executable and Linking Format (ELF) Specification Version 1.2 Book II: Processor Specific (Intel Architecture). 80x86-specific parts of ELF.

[ELF3]. Tool Interface Standard (TIS) Executable and Linking Format (ELF) Specification Version 1.2 Book III: Operating System Specific (UNIX System V Release 4). Unix-specific parts of ELF.

[SysV-ABI]. System V Application Binary Interface: Edition 4.1. Specifies how applications interface with the OS under Unix.

[SysV-i386]. System V Application Binary Interface: Intel386 Architecture Processor Supplement: Fourth Edition. 80x86-specific parts of the Unix interface.

[SysV-ABI-update]. System V Application Binary Interface—DRAFT—24 April 2001. A draft of a revised version of [SysV-ABI] which was never completed.

[SUSv3]. The Open Group, Single UNIX Specification V3, 2001.

[Partitions]. A. E. Brouwer, Minimal partition table specification, 1999.

[IntrList]. R. Brown, Ralf Brown's Interrupt List, 2000.

Operating System Design References

[Christopher]. W. A. Christopher, S. J. Procter, T. E. Anderson, *The Nachos instructional operating system*. Proceedings of the USENIX Winter 1993 Conference. `http://portal.acm.org/citation.cfm?id=1267307`.

[Dijkstra]. E. W. Dijkstra, *The structure of the "THE" multiprogramming system*. Communications of the ACM 11(5):341–346, 1968. `http://doi.acm.org/10.1145/363095.363143`.

[Hoare]. C. A. R. Hoare, *Monitors: An Operating System Structuring Concept*. Communications of the ACM, 17(10):549–557, 1974. `http://www.acm.org/classics/feb96/`.

[Lampson]. B. W. Lampson, D. D. Redell, *Experience with processes and monitors in Mesa*. Communications of the ACM, 23(2):105–117, 1980. `http://doi.acm.org/10.1145/358818.358824`.

[McKusick]. M. K. McKusick, K. Bostic, M. J. Karels, J. S. Quarterman, *The Design and Implementation of the 4.4BSD Operating System*. Addison-Wesley, 1996.

[Wilson]. P. R. Wilson, M. S. Johnstone, M. Neely, D. Boles, *Dynamic Storage Allocation: A Survey and Critical Review*. International Workshop on Memory Management, 1995. `http://www.cs.utexas.edu/users/oops/papers.html#allocsrv`.

License

Pintos, including its documentation, is subject to the following license:

> Copyright © 2004, 2005, 2006 Board of Trustees, Leland Stanford Jr. University. All rights reserved.
>
> Permission is hereby granted, free of charge, to any person obtaining a copy of this software and associated documentation files (the "Software"), to deal in the Software without restriction, including without limitation the rights to use, copy, modify, merge, publish, distribute, sublicense, and/or sell copies of the Software, and to permit persons to whom the Software is furnished to do so, subject to the following conditions:
>
> The above copyright notice and this permission notice shall be included in all copies or substantial portions of the Software.
>
> THE SOFTWARE IS PROVIDED "AS IS", WITHOUT WARRANTY OF ANY KIND, EXPRESS OR IMPLIED, INCLUDING BUT NOT LIMITED TO THE WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE AND NONINFRINGEMENT. IN NO EVENT SHALL THE AUTHORS OR COPYRIGHT HOLDERS BE LIABLE FOR ANY CLAIM, DAMAGES OR OTHER LIABILITY, WHETHER IN AN ACTION OF CONTRACT, TORT OR OTHERWISE, ARISING FROM, OUT OF OR IN CONNECTION WITH THE SOFTWARE OR THE USE OR OTHER DEALINGS IN THE SOFTWARE.

A few individual files in Pintos were originally derived from other projects, but they have been extensively modified for use in Pintos. The original code falls under the original license, and modifications for Pintos are additionally covered by the Pintos license above.

In particular, code derived from Nachos is subject to the following license:

> Copyright © 1992-1996 The Regents of the University of California. All rights reserved.
>
> Permission to use, copy, modify, and distribute this software and its documentation for any purpose, without fee, and without written agreement is hereby granted, provided that the above copyright notice and the following two paragraphs appear in all copies of this software.
>
> IN NO EVENT SHALL THE UNIVERSITY OF CALIFORNIA BE LIABLE TO ANY PARTY FOR DIRECT, INDIRECT, SPECIAL, INCIDENTAL, OR CONSEQUENTIAL DAMAGES ARISING OUT OF THE USE OF THIS SOFTWARE AND ITS DOCUMENTATION, EVEN IF THE UNIVERSITY OF CALIFORNIA HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGE.
>
> THE UNIVERSITY OF CALIFORNIA SPECIFICALLY DISCLAIMS ANY WARRANTIES, INCLUDING, BUT NOT LIMITED TO, THE IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE. THE SOFTWARE PROVIDED HEREUNDER IS ON AN "AS IS" BASIS, AND THE UNIVERSITY OF CALIFORNIA HAS NO OBLIGATION TO PROVIDE MAINTENANCE, SUPPORT, UPDATES, ENHANCEMENTS, OR MODIFICATIONS.