The Pintos Instructional Operating System Kernel

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Overview

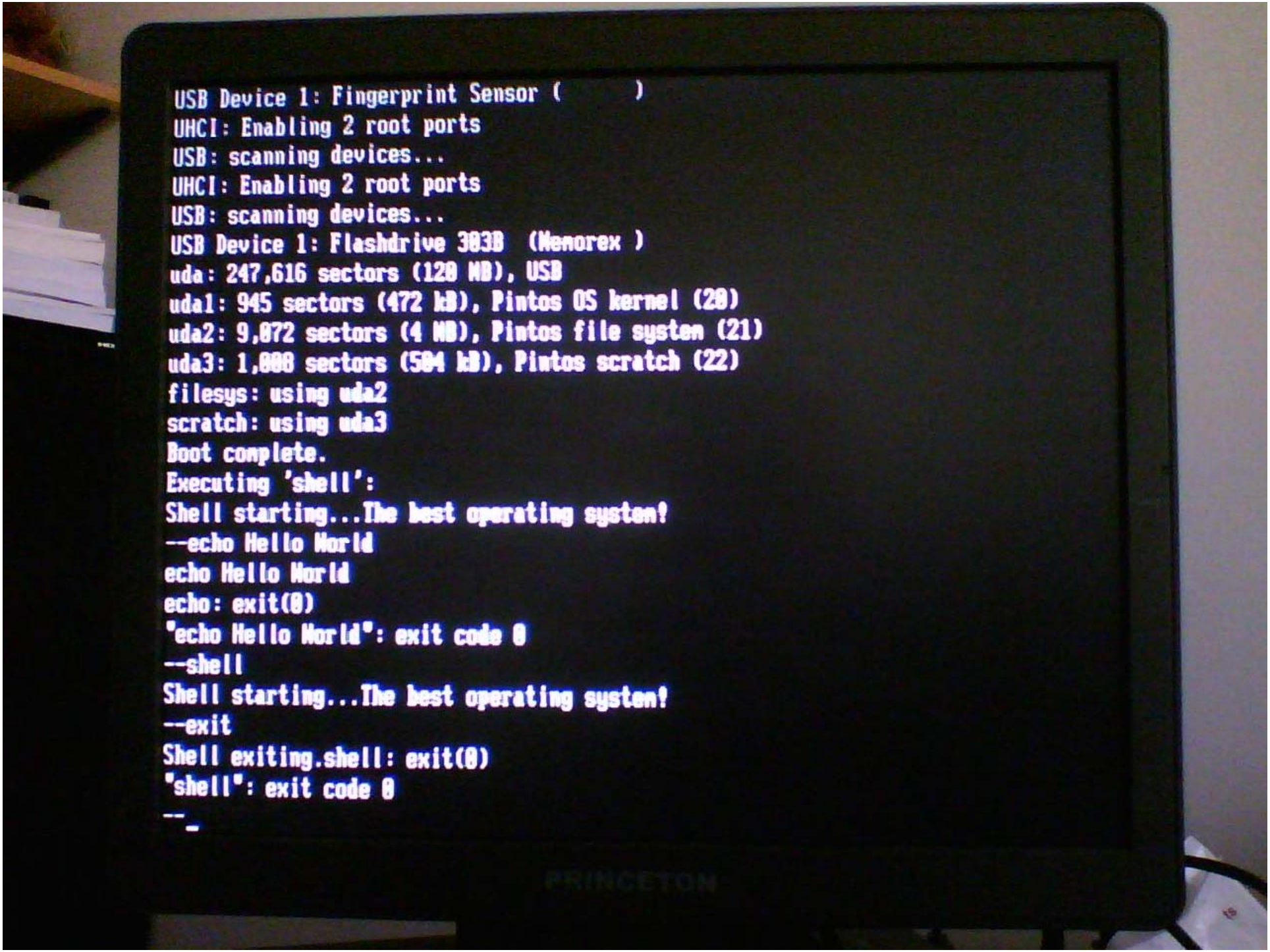
- Tool paper
- Series of 4 projects that provide backbone of lab component that accompanies OS course
- Suitable for Junior/Senior/1st Grad students
- Used by several institutions
  - Stanford (4 years+), Virginia Tech (3 years), University of San Francisco, William and Mary, University of Salzburg, Linköping Universitet, KAIST, Seoul National University, POSTECH

Teaching OS

- Internal Perspective
  - Teaches how an OS works from the inside, specifically, the kernel
  - Places students in the perspective of OS designer, rather than OS user
- Concrete Approach
  - Design and create realistic artifacts
  - Internalize abstractions by seeing concrete incarnation

Pintos Features

- Small enough so entire code can be read and understood by students
  - Unlike Linux or Windows
- Runs and debugs in simulated environment
  - 100% reproducible, like single-threaded user code
- Runs and debugs in emulated environment
  - facilitates non-intrusive analysis tools
- Runs on real hardware
  - boots on student's PC/laptop


USB Device 1: Fingerprint Sensor ( )
UHCI: Enabling 2 root ports
USB: scanning devices...
UHCI: Enabling 2 root ports
USB: scanning devices...
USB Device 1: Flashdrive 303B (Memorex)
uda: 247,616 sectors (120 MB), USB
uda1: 945 sectors (472 kB), Pintos OS kernel (20)
uda2: 9,072 sectors (4 MB), Pintos file system (21)
uda3: 1,008 sectors (504 kB), Pintos scratch (22)
filesys: using uda2
scratch: using uda3
Boot complete.
Executing 'shell':
Shell starting...The best operating system!
--echo Hello World
echo Hello World
echo: exit(0)
"echo Hello World": exit code 0
--shell
Shell starting...The best operating system!
--exit
Shell exiting.shell: exit(0)
"shell": exit code 0
--_

Project Principles (1)

- Read Before You Code
  - Provide well-documented code that serves as example of what we expect from students
  - Between 0-600 lines per project

Project Principles (2)

- Maximize Creative Freedom
  - Specify requirements
  - Don’t prescribe solution approaches

Project Principles (3)

- Practice Test-driven Development
  - All tests are public, reading tests makes requirements concrete
  - Student can add their own tests

Project	Functionality	Robustness	Regression
1	27		
2	41	35	
3	20	14	75
4	39	7	75

Project Principles (4)

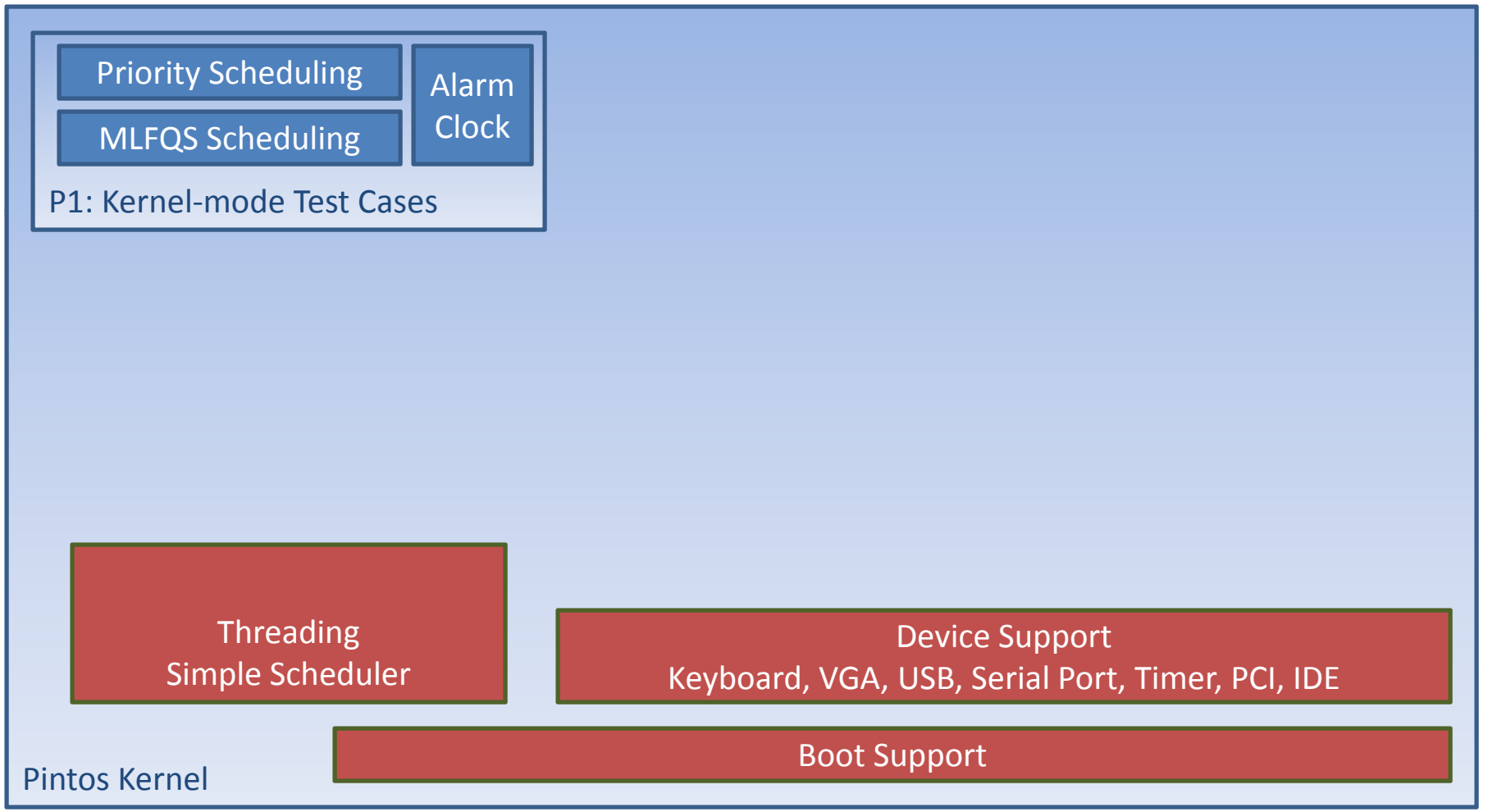
- Justify Your Design
  - Provide structured questionnaires that students use to describe and justify their design rationale

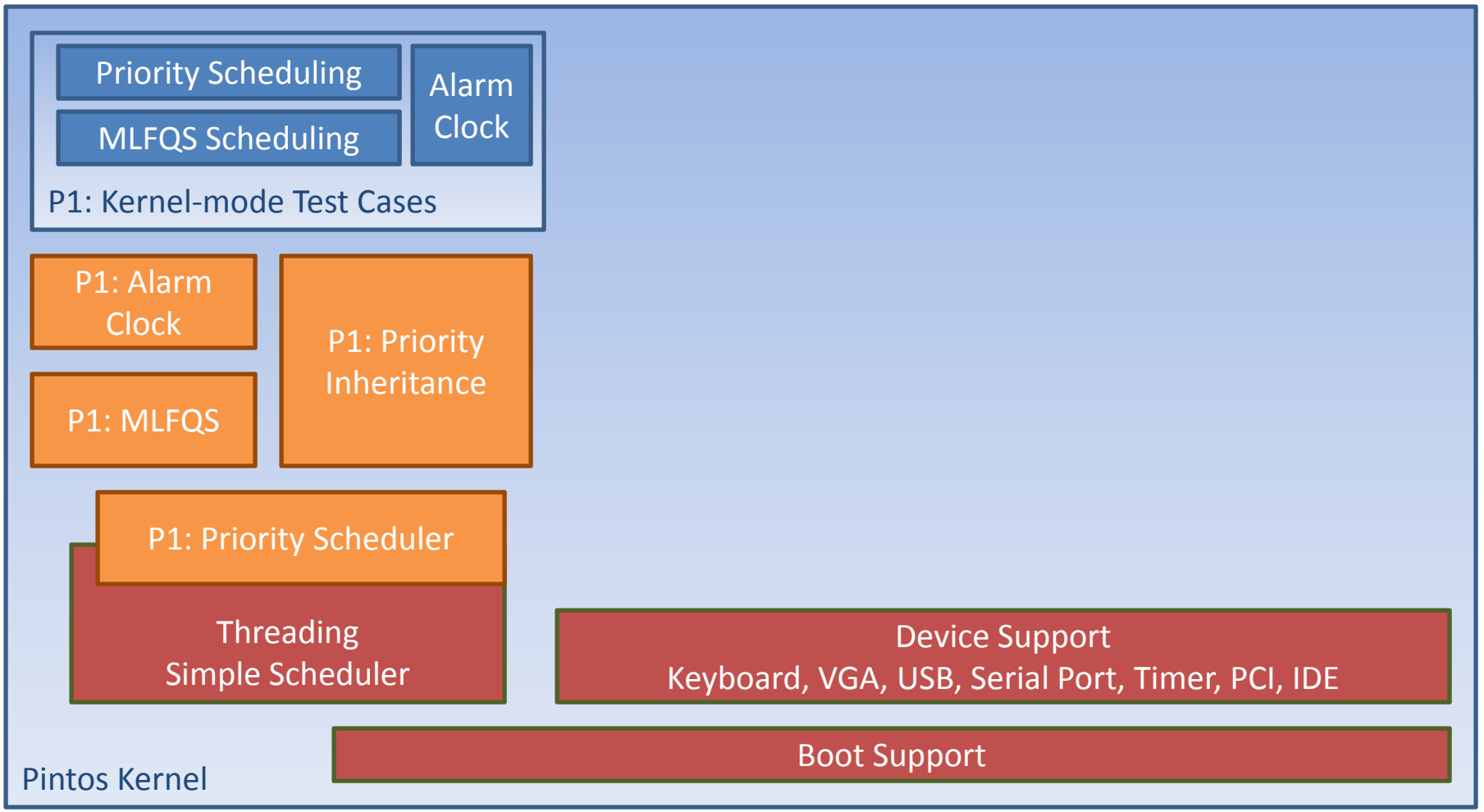
Project Principles (5)

- Work In Teams
  - 2-4 students
  - Allows for brainstorming and mutual support
  - Mimics industrial setting, e.g., use of shared source code repository and versioning
  - Design questionnaires still submitted individually

Pintos Project Themes

1. Threads
2. User Programs
3. Virtual Memory
4. File Systems


Priority Scheduling
MLFQS Scheduling
Alarm Clock
P1: Kernel-mode Test Cases
Threading
Simple Scheduler
Device Support
Keyboard, VGA, USB, Serial Port, Timer, PCI, IDE
Boot Support
Pintos Kernel
Support Code
Public Tests


Priority Scheduling
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P1: MLFQS
P1: Priority Inheritance
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Example of Project 1 Test

```
void
test_priority_change (void)
{
  msg ("Creating a high-priority thread 2.");
  thread_create ("thread 2", PRI_DEFAULT + 1, changing_thread, NULL);
  msg ("Thread 2 should have just lowered its priority.");
  thread_set_priority (PRI_DEFAULT - 2);
  msg ("Thread 2 should have just exited.");
}

static void
changing_thread (void *aux UNUSED)
{
  msg ("Thread 2 now lowering priority.");
  thread_set_priority (PRI_DEFAULT - 1);
  msg ("Thread 2 exiting.");
}
```

Expected output:

Creating a high-priority thread 2.
Thread 2 now lowering priority.
Thread 2 should have just lowered its priority.
Thread 2 exiting.
Thread 2 should have just exited.

make grade (1)

```
TOTAL TESTING SCORE: 100.0%
ALL TESTED PASSED -- PERFECT SCORE

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

SUMMARY BY TEST SET

Test Set                                          Pts Max  % Ttl  % Max
------------------------------------------------ --- --- ------ ------
tests/threads/Rubric.alarm                         18/ 18  20.0%/ 20.0%
tests/threads/Rubric.priority                      38/ 38  40.0%/ 40.0%
tests/threads/Rubric.mlfqs                         37/ 37  40.0%/ 40.0%
------------------------------------------------ --- --- ------ ------
Total                                                     100.0%/100.0%

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

Pintos include fully automated grading scripts, students see score before submission

make grade (2)

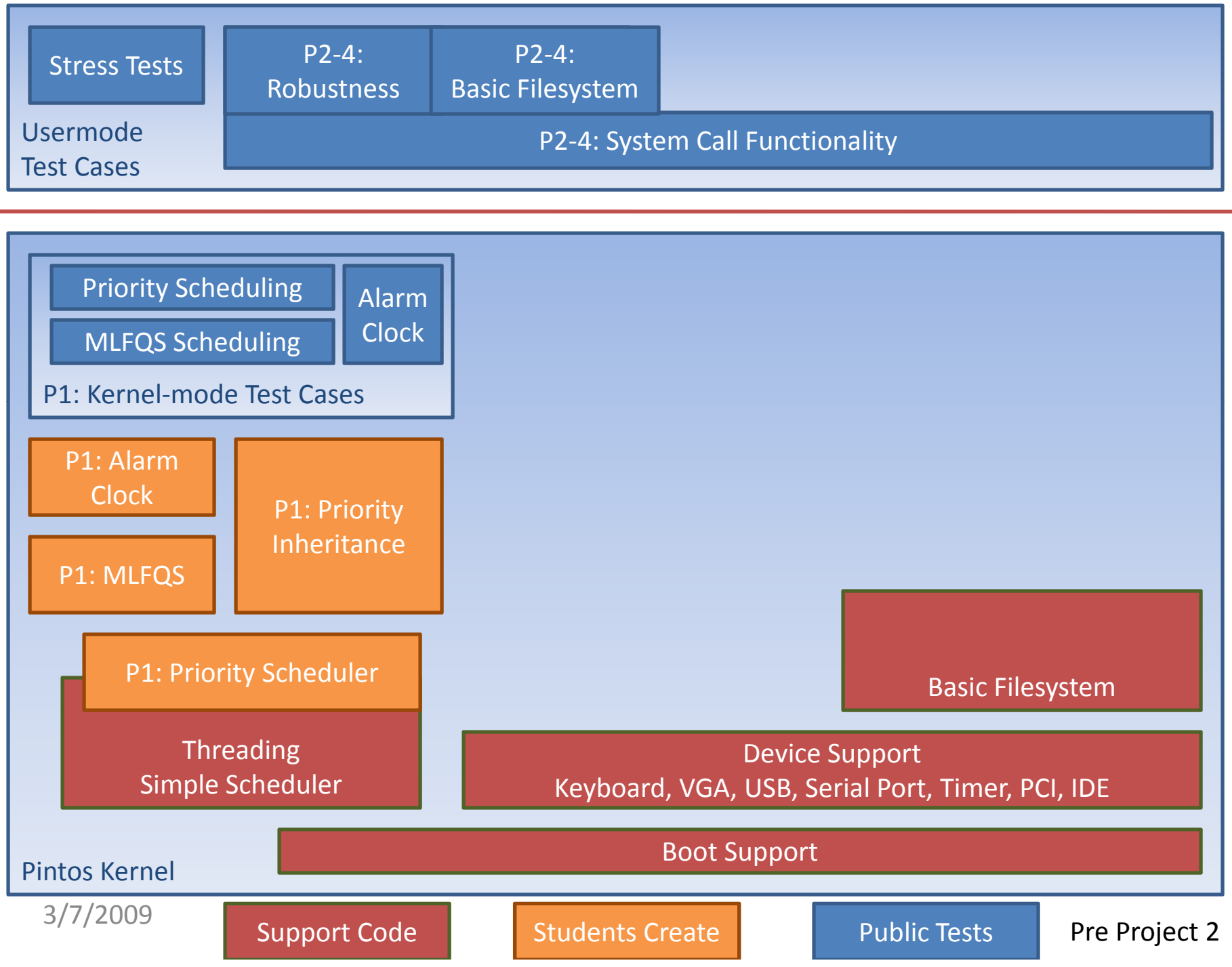
```
SUMMARY OF INDIVIDUAL TESTS

Functionality and robustness of alarm clock (tests/threads/Rubric.alarm):
        4/ 4 tests/threads/alarm-single
        4/ 4 tests/threads/alarm-multiple
        4/ 4 tests/threads/alarm-simultaneous
        4/ 4 tests/threads/alarm-priority

        1/ 1 tests/threads/alarm-zero
        1/ 1 tests/threads/alarm-negative

   - Section summary.
         6/  6 tests passed
        18/ 18 points subtotal

Functionality of priority scheduler (tests/threads/Rubric.priority):
        3/ 3 tests/threads/priority-change
        3/ 3 tests/threads/priority-preempt
```


Stress Tests
P2-4: Robustness
P2-4: Basic Filesystem
Usermode Test Cases
P2-4: System Call Functionality
Priority Scheduling
Alarm Clock
MLFQS Scheduling
P1: Kernel-mode Test Cases
P1: Alarm Clock
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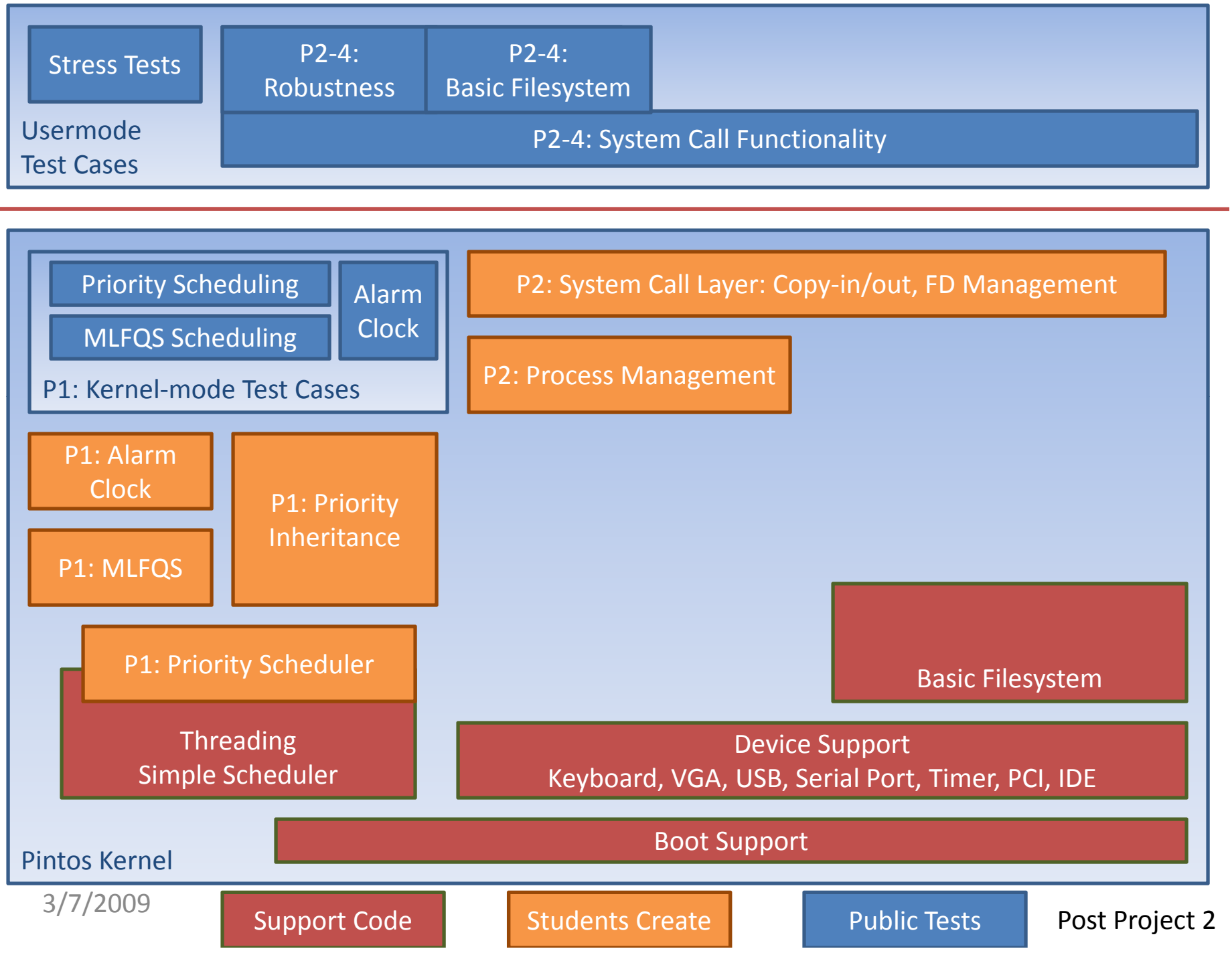


Support Code | Students Create | Public Tests

Project 2 Functionality Test

```
/* This program echoes its command-line arguments */
int
main (int argc, char *argv[])
{
  int i;
  msg ("begin");
  msg ("argc = %d", argc);
  for (i = 0; i <= argc; i++)
    if (argv[i] != NULL)
      msg ("argv[%d] = '%s'", i, argv[i]);
    else
      msg ("argv[%d] = null", i);
  msg ("end");
  return 0;
}
```

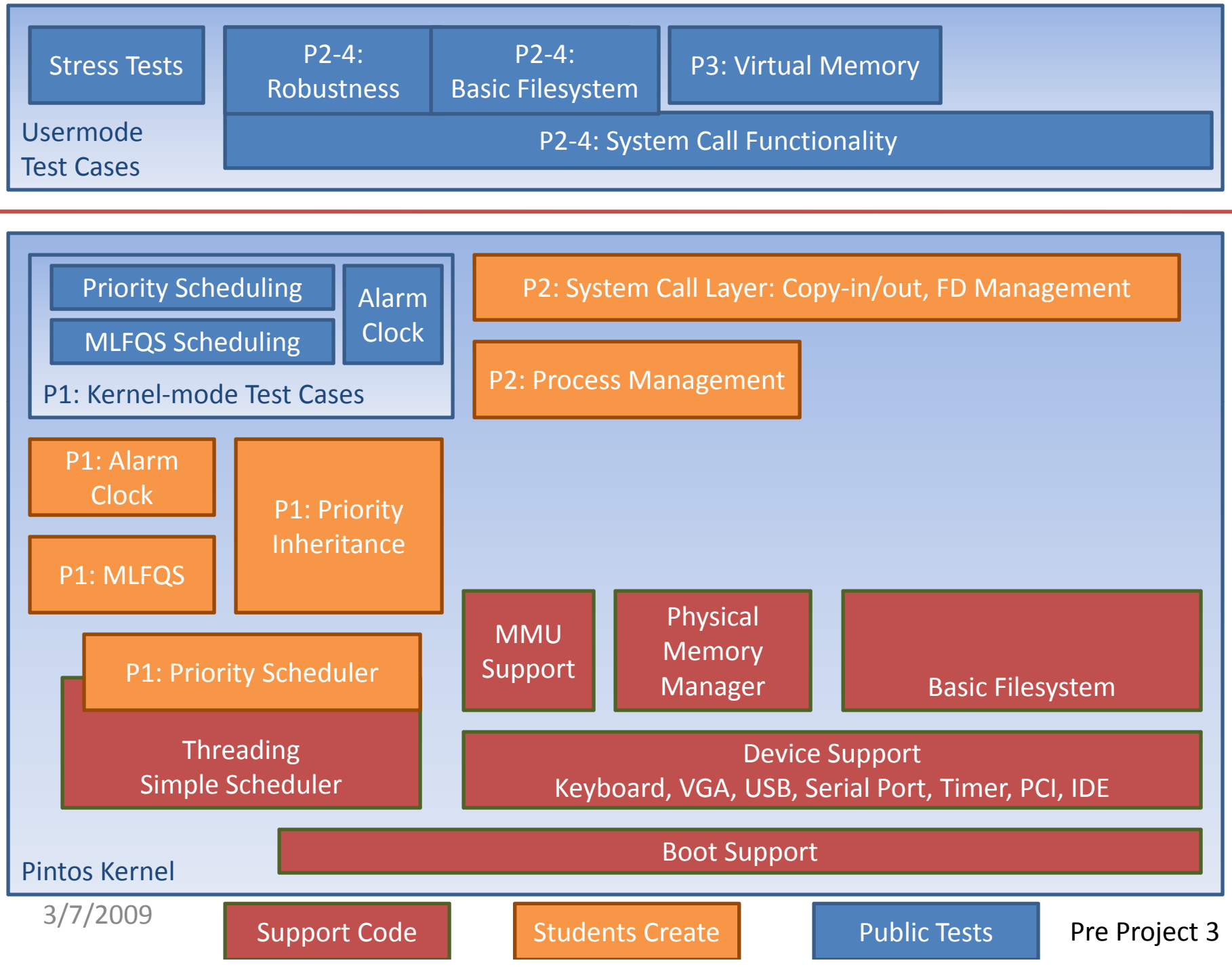
Expected output for 'args 1 2'

begin
argc=3
argv[0] = 'args'
argv[1] = '1'
argv[2] = '2'
argv[3] = null
end

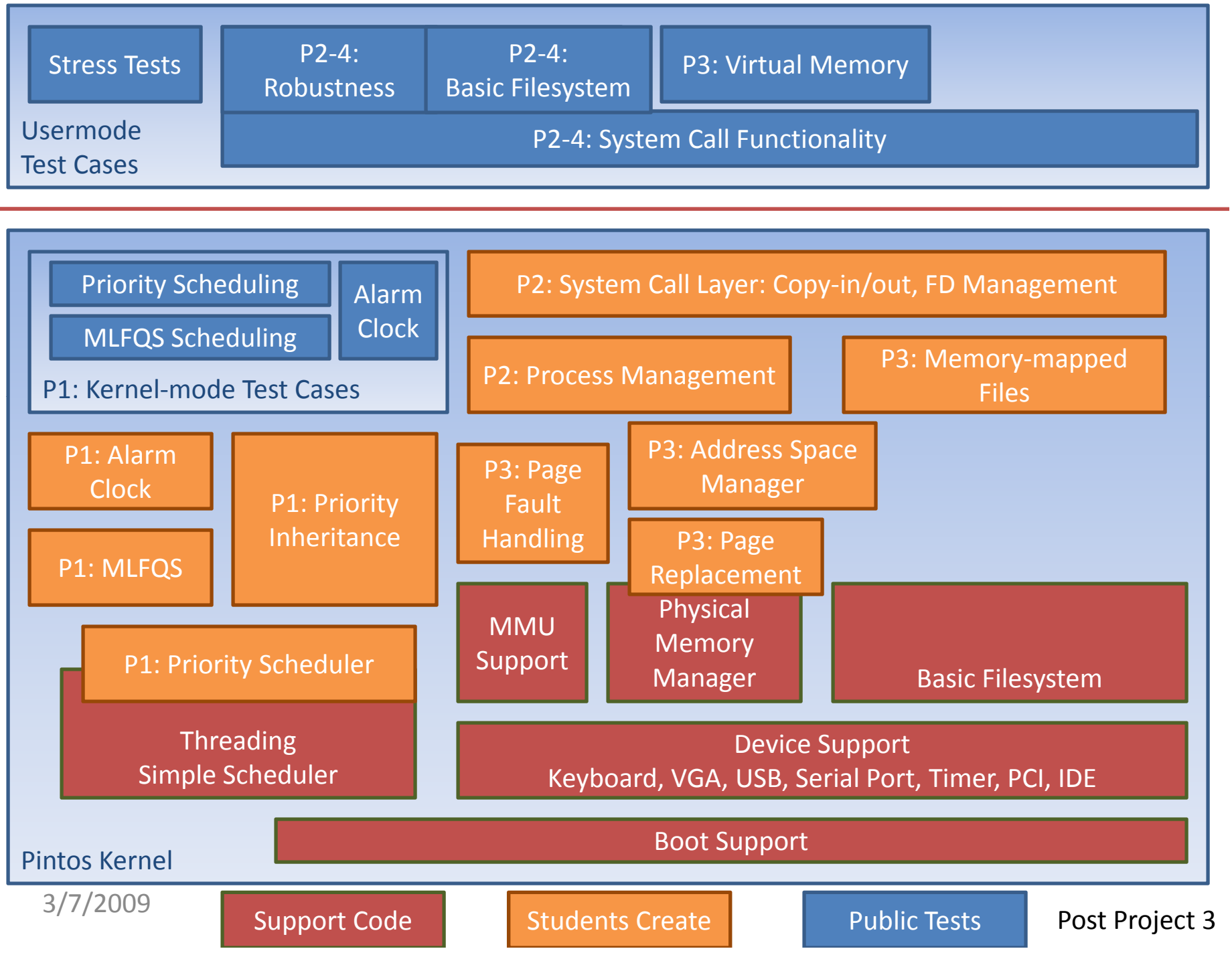
Project 2 Robustness Test

```
/* This program attempts to read memory at an address that is not mapped.
   This should terminate the process with a -1 exit code. */

#include "tests/lib.h"
#include "tests/main.h"

void
test_main (void)
{
  msg ("Congratulations - you have successfully dereferenced NULL: %d",
       *(int *)NULL);
  fail ("should have exited with -1");
}
```

Expected output:
bad-read: exit(-1)



Support Code | Students Create | Public Tests



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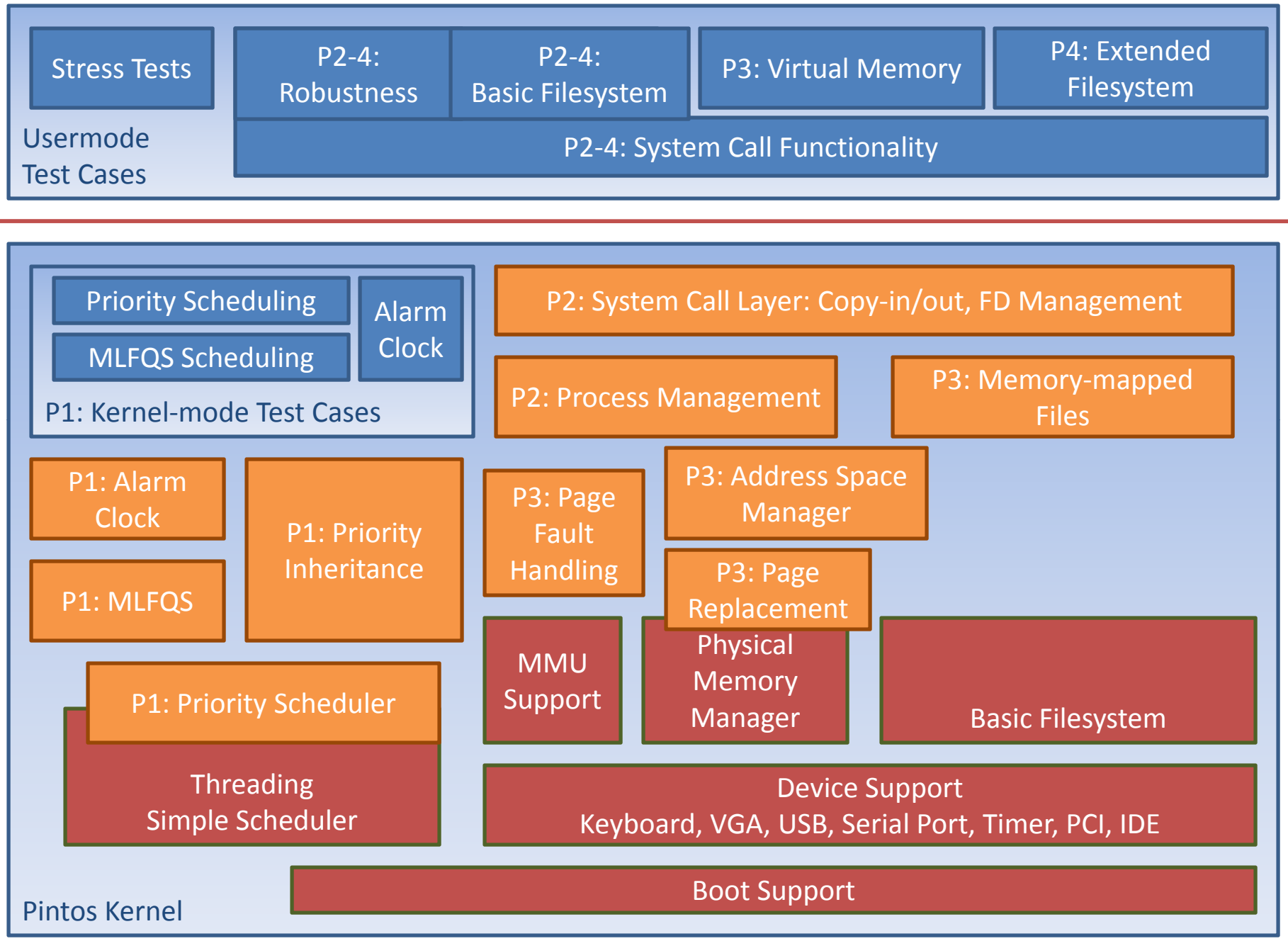
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P3: Virtual Memory
P4: Extended Filesystem
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P2: System Call Layer: Copy-in/out, FD Management
P2: Process Management
P3: Memory-mapped Files
P1: Alarm Clock
P1: Priority Inheritance
P3: Page Fault Handling
P3: Address Space Manager
P1: MLFQS
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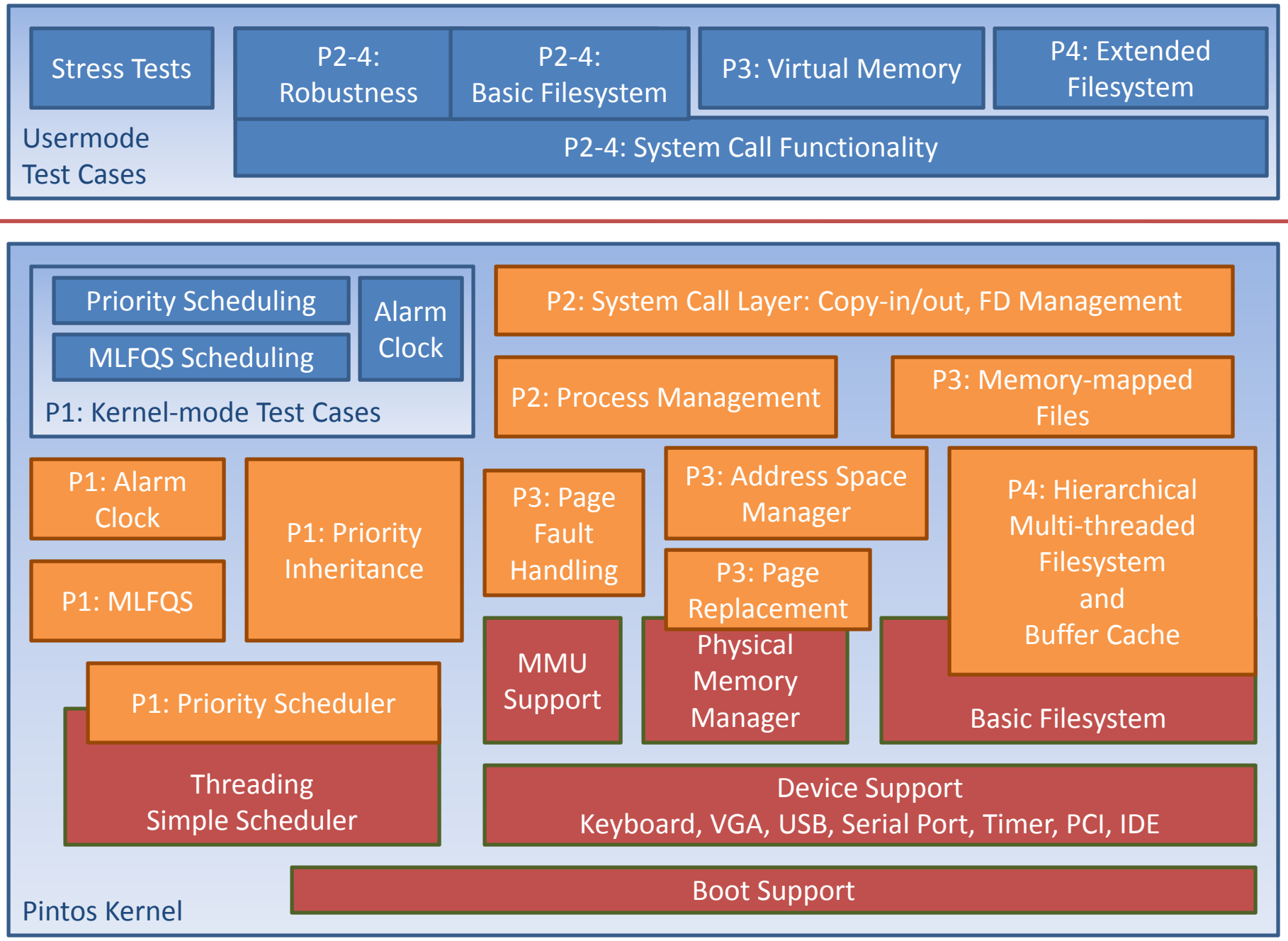
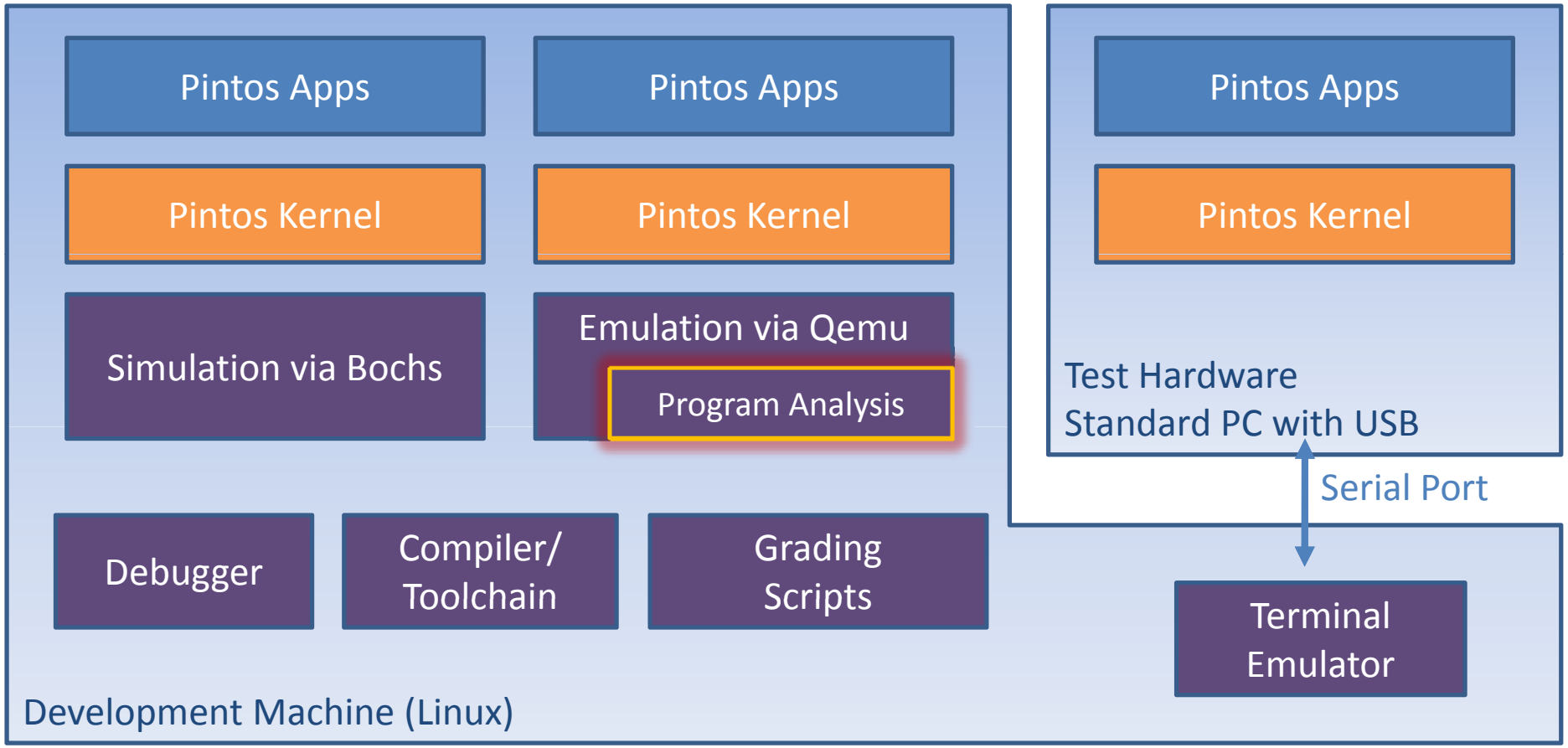


Support Code | Students Create | Public Tests

Post Project 4

Program Analysis



Race Detection Example

```
*** Race #1 ***
- Fault Point -
  IP: c002da7d
  Function: list_begin
  Memory address at which race occurred: c003afc4
  Memory base of object in which race occurred: c003afc0
  This race affects global variable: open_inodes
  Lockset:

- Threads involved in race -

  * Backtrace (thread #1) *
     list_remove (c002d565)(lib/kernel/list.c:260)
     inode_close (c0032c1f)(filesys/inode.c:177)
     file_close (c0032224)(filesys/file.c:52)
     syscall_handler (c003175c)(userprog/syscall.c:288)
     intr_handler (c0021f47)(threads/interrupt.c:377)
     ??? (c0022107)(../../threads/intr-stubs.S:38)

  * Lockset (thread #1) *
```

In this example, students forgot to protect the list of open inodes, which is accessed concurrently by an exiting process (left backtrace) trying to close its files and a starting process (right backtrace) trying to open and read its executable

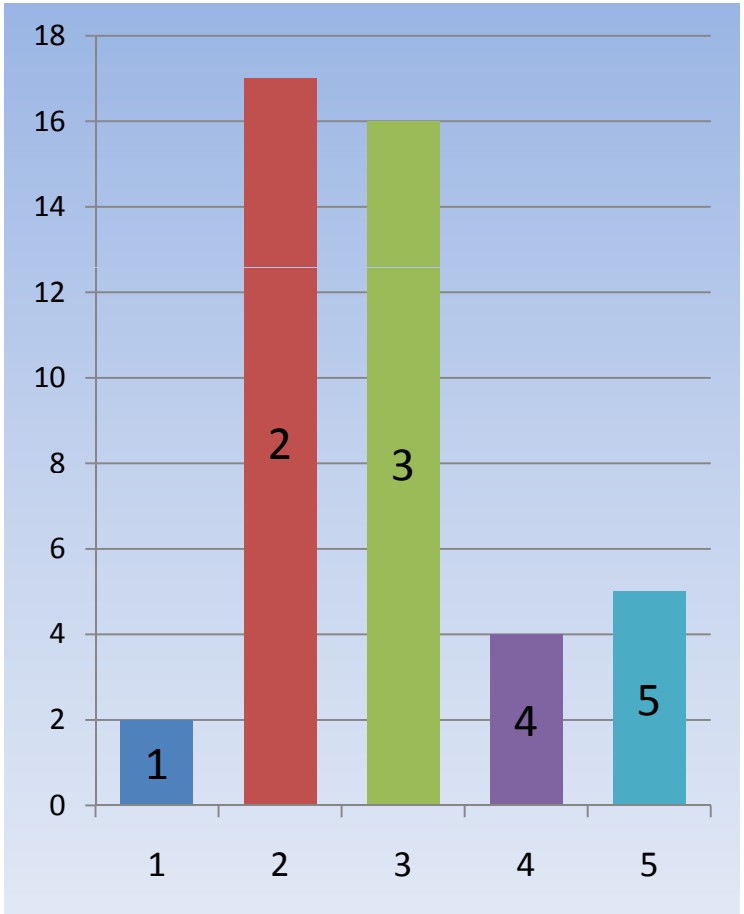
```
  * Backtrace (thread #2) *
     list_begin (c002da7d)(lib/kernel/list.c:74)
     inode_open (c0032c83)(filesys/inode.c:118)
     dir_open_root (c00327c0)(filesys/directory.c:57)
     filesys_open (c0031b27)(filesys/filesys.c:69)
     start_process (c002f7fb)(userprog/process.c:358)
     kernel_thread (c002170f)(threads/thread.c:538)

  * Lockset (thread #2) *
```

Evaluation (Fall 2008)

- How confident are you in your ability to understand the output of the race condition checker?

1. Not at all confident, the output was very confusing. (2/44)
2. I sort of understood what it was trying to tell me, but my understanding was vague. (17/44)
3. After careful analysis of the output, I understood the causes leading to the displayed race and was able to fix it. (16/44)
4. Once I learned the general format of the output, I quickly found the underlying race condition that was flagged. (4/44)
5. No answer (5/44)



- Based on survey given during final exam
- In addition, more than 50% of students reported that the race condition checker helped them find actual bugs that made them pass project tests!

Setting Up Pintos

- Requires simple Linux server
  - 1 quad core machine can support 8-10 students easily
  - All work can be done using remote ssh access, or an IDE can be used
  - No root user access required
  - Uses mostly host tools (gcc, binutils) and packages (bochs, qemu)
- Includes texinfo manual (HTML, 129-page PDF)
  - Documentation separates generic and institution-specific parts in separate files, e.g.

    Stanford: @set coursenumber CS140

    Virginia Tech: @set coursenumber CS 3204

Placement in Curriculum

- Cannot be a first course in C
- Should probably be 4th or 5th programming course
- Can be a first or second course in OS
- Pintos projects can stretch over 10-15 weeks
- Satisfies a “deep design” requirement

Related Work

- Systems that provide internal kernel perspective
- Simulated architecture only:
  - Nachos, ToyOS, OS/161, Yalnix
- Emulated:
  - GeekOS, JOS
- Real hardware:
  - GeekOS, Xinu, PortOS, JOS, Minix, Windows CRK, adapted versions of Linux

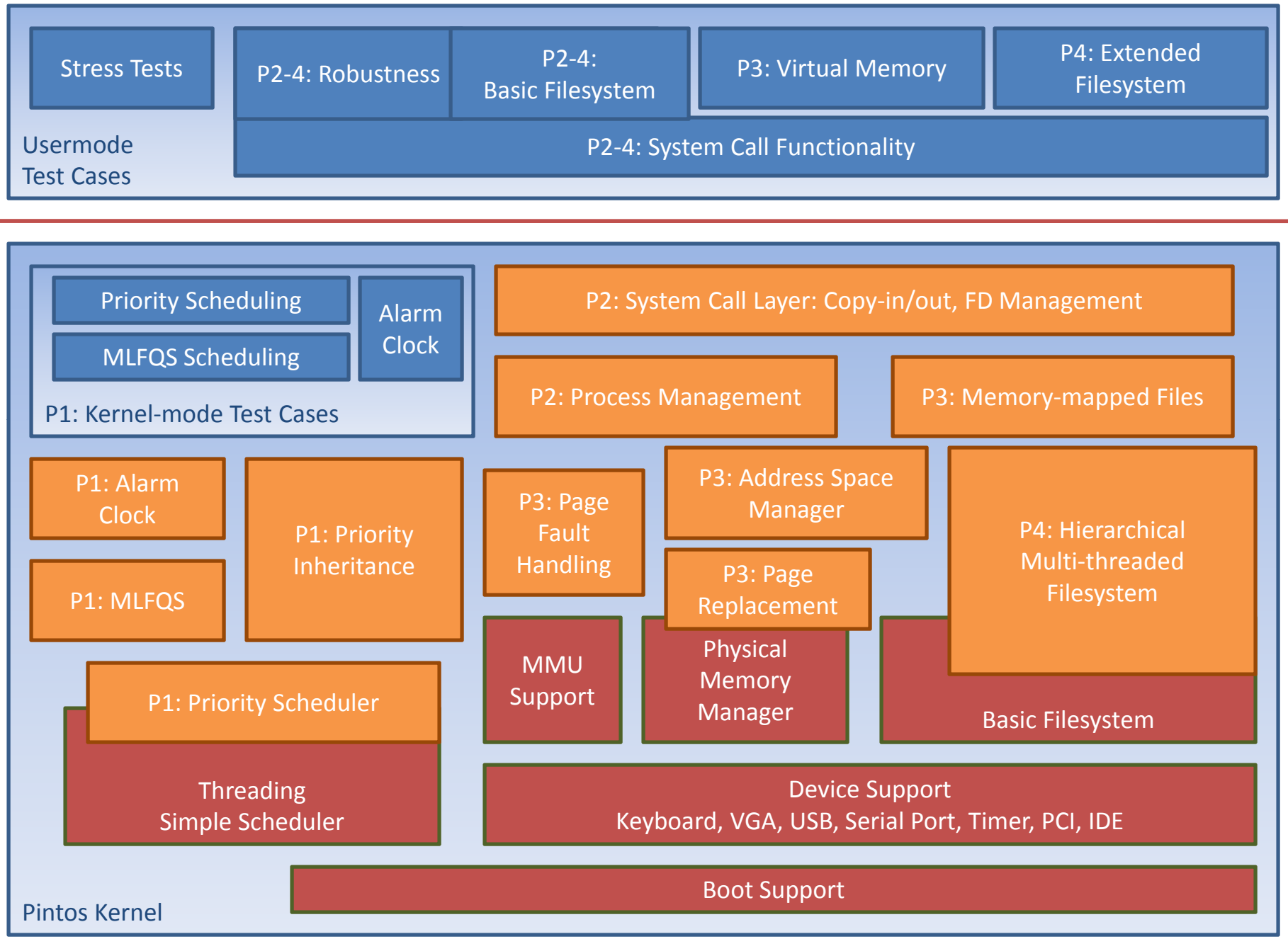
Future Work

- Educational:
  - Introduce modular assignment structure to allow instructor to tailor assignments with reduced or varied scope
  - Integrate assessment tools
  - Integrate static analysis tools
  - Integrate performance measures
- Technological:
  - Introduce multi-core/multi-processor support

Thank You!

- Ben Pfaff
- Anthony Romano
- Godmar Back
- Many Instructors, TA's, and students who have contributed with tests and suggestions

- URL: www.pintos-os.org
- Mailing list: pintos-os@googlegroups.com



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Post Project 1