CSE 421/521 - Operating Systems
Spring 2018

LECTURE - V

PROJECT-1 DISCUSSION

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Pintos Projects

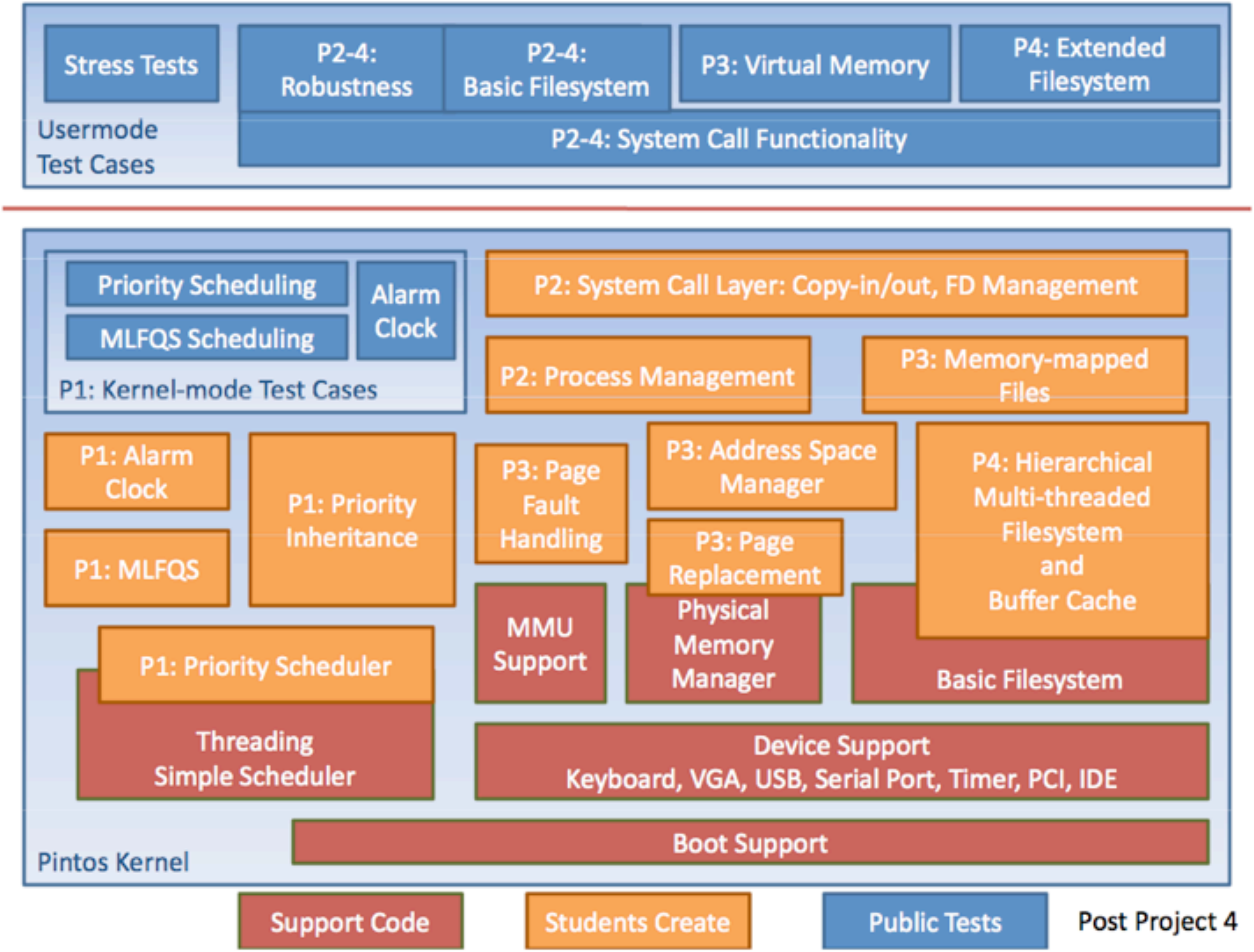
1. Threads <-- CSE 421/521 Project 1

2. User Programs

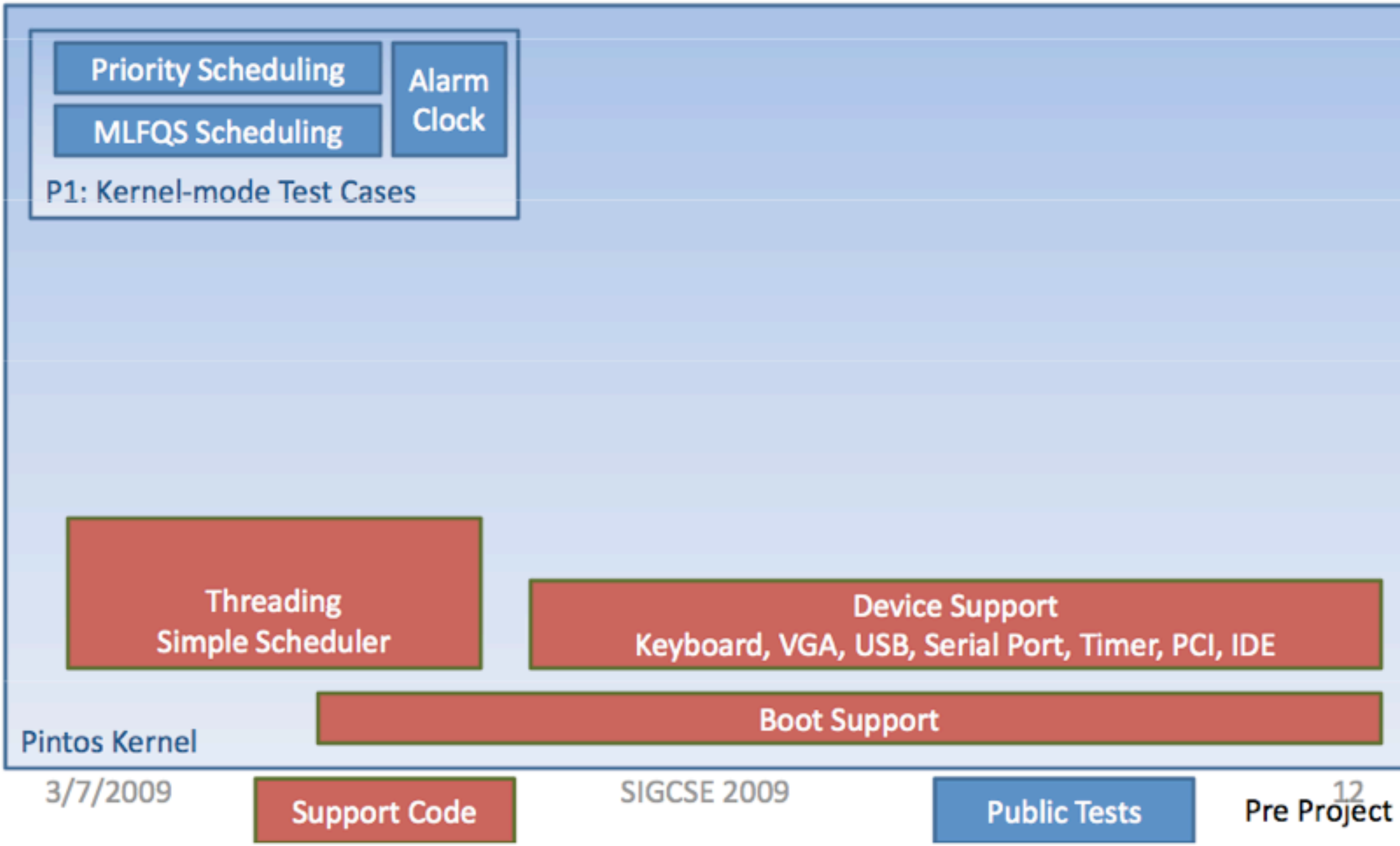
3. Virtual Memory

4. File Systems

Pintos after full implementation (post prj-4)

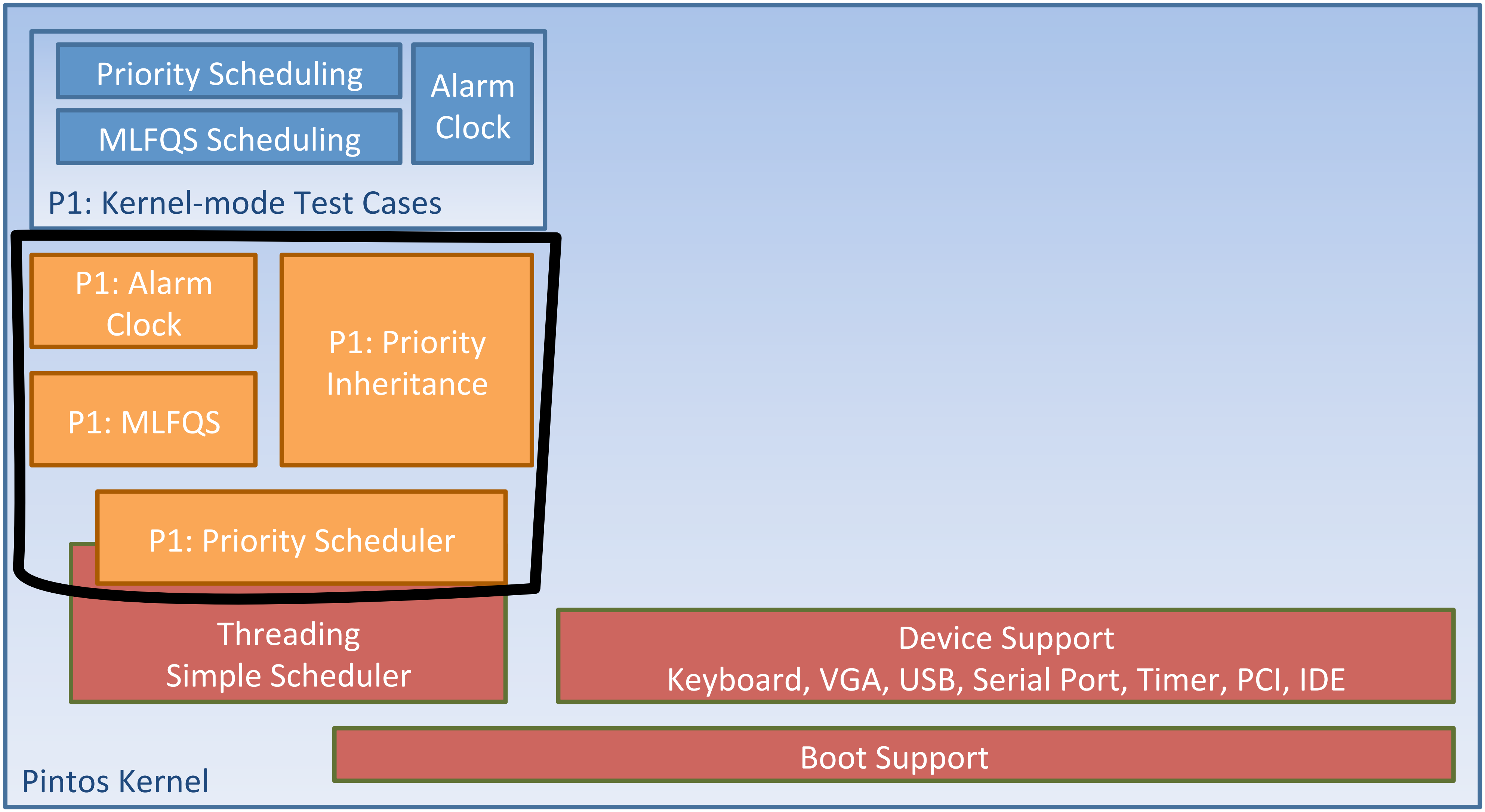


Yo will be provided with this (pre prj-1)



Pre Project 1

You will implement this (post prj-1)



Step 1: Preparation

READ:

Chapters 3-5 from Silberschatz

Lecture slides on Processes, Threads and CPU Scheduling

From Pintos Documentation:

- Section 1 - Introduction
- Section 2 - Threads
- Appendix A1- Pintos Loading
- Appendix A2 - Threads
- Appendix A3 - Synchronization
- Appendix B - 4.4BSD Scheduler

Step 2: Setting Up Pintos

- Use the Pintos **VM** we have prepared for you:

  http://ftp.cse.buffalo.edu/CSE421/UB-pintos.ova

- It requires **Virtualbox** software

  ==> will work on most Linux, Windows, Mac systems

  https://www.virtualbox.org/wiki/Downloads

- Detailed setup instructions are available on Piazza.

Step 3: Implementation

1. Alarm Clock

2. Priority Scheduler (with priority donation)

3. Multilevel Feedback Queue Scheduler

Task 0: Get Familiar with the Code

- The first task is to read and understand the code for the initial thread system (under the "pintos/src/threads/" directory).

- 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).

- For a brief overview of the files in the "threads/" directory, please see "Section 2.1.2 Source Files" in the Pintos Reference Guide

Pintos Thread System

- Read threads/thread.c and threads/synch.c to understand
  - How the switching between threads occur
  - How the provided scheduler works
  - How the various synchronizations primitives work

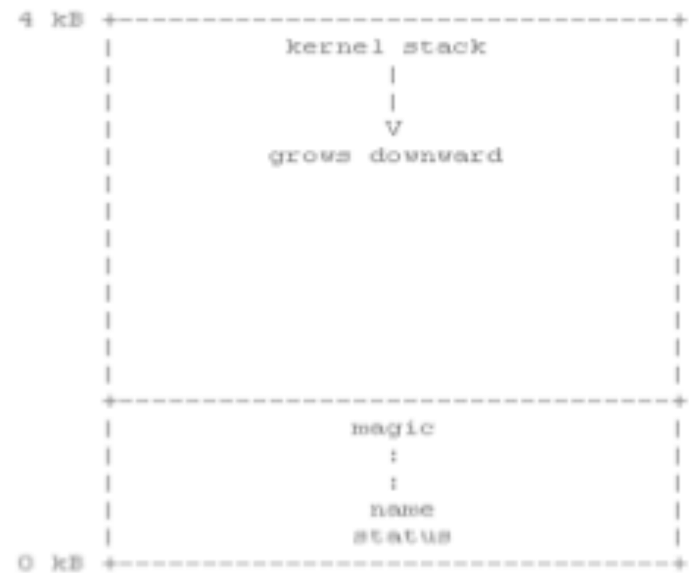
Pintos Thread System

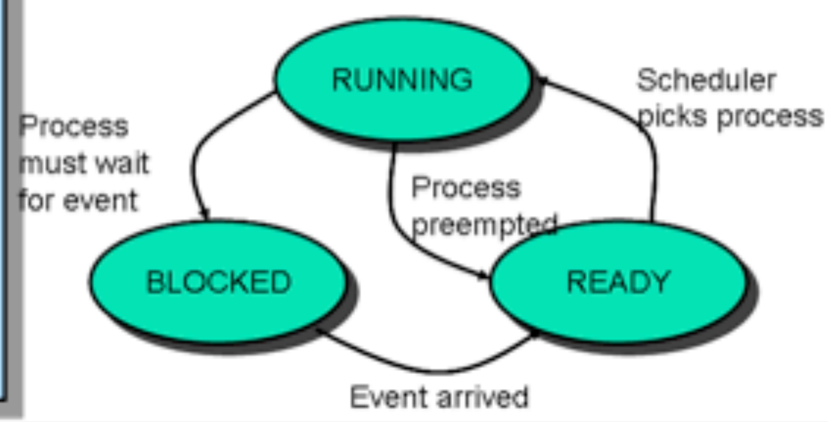
Defined in threads/thread.h:

```
struct thread
  {
    tid_t tid;              /* Thread identifier. */
    enum thread_status status;          /* Thread state. */
    char name[16];   /* Name (for debugging purposes). */
    uint8_t *stack;    /* Saved stack pointer. */
    int priority;        /* Priority. */
    struct list_elem allelem;  /* List element for all-threads list.*/
    /* Shared between thread.c and synch.c. */
    struct list_elem elem;               /* List element. */

You add more fields here as you need them.

#ifdef USERPROG
    /* Owned by userprog/process.c. */
    uint32_t *pagedir;                  /* Page directory. */
#endif
    /* Owned by thread.c. */
    unsigned magic;  /* Detects stack overflow. */
  };
```





Task 1: Implement Alarm Clock

- Reimplement timer_sleep( ) in devices/timer.c without busy waiting

```
/* Suspends execution for approximately TICKS timer ticks. */
void timer_sleep (int64_t ticks){
  int64_t start = timer_ticks ();
  ASSERT (intr_get_level () == INTR_ON);
  while (timer_elapsed (start) < ticks)
    thread_yield ();
}
```

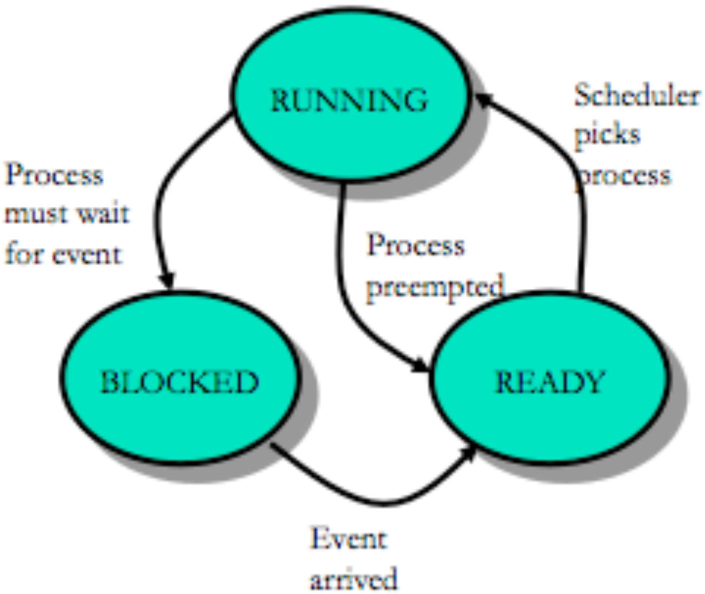
- Implementation details
  - Remove thread from ready list and put it back after sufficient ticks have elapsed

Any implementation using busy-waiting will not get full credits!

Task 2A: Implement Priority Scheduler

- Ready thread with highest priority gets the processor
- When a thread is added to the ready list that has a higher priority than the currently running thread, immediately yield the processor to the new thread
- When threads are waiting for a lock, semaphore or a condition variable, the highest priority waiting thread should be woken up first
- Implementation details
  - compare priority of the thread being added to the ready list with that of the running thread ← **Preemptive**
  - select next thread to run based on priorities
  - compare priorities of waiting threads when releasing locks, semaphores, condition variables

use thread_yield() to implement preemption



- Current thread ("RUNNING") is moved to READY state, added to READY list.
- Then scheduler is invoked. Picks a new READY thread from READY list.
- Case a): there's only 1 READY thread. Thread is rescheduled right away
- Case b): there are other READY thread(s)
  - b.1) another thread has higher priority – it is scheduled
  - b.2) another thread has same priority – it is scheduled provided the previously running thread was inserted in tail of ready list.
- "thread_yield()" is a call you can use whenever you identify a need to preempt current thread.
- Exception: inside an interrupt handler, use "intr_yield_on_return()" instead

✴ re-implement **next_thread_to_run()** for priority scheduling

Priority Inversion

- Strict priority scheduling can lead to a phenomenon called "priority inversion"
- Supplemental reading:
  - What really happened to the Pathfinder on Mars?
- Consider the following example where prio(H) > prio(M) > prio(L)

  H needs a lock currently held by L, so H blocks

  M that was already on the ready list gets the processor before L

  H indirectly waits for M

  - (on Path Finder, a watchdog timer noticed that H failed to run for some time, and continuously reset the system)

Task 2B: Implement Priority Donation

- When a high priority thread H waits on a lock held by a lower priority thread L, donate H's priority to L and recall the donation once L releases the lock
- Implement priority donation for locks

- Important:
  - Remember to return L to previous priority once it releases the lock.
  - Be sure to handle multiple donations (max of all donations)
  - Be sure to handle nested donations, e.g., H waits on M which waits on L...

Synchronization

- 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. **But, you should NOT do this!**

- Instead, **use semaphores, locks, and condition variables** to solve the bulk of your synchronization problems.

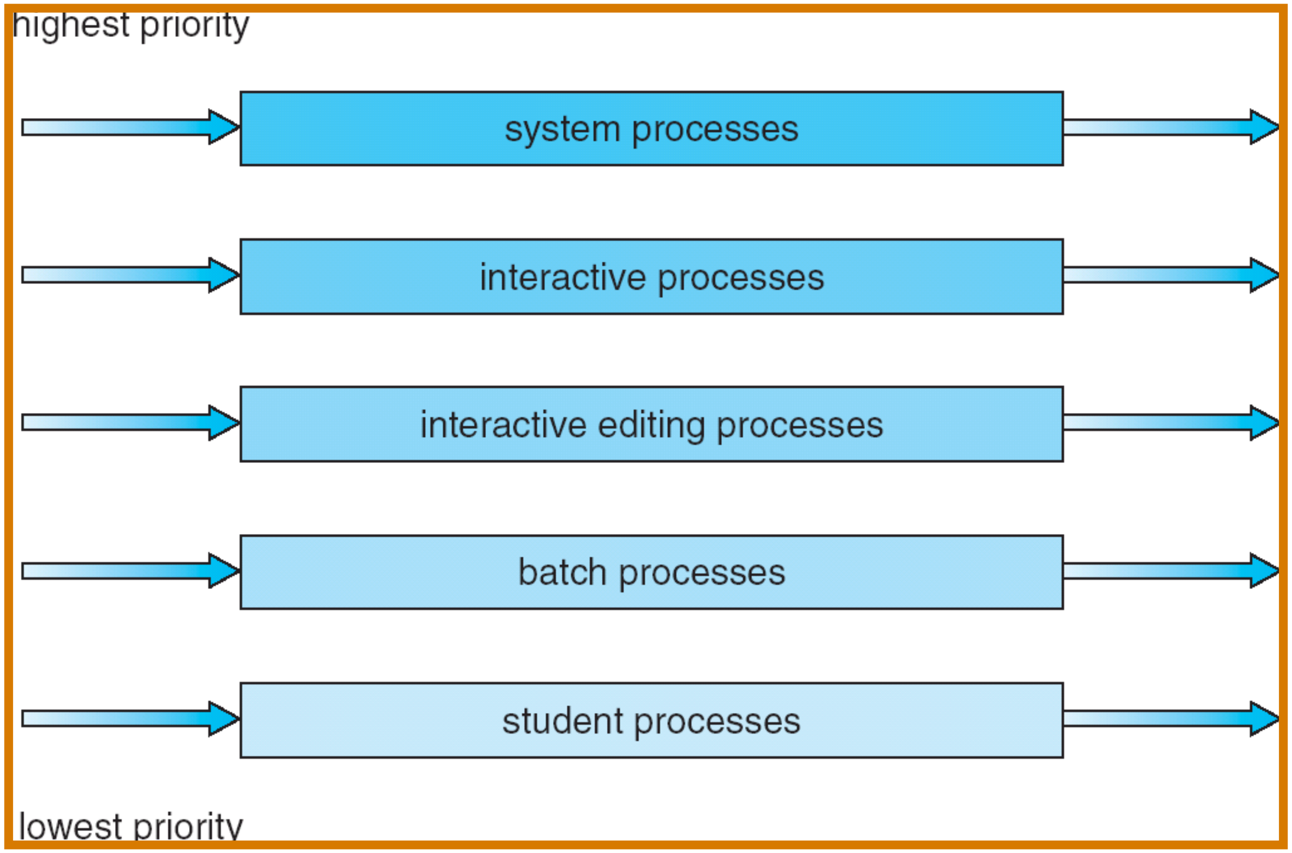
- **Any implementation turning the interrupts off for synchronization purposes, will not get full credits!**

- **The only place you are allowed to turn interrupts off is,** when coordinating data shared between a kernel thread and an interrupt handler. Because interrupt handlers can't sleep, they can't acquire locks.

Task 3: Implement Advanced Scheduler

- Implement Multi Level Feedback Queue Scheduler
- Priority donation not needed in the advanced scheduler – two implementations are not required to coexist
  - Only one is active at a time
- Advanced Scheduler must be chosen only if '–mlfqs' kernel option is specified
- Read section on 4.4 BSD Scheduler in the Pintos manual for detailed information
- Some of the parameters are real numbers and calculations involving them have to be simulated using integers.
  - Write a fixed-point layer (header file)

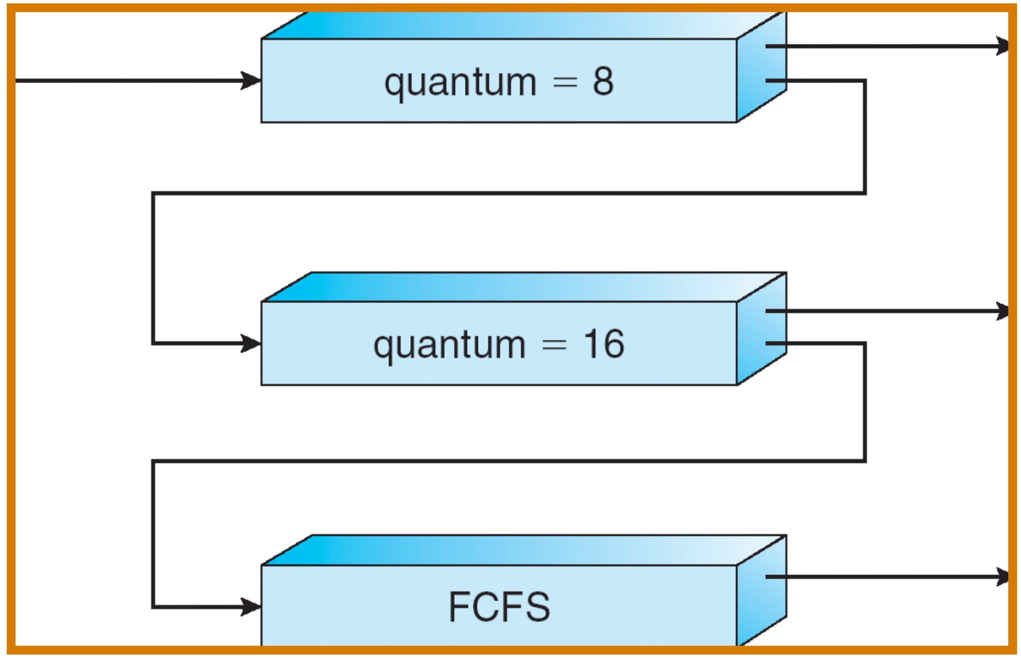
Multilevel Queue Scheduling



Multilevel Feedback Queue

- A process can move between the various queues; aging can be implemented this way
- Multilevel-feedback-queue scheduler defined by the following parameters:
  - number of queues
  - scheduling algorithms for each queue
  - method used to determine which queue a process will enter when that process needs service
  - method used to determine when to upgrade a process
  - method used to determine when to degrade a process

Example of Multilevel Feedback Queue

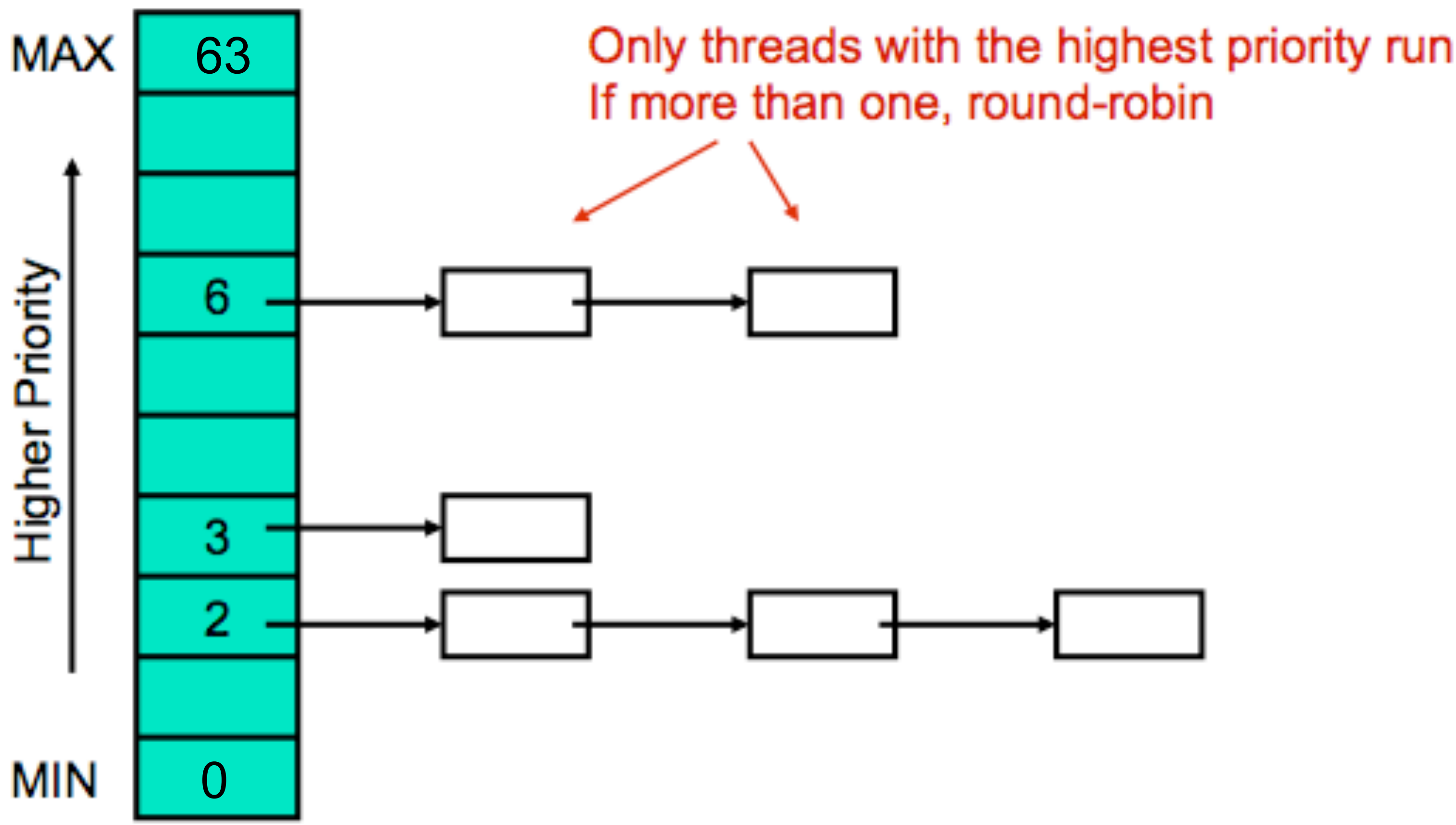


- Three queues:
  - Q_0 – RR with q = 8 ms
  - Q_1 – RR with q = 16 ms
  - Q_2 – FCFS

- Scheduling
  - A new job enters queue Q_0 which is served FCFS. When it gains CPU, job receives 8 milliseconds. If it does not finish in 8 milliseconds, job is moved to queue Q_1.
  - At Q_1 job is again served FCFS and receives 16 additional milliseconds. If it still does not complete, it is preempted and moved to queue Q_2.

4.4BSD Priority Based Scheduling

4.4BSD scheduler has 64 priorities and thus 64 ready queues, numbered 0 (PRI_MIN) through 63 (PRI_MAX).



Calculating Priority

- NOTE: Lower numbers correspond to lower priorities in 4.4BSD, so that priority 0 is the lowest priority and priority 63 is the highest.

- Every 4 clock ticks, calculate:

  priority = PRI_MAX - (recent_cpu / 4) - (nice * 2)

  (rounded down to the nearest integer)

- It gives a thread that has received CPU time recently lower priority for being reassigned the CPU the next time the scheduler runs. **Aging**

Nice Value

==> 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.

A negative nice, to the **minimum of -20**, tends to take away CPU time from other threads.

Calculating recent_cpu

- An array of n elements to track the CPU time received in each of the last n seconds 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:

  - **`recent_cpu(0) = 0`** *// or parent thread's value*
  - *at each timer interrupt,* **`recent_cpu++`** *for the running thread.*
  - *and once per second, for each thread:*

recent_cpu(t) = a * recent_cpu(t-1) + nice

where, **`a = (2*load_avg)/(2*load_avg + 1)`**

Calculating load_avg

- 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(t) = (59/60)*load_avg(t-1) + (1/60)*ready_threads

- ready_threads: number of threads that are either running or ready to run at the time of update

Functions to implement

- Skeletons of these functions are provided in “threads/threads.c”:

- `int thread_get_nice (void)`
- `void thread_set_nice (int new_nice)`

- `void thread_set_priority (int new_priority)`
- `int thread_get_priority (void)`

- `int thread_get_recent_cpu (void)`

- `int thread_get_load_avg (void)`

Suggested Order of Implementation

- Alarm Clock
  - easier to implement compared to the other parts
  - other parts not dependent on this
- Priority Scheduler
  - needed for implementing Priority Donation and Advanced Scheduler
- Priority Donation | Advanced Scheduler
  - these two parts are independent of each other
  - can be implemented in any order but only after Priority Scheduler is ready

Debugging your Code

- printf, ASSERT, backtraces, gdb
- Running pintos under gdb
  - Invoke pintos with the gdb option

    pintos --gdb -- run testname
  - On another terminal invoke gdb

    pintos-gdb kernel.o
  - Issue the command

    debugpintos
  - All the usual gdb commands can be used: step, next, print, continue, break, clear etc
  - Use the pintos debugging macros described in manual

Step 4: Testing

Pintos provides a very systematic testing suite for your project:

1. Run all tests:

```
$ make check
```

2. Run individual tests:

```
$ make tests/threads/alarm-multiple.result
```

3. Run the grading script:

```
$ make grade
```

make check

- **pass** tests/threads/alarm-single
- **pass** tests/threads/alarm-multiple
- **pass** tests/threads/alarm-simultaneous
- FAIL tests/threads/alarm-priority
- **pass** tests/threads/alarm-zero
- **pass** tests/threads/alarm-negative

- FAIL tests/threads/priority-change
- FAIL tests/threads/priority-donate-one
- FAIL tests/threads/priority-donate-multiple
- FAIL tests/threads/priority-donate-multiple2
- FAIL tests/threads/priority-donate-nest
- FAIL tests/threads/priority-donate-sema
- FAIL tests/threads/priority-donate-lower
- FAIL tests/threads/priority-fifo
- FAIL tests/threads/priority-preempt
- FAIL tests/threads/priority-sema
- FAIL tests/threads/priority-condvar
- FAIL tests/threads/priority-donate-chain

- FAIL tests/threads/mlfqs-load-1
- FAIL tests/threads/mlfqs-load-60
- FAIL tests/threads/mlfqs-load-avg
- FAIL tests/threads/mlfqs-recent-1
- **pass** tests/threads/mlfqs-fair-2
- **pass** tests/threads/mlfqs-fair-20
- FAIL tests/threads/mlfqs-nice-2
- FAIL tests/threads/mlfqs-nice-10
- FAIL tests/threads/mlfqs-block

Grading - Alarm Clock: 18 pts

- 4 pts - tests/threads/alarm-single
- 4 pts - tests/threads/alarm-multiple
- 4 pts - tests/threads/alarm-simultaneous
- 4 pts - tests/threads/alarm-priority
- 1 pts - tests/threads/alarm-zero
- 1 pts - tests/threads/alarm-negative

- If Alarm clock implementation is based on “busy-waiting” (-14 points)
- If interrupts are turned off as the only synchronization mechanism (-14 points)

Grading - Priority Scheduler: 38 pts

3 pts - tests/threads/priority-change
3 pts - tests/threads/priority-preempt
3 pts - tests/threads/priority-fifo
3 pts - tests/threads/priority-sema
3 pts - tests/threads/priority-condvar
3 pts - tests/threads/priority-donate-one
3 pts - tests/threads/priority-donate-multiple
3 pts - tests/threads/priority-donate-multiple2
3 pts - tests/threads/priority-donate-nest
5 pts - tests/threads/priority-donate-chain
3 pts - tests/threads/priority-donate-sema
3 pts - tests/threads/priority-donate-lower

Grading - MLFQ Scheduler: 37 pts

5 pts - tests/threads/mlfqs-load-1
5 pts - tests/threads/mlfqs-load-60
5 pts - tests/threads/mlfqs-load-avg
5 pts - tests/threads/mlfqs-recent-1
5 pts - tests/threads/mlfqs-fair-2
3 pts - tests/threads/mlfqs-fair-20
4 pts - tests/threads/mlfqs-nice-2
2 pts - tests/threads/mlfqs-nice-10
5 pts - tests/threads/mlfqs-block

Grading

TOTAL 105 points: 93 points for the implementation + 12 points for the design document:

- **18 points:** A completely working Alarm Clock implementation that passes all six (6) tests.
- **38 points:** A fully functional Priority Scheduler that passes all twelve (12) tests.
- **37 points:** A working advanced scheduler that passes all nine (9) tests.
- **12 points:** A complete design document.

make grade (1)

```
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

             3/ 3 tests/threads/priority-fifo
             3/ 3 tests/threads/priority-sema
             3/ 3 tests/threads/priority-condvar
```

make grade (2)

```
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

Grading - an important note!

- **CHECK CODE:** If Alarm clock implementation is based on "busy-waiting" (-14 points)

- **CHECK CODE:** If interrupts are turned off as the only synchronization mechanism (-14 points)

Step 5: Design Document

Use the template in Section 2.2.1 of the Pintos documentation.

```
                        ALARM CLOCK
                        ===========

---- DATA STRUCTURES ----

>> A1: 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.

---- ALGORITHMS ----

>> A2: Briefly describe what happens in a call to timer_sleep(),
>> including the effects of the timer interrupt handler.

>> A3: What steps are taken to minimize the amount of time spent in
>> the timer interrupt handler?

---- SYNCHRONIZATION ----

>> A4: How are race conditions avoided when multiple threads call
>> timer_sleep() simultaneously?

>> A5: How are race conditions avoided when a timer interrupt occurs
>> during a call to timer_sleep()?

---- RATIONALE ----

>> A6: Why did you choose this design?  In what ways is it superior to
>> another design you considered?
```

Submission

1. Design document
   - due by March 8th @11:59PM
   - submit using your submit_cse421 or submit_cse521 script

2. All source code (the full source tree)
   - due by March 29th @11:59PM
   - submit via AutoLab auto-grading system

Late Policy

Up to 24 hour late submission is accepted with 20% penalty:

❖ before 11:59pm on 3/29 --> no penalty

between 11:59pm on 3/29 and 11:59pm on 3/30 --> 20% penalty

after 11:59pm on 3/30 --> submission not accepted!