CSE 421/521 - Operating Systems
Fall 2019

Lecture - V

Project-1 Discussion

Tevfik Koşar

University at Buffalo

September 10th, 2019

Pintos Projects

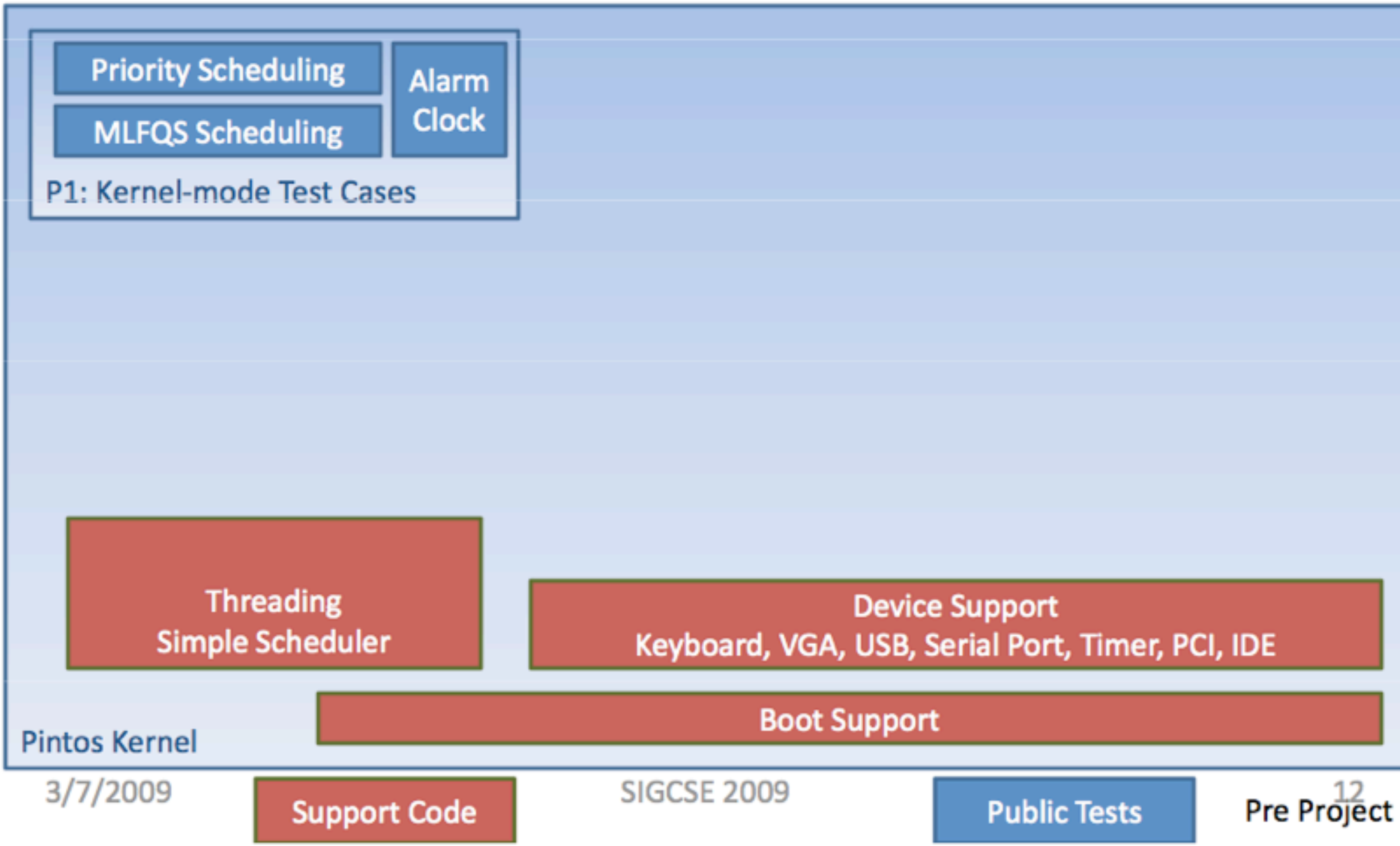
1. Threads <-- CSE 421/521 Project 1

2. User Programs

3. Virtual Memory

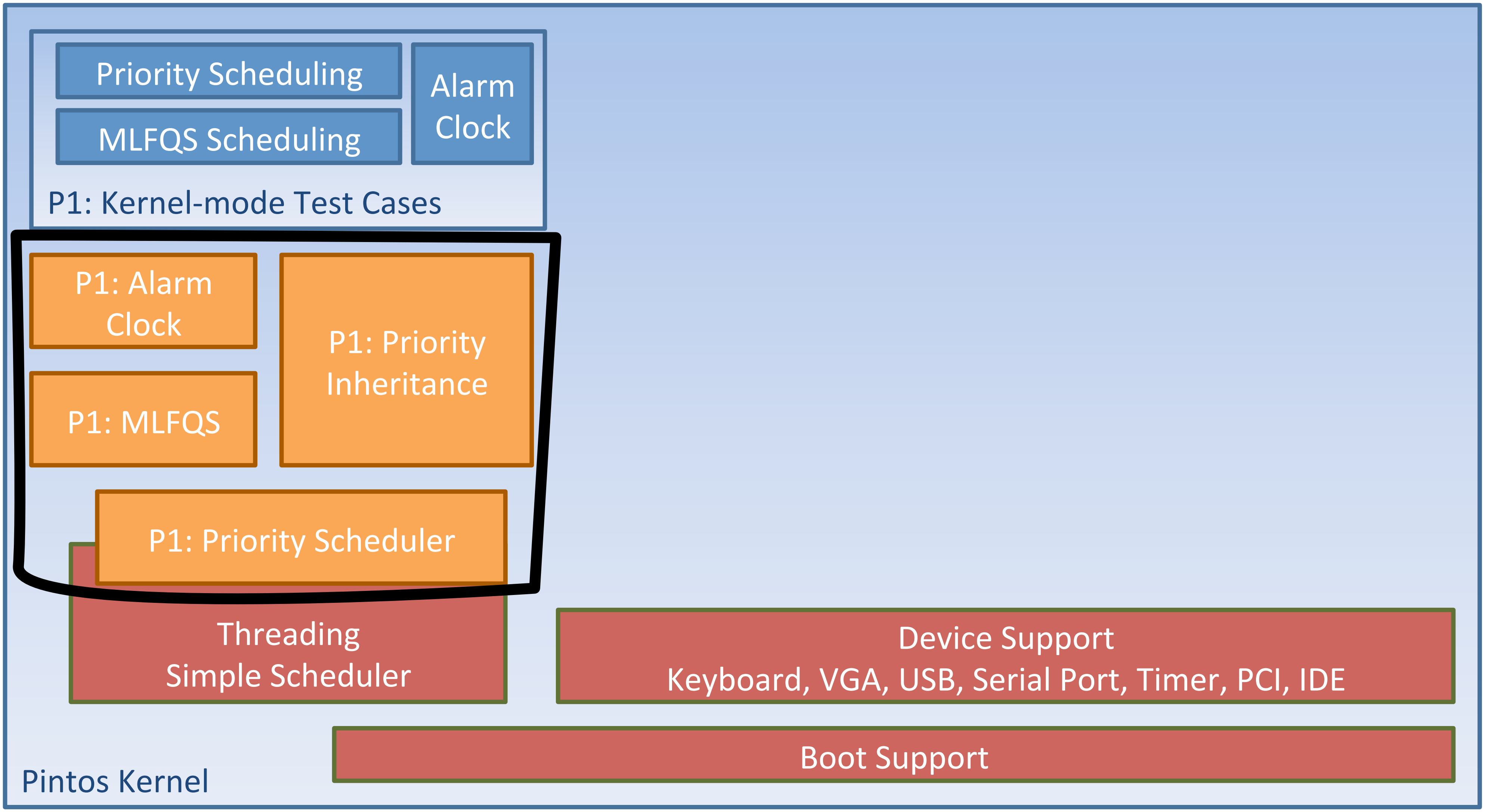
4. File Systems

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 2b: Verify Setup

- Compile
  - $ cd $PINTOSDIR/src/threads
  - $ make

- Test
  - $ cd build
  - $ pintos run alarm-multiple

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

Important Directories

- ***threads/***
  - Source code for the base kernel, which you will modify starting in project 1.
- ***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/kernel/***
  - Parts of the C library that are included only in the Pintos kernel. Feel free to reuse this code
- ***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.

Files of Interest

- ***thread.c* and *thread.h***
  - Basic thread support. Most of project 1 work. Also see struct thread.
- ***synch.c and synch.h***
  - Synchronization primitives which you can use in all projects
- ***devices/timer.c and devices/timer.h***
  - Timer ticks, has to be modified for project 1
- ***lib/kernel/list.c***
  - Linked list implementation, feel free to reuse
- ***init.c* and *init.h***
  - Kernel initialization, including main(), the kernel's "main program."

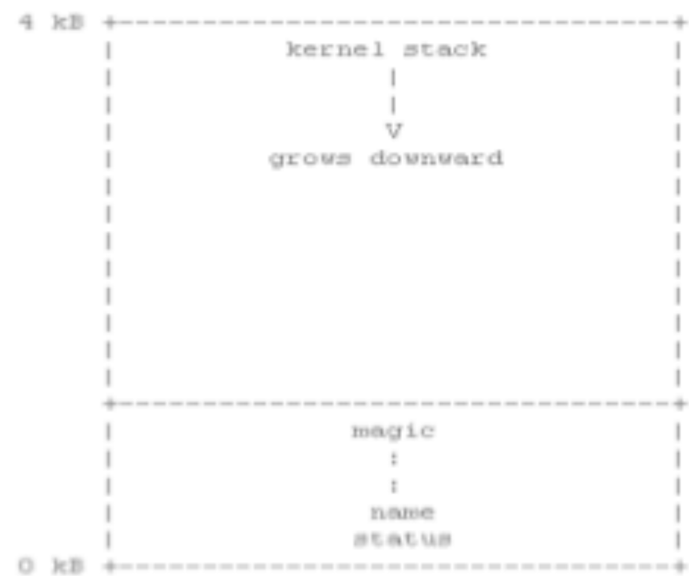
Pintos Thread System

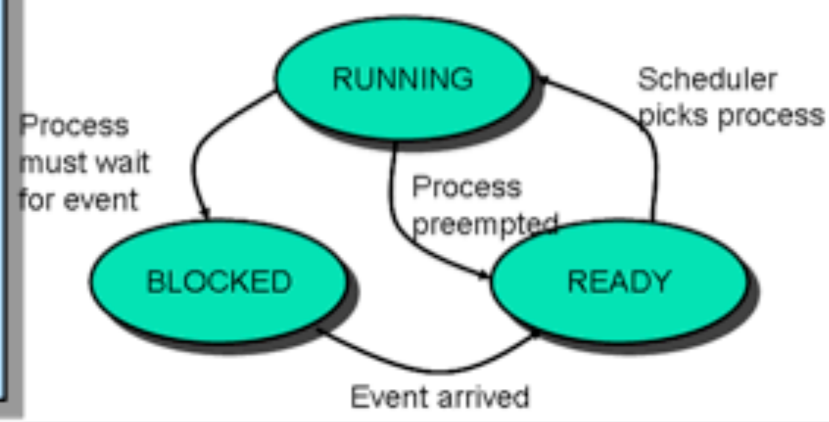
Defined in threads/thread.h:

```
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

=> Get rid of the while loop!

=> Put the thread in to the waiting queue

=> sema_down()   // the thread will be waken up when sema_up() is called

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

Task 2A: Implement Priority Scheduler

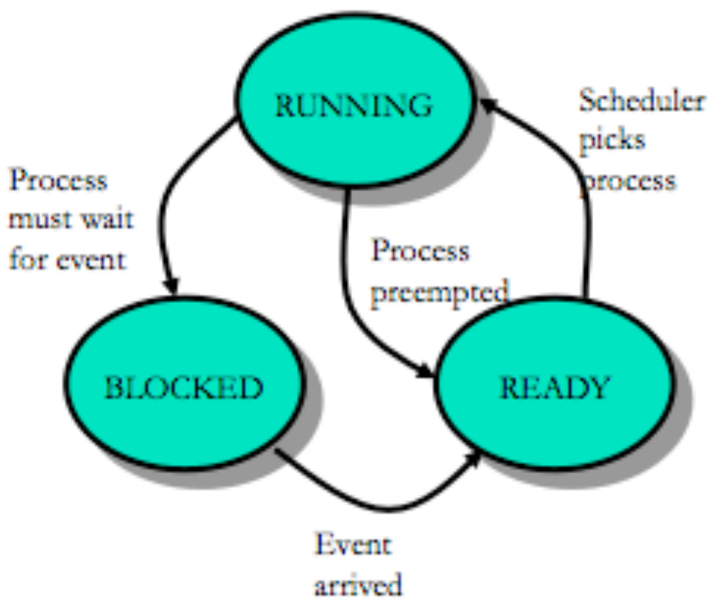
- Ready thread with highest priority gets the processor
- When a thread is added to the ready list that has a higher priority than the currently running thread, immediately yield the processor to the new thread
- When threads are waiting for a lock, semaphore or a condition variable, the highest priority 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

=> The default scheduler is very primitive, FCFS, and needs to be changed

=> Search the threads according to their priorities, and release highest…

=> You can reuse code from lib/kernel/list.c

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.

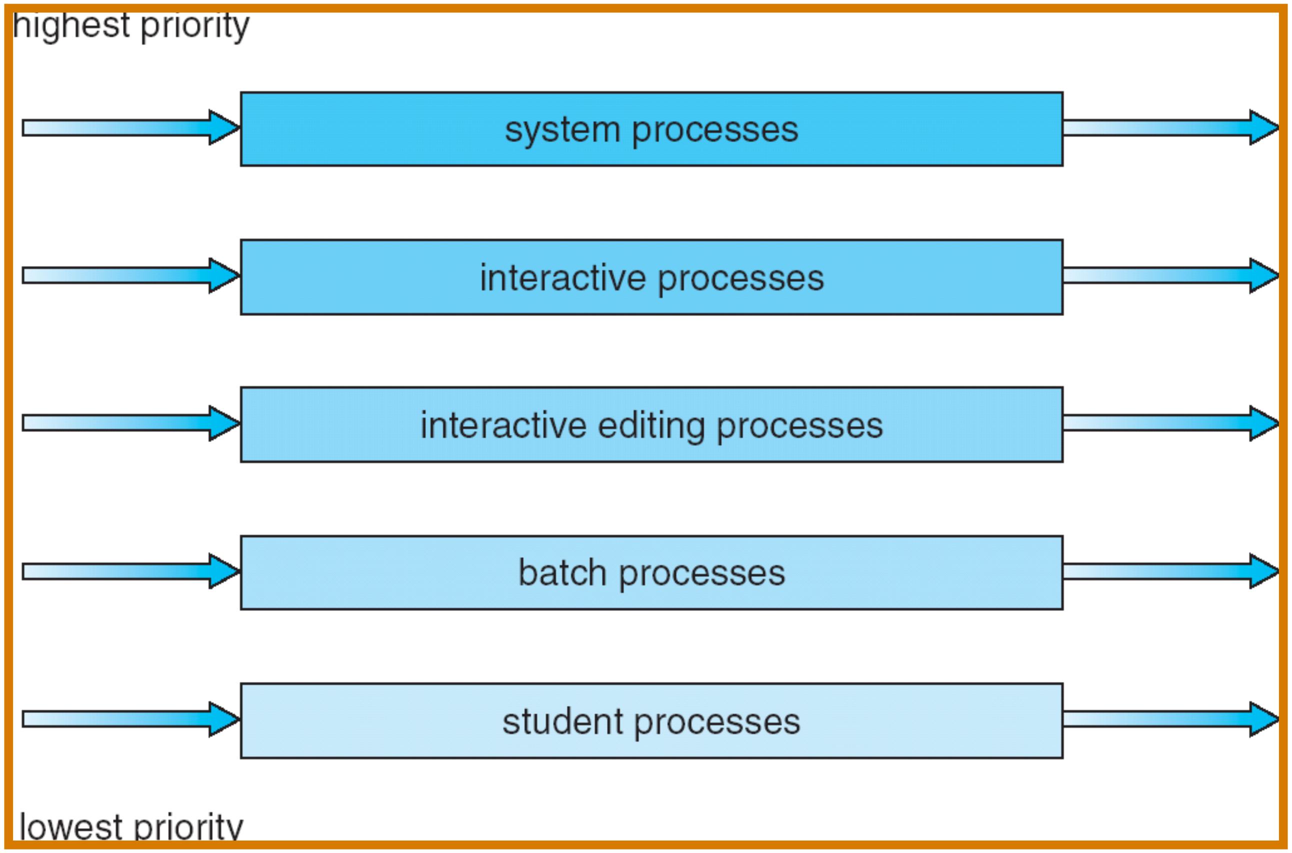
- **Any implementation turning the interrupts off for synchronization purposes, will not get full credits!**

- **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)

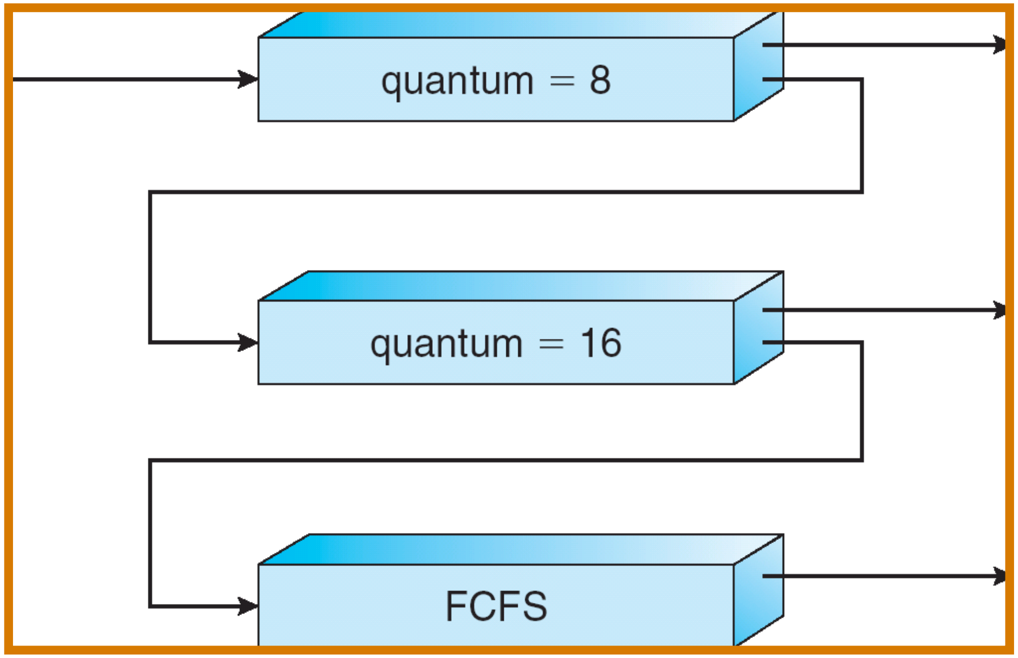
Multilevel Queue Scheduling



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

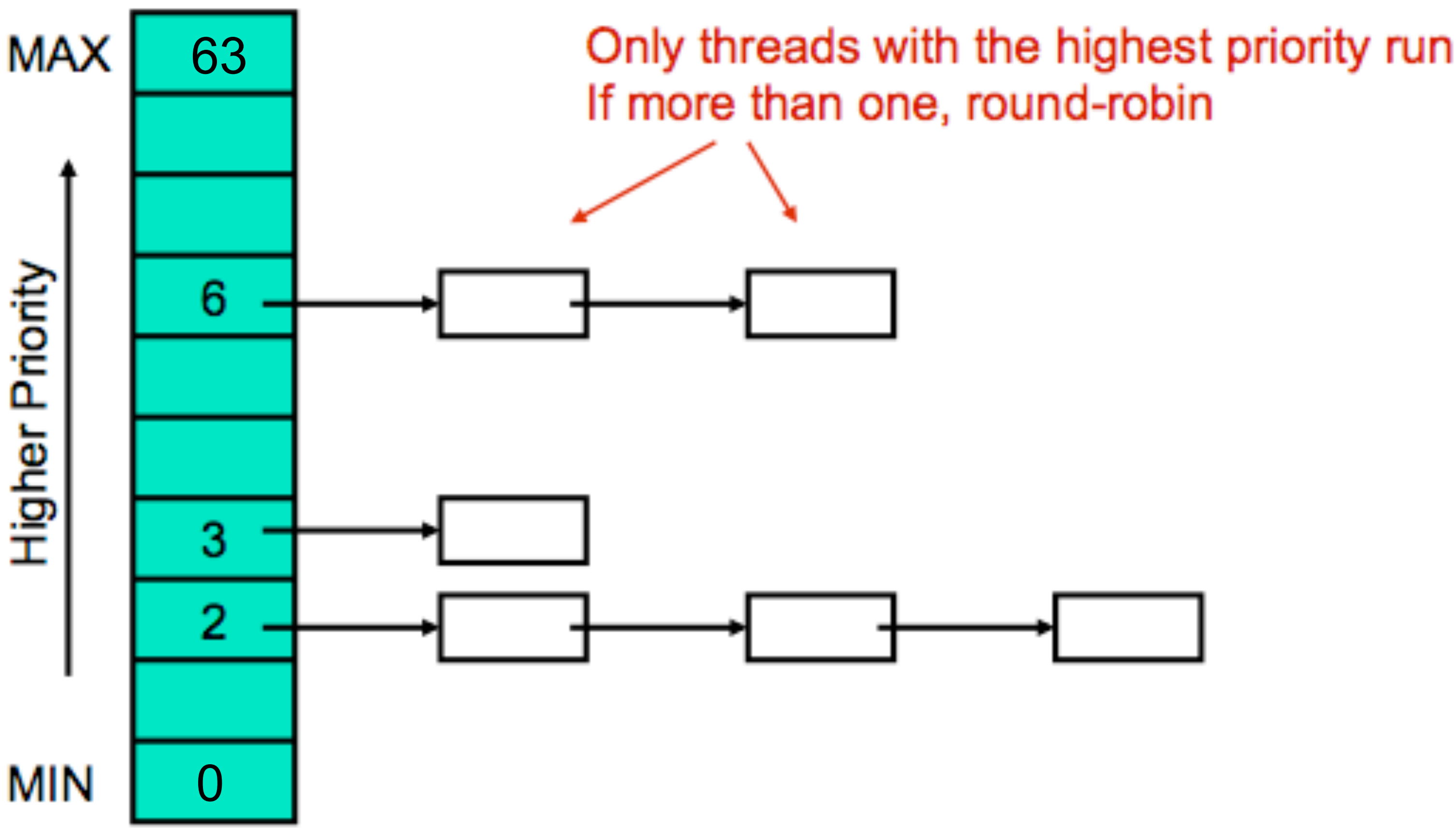


- Three queues:
  - Q_0 – RR with q = 8 ms
  - Q_1 – RR with q = 16 ms
  - Q_2 – FCFS

- 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

- will be implemented in **thread_get_recent_cpu(void)**

- 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

- will be implemented in **thread_get_load_avg(void)**
- 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 September 29th @11:59PM
   - submit using your submit_cse421 or submit_cse521 script

2. All source code (the full source tree)
   - due by October 20th @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 10/20 --> no penalty

  between 11:59pm on 10/20 and 11:59pm on 10/21 --> 20% penalty

  after 11:59pm on 10/21 --> submission not accepted!