Project #3: Threads

[CSE4070]

Fall 2019

Hyeongu Kang

Contents

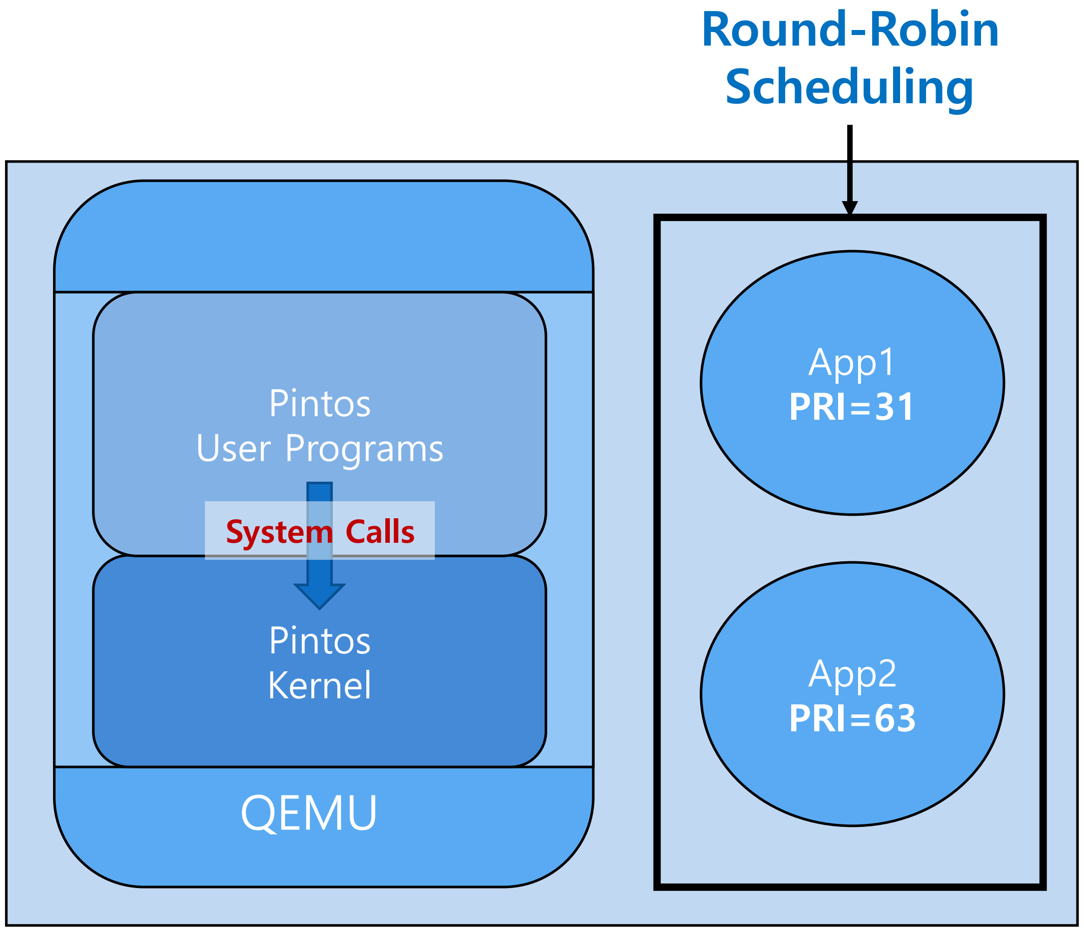
Notes

- "Project #3: Threads" in the class matches "Project 1: Threads" in Pintos document.
- You can find the information of this project in Chapter 2 of Pintos document.

Process Scheduling

Sketch of Pintos

- Until project #2, we focused on the things related with user programs.
  - User stack and argument passing
  - System call handler and system calls (using file system API)
  - Protecting inappropriate memory access
- Due to your efforts, current Pintos can run most of user programs which resides in src/examples.
- However, Pintos uses simple scheduler, round-robin scheduler.
- **It means Pintos doesn't consider the priority of each process or thread.**



Schedulers

- We've learned variety of schedulers in Chapter 5.
  - FIFO (First In, First Out)
  - SJF (Shortest Job First)
  - STCF (Shortest Time-to-Completion First)
  - RR (Round-Robin)
- Pintos uses **round-robin scheduler** as default scheduler.

Default Scheduler in Pintos

```c
void
thread_yield (void)
{
  struct thread *cur = thread_current ();
  enum intr_level old_level;

  ASSERT (!intr_context ());

  old_level = intr_disable ();
  if (cur != idle_thread)
    list_push_back (&ready_list, &cur->elem);
  cur->status = THREAD_READY;
  schedule ();
  intr_set_level (old_level);
}
```

`thread_yield()` push current thread at the end of the ready list and calls **`schedule()`**.

Default Scheduler in Pintos

```c
static void
schedule (void)
{
  struct thread *cur = running_thread ();
  struct thread *next = next_thread_to_run ();
  struct thread *prev = NULL;

  ASSERT (intr_get_level () == INTR_OFF);
  ASSERT (cur->status != THREAD_RUNNING);
  ASSERT (is_thread (next));

  if (cur != next)
    prev = switch_threads (cur, next);
  thread_schedule_tail (prev);
}
```

schedule() calls **next_thread_to_run()** to find next thread to be run

Default Scheduler in Pintos

```c
static struct thread *
next_thread_to_run (void)
{
  if (list_empty (&ready_list))
    return idle_thread;
  else
    return list_entry (list_pop_front (&ready_list), struct thread, elem);
}
```

next_thread_to_run() pops the first thread in the ready list

Default Scheduler in Pintos

```c
static void
schedule (void)
{
  struct thread *cur = running_thread ();
  struct thread *next = next_thread_to_run ();
  struct thread *prev = NULL;

  ASSERT (intr_get_level () == INTR_OFF);
  ASSERT (cur->status != THREAD_RUNNING);
  ASSERT (is_thread (next));

  if (cur != next)
    prev = switch_threads (cur, next);
  thread_schedule_tail (prev);
}
```

`schedule()` calls **`switch_threads()`** to switch process

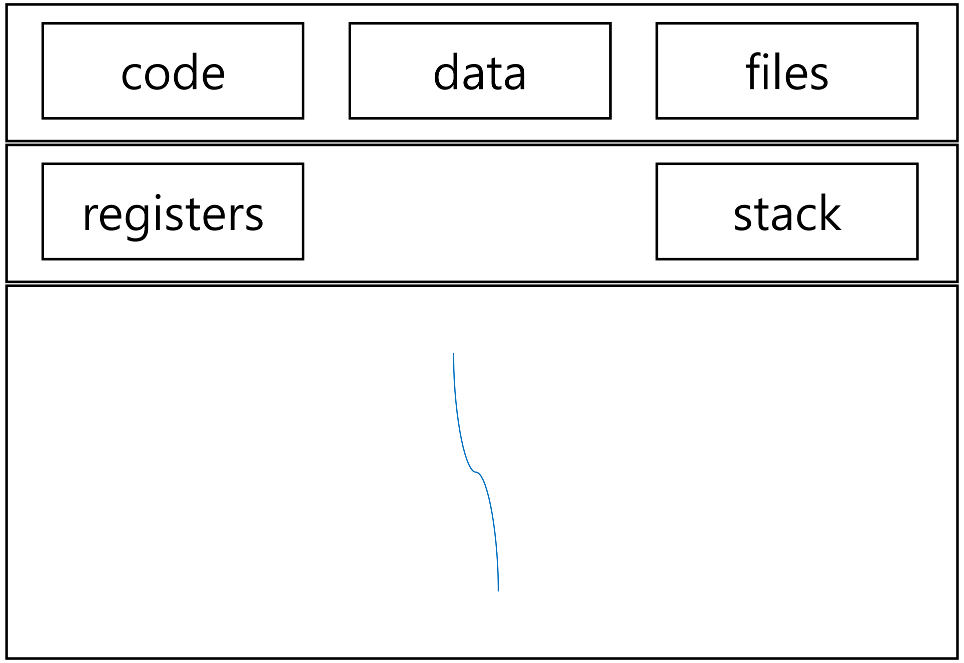
Schedulers

- Implement complex scheduler which considers thread's priority
- For scheduler, relevant components are threads and synchronization techniques.
- Threads are the objects of scheduling.
- Synchronization such as semaphores or locks should be used in the scheduler to arrange order of thread execution.

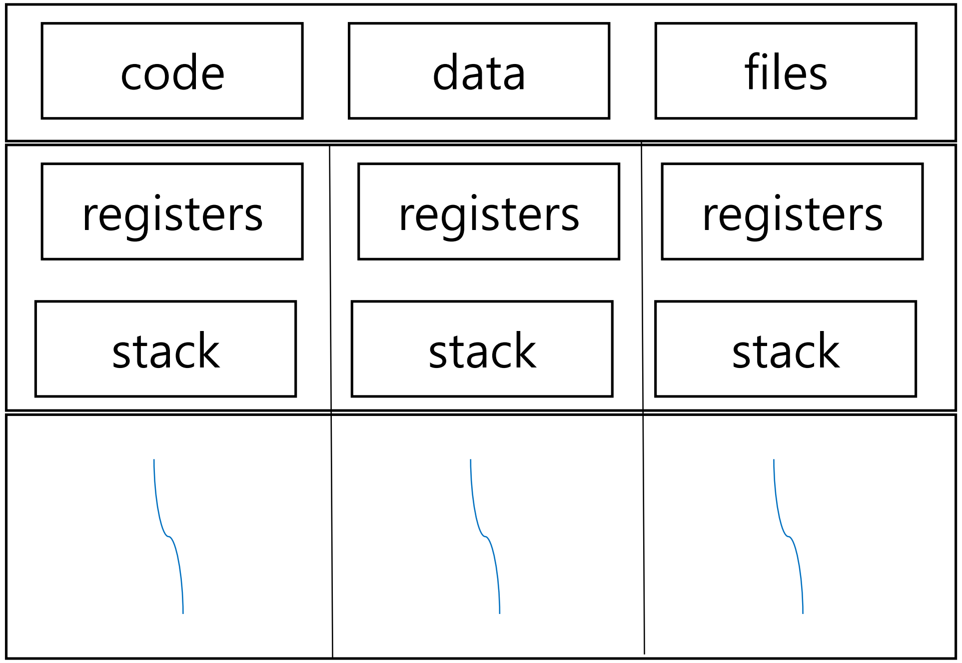
Threads

Threads

- A thread is a basic unit of CPU utilization.
- It shares code, data and other resources with other threads belonging to the same process.
- If a process only has one thread in it, we can consider this thread as a process.



Single-threaded process

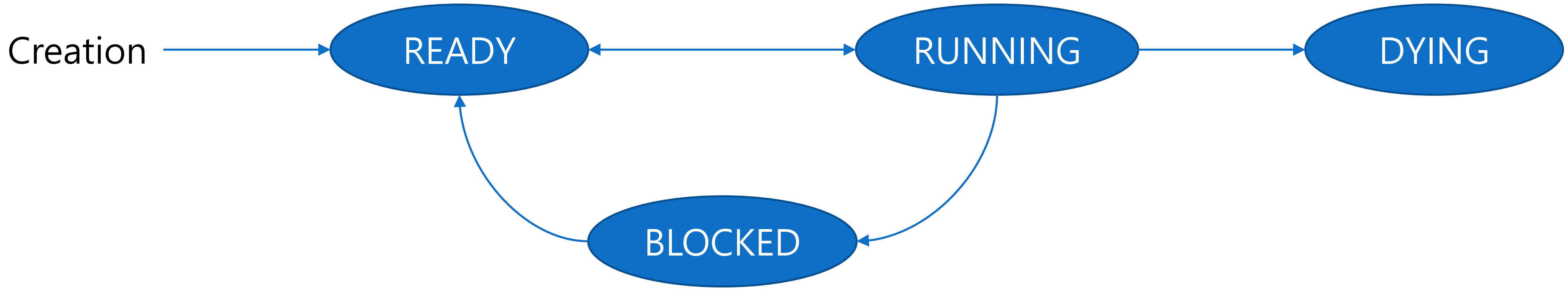


Multithreaded process

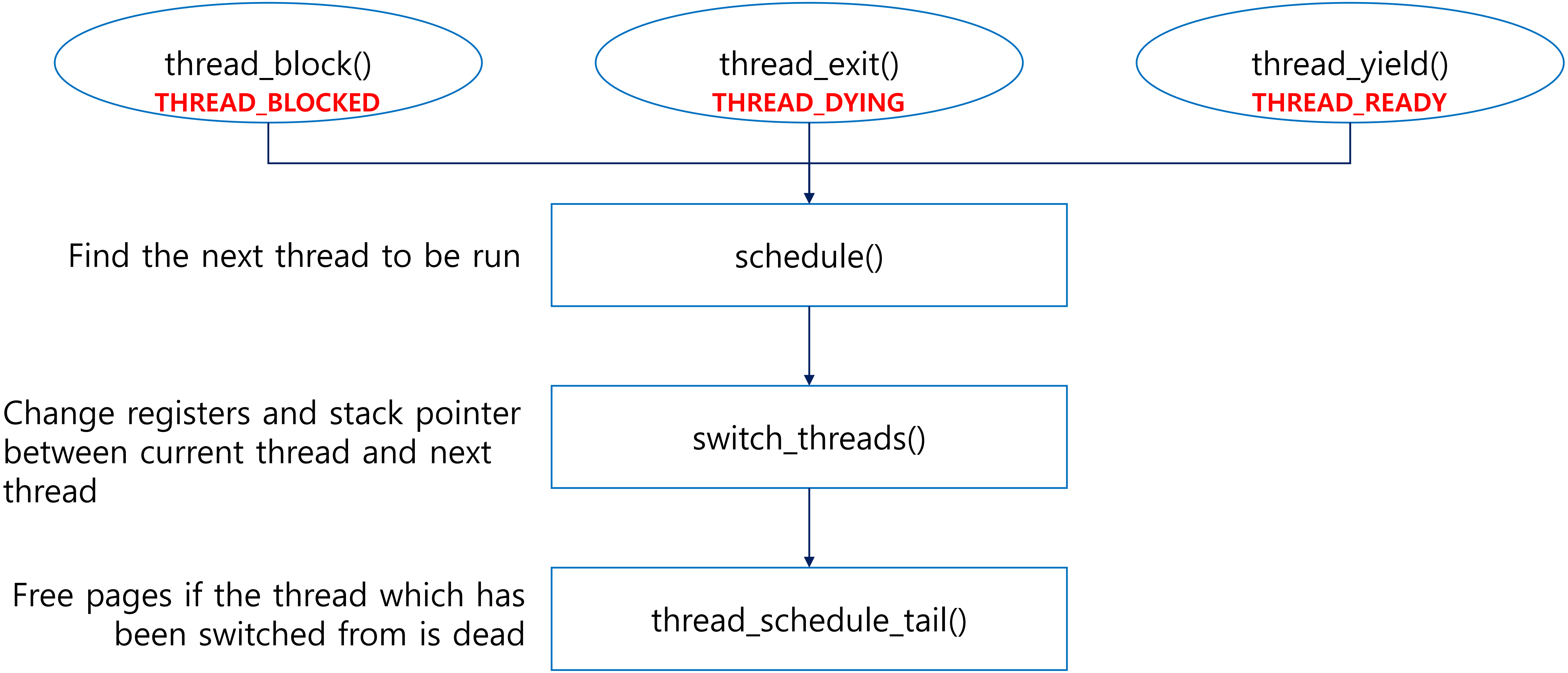
Thread Status

- A thread can have one of four status.

```
/* States in a thread's life cycle. */
enum thread_status
  {
    THREAD_RUNNING,     /* Running thread. */
    THREAD_READY,       /* Not running but ready to run. */
    THREAD_BLOCKED,     /* Waiting for an event to trigger. */
    THREAD_DYING        /* About to be destroyed. */
  };
```



Thread Switching



Synchronization

Semaphores

- **A semaphore is a nonnegative integer** with down and up operators.
- When sema_down() is called, if the value of semaphore is 0, the thread that calls sema_down() is blocked.
- sema_up() wakes up one of blocked threads.

```
void
sema_init (struct semaphore *sema, unsigned value)
{
  ASSERT (sema != NULL);

  sema->value = value;
  list_init (&sema->waiters);
}
```


※ threads/synch.c

Semaphores

- A semaphore is a nonnegative integer with down and up operators.
- When sema_down() is called, **if the value of semaphore is 0, the thread that calls sema_down() is blocked**.
- sema_up() wakes up one of blocked threads.

```c
void
sema_down (struct semaphore *sema)
{
  enum intr_level old_level;

  ASSERT (sema != NULL);
  ASSERT (!intr_context ());

  old_level = intr_disable ();
  while (sema->value == 0)
    {
      list_push_back (&sema->waiters, &thread_current ()->elem);
      thread_block ();
    }
  sema->value--;
  intr_set_level (old_level);
}
```


※ threads/synch.c

Semaphores

- A semaphore is a nonnegative integer with down and up operators.
- When sema_down() is called, if the value of semaphore is 0, the thread that calls sema_down() is blocked.
- sema_up() **wakes up one of blocked threads**.

```
void
sema_up (struct semaphore *sema)
{
  enum intr_level old_level;

  ASSERT (sema != NULL);

  old_level = intr_disable ();
  if (!list_empty (&sema->waiters))
    thread_unblock (list_entry (list_pop_front (&sema->waiters),
                                struct thread, elem));
  sema->value++;
  intr_set_level (old_level);
}
```


※ threads/synch.c

Locks

- Lock is a specialization of a semaphore with an **initial value of 1**.
- It also has two operators, acquire (equivalent of down in semaphore) and release (equivalent of up)

```
void
lock_init (struct lock *lock)
{
  ASSERT (lock != NULL);

  lock->holder = NULL;
  sema_init (&lock->semaphore, 1);
}
```


※ threads/synch.c

Locks

- Lock is a specialization of a semaphore with an initial value of 1.
- It also has two operators, **acquire (equivalent of down in semaphore)** and release (equivalent of up)

```
void
lock_acquire (struct lock *lock)
{
  ASSERT (lock != NULL);
  ASSERT (!intr_context ());
  ASSERT (!lock_held_by_current_thread (lock));

  sema_down (&lock->semaphore);
  lock->holder = thread_current ();
}
```


※ threads/synch.c

Locks

- Lock is a specialization of a semaphore with an initial value of 1.
- It also has two operators, acquire (equivalent of down in semaphore) and **release (equivalent of up)**

```
void
lock_release (struct lock *lock)
{
  ASSERT (lock != NULL);
  ASSERT (lock_held_by_current_thread (lock));

  lock->holder = NULL;
  sema_up (&lock->semaphore);
}
```


※ threads/synch.c

Requirements

- Alarm Clock
- Priority Scheduling
- Advanced Scheduler (BSD Scheduler)
  -> Additional

Alarm Clock

- timer_sleep() is used to let the thread fall asleep.
- It is implemented with busy waiting technique.
- Though it calls thread_yield() immediately when the timer is not expired, it's not efficient since the thread iterates between RUNNING state and READY state.
- Thus, we will modify this to avoid busy waiting.

```c
/* Sleeps for approximately TICKS timer ticks.  Interrupts must
   be turned on. */
void
timer_sleep (int64_t ticks)
{
  int64_t start = timer_ticks ();

  ASSERT (intr_get_level () == INTR_ON);
  while (timer_elapsed (start) < ticks)
    thread_yield ();
}
```

← Get current time

← Yield CPU until the "ticks" has gone by

Alarm Clock

- How to avoid busy waiting?
  - After checking that "ticks" has gone by, if not, block the thread (BLOCKED state).
  - To manage these threads, **create a new queue** to store it.
  - When the thread is inserted into the queue, wake up time should be saved as well.
  - When time is up, wake up the thread and insert it into ready queue (ready_list).

- How can you check that the time is up after the thread is blocked?
  - **`timer_interrupt()`** is called every tick.
  - Find the threads that need to be woken up in this function.
  - If it is the case, insert it into ready queue.

```c
/* Timer interrupt handler. */
static void
timer_interrupt (struct intr_frame *args UNUSED)
{
  ticks++;
  thread_tick ();
}
```

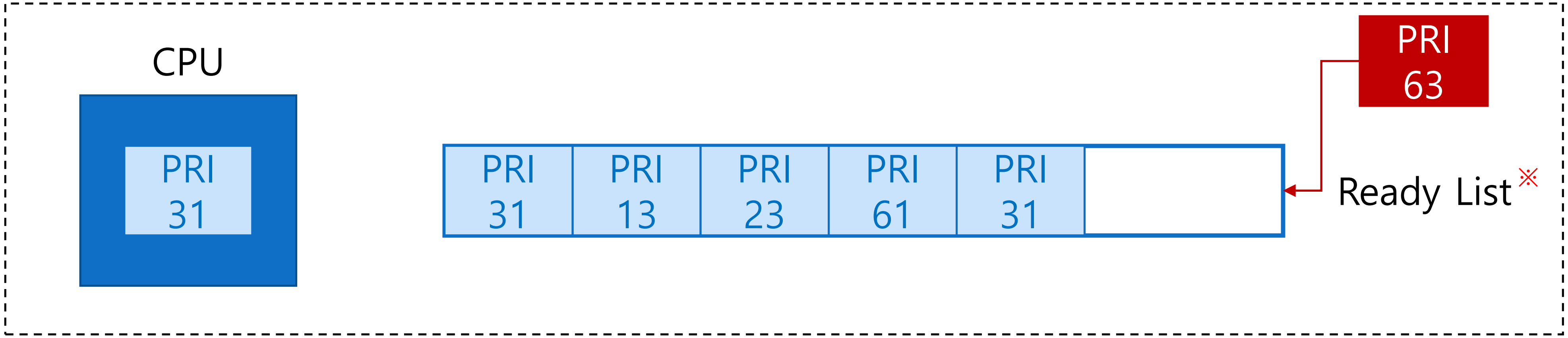
Priority Scheduling

- Until now, Pintos performs round-robin scheduling for threads.
- When thread_yield() or thread_unblock() is called, the current thread or unblocked thread are inserted at the end of the ready list regardless of its priority.

※ Ready list can be ordered in advance or scheduler can find the thread that has highest priority every time

Priority Scheduling

- In this project, we are to implement complex scheduler which considers priority of the threads.
- If there comes new thread that has higher priority than current thread in ready list, the current thread should immediately yield the CPU to new thread.

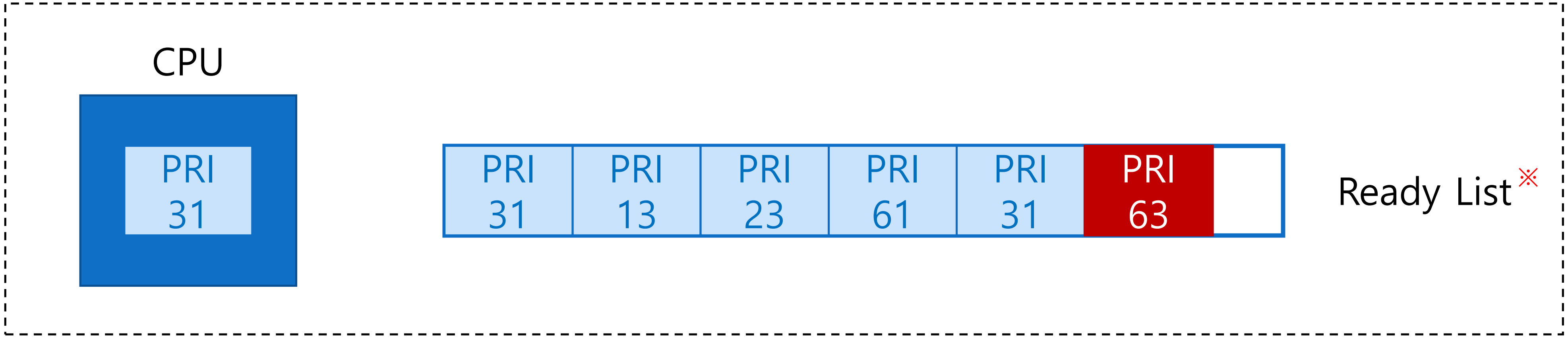


Priority Scheduler

※ Ready list can be ordered in advance or scheduler can find the thread that has highest priority every time

Priority Scheduling

- In this project, we are to implement complex scheduler which considers priority of the threads.
- If there comes new thread that has higher priority than current thread in ready list, the current thread should immediately yield the CPU to new thread.



Priority Scheduler

※ Ready list can be ordered in advance or scheduler can find the thread that has highest priority every time

Priority Scheduling

- Thread priorities range from PRI_MIN (0) to PRI_MAX (63).
- Default priority value is PRI_DEFAULT (31).
- Lower numbers correspond to lower priorities, so that priority 0 is the lowest and 63 is the highest.
- The initial thread priority is passed as an argument to thread_create ().

```
/* Thread priorities. */
#define PRI_MIN 0                       /* Lowest priority. */
#define PRI_DEFAULT 31                  /* Default priority. */
#define PRI_MAX 63                      /* Highest priority. */
```

Priority Scheduling

- Thread priorities range from PRI_MIN (0) to PRI_MAX (63).
- Default priority value is PRI_DEFAULT (31).
- Lower numbers correspond to lower priorities, so that priority 0 is the lowest and 63 is the highest.
- The initial thread priority is passed as an argument to thread_create ().

```
tid_t
thread_create (const char *name, int priority,
               thread_func *function, void *aux)
```

Priority Scheduling - Aging

- Default priority scheduling invokes starvation of processes which have low priority.
- Thus, we need aging technique that increases the priority in proportion to the time passed after the process resides in ready list.
- **Before implementing aging technique, modify the codes as in the next page.**
- The codes indicate that aging technique is used only when Pintos kernel gets -aging option and sets aging flag to TRUE.

Priority Scheduling - Aging

```c
#include <debug.h>
#include <list.h>
#include <stdint.h>
#include "threads/synch.h" /* Project #3. */

#ifndef USERPROG
/* Project #3. */
extern bool thread_prior_aging;
#endif

/* States in a thread's life cycle. */
enum thread_status
  {
    THREAD_RUNNING,     /* Running thread. */
    THREAD_READY,       /* Not running but ready to run. */
    THREAD_BLOCKED,     /* Waiting for an event to trigger. */
    THREAD_DYING        /* About to be destroyed. */
  };
```

src/threads/thread.h

```c
/* Scheduling. */
#define TIME_SLICE 4
static unsigned thread_ticks;

#ifndef USERPROG
/* Project #3. */
bool thread_prior_aging;
#endif

/* If false (default), use ro
   If true, use multi-level f
   Controlled by kernel comma
bool thread_mlfqs;
```

```c
      else if (!strcmp (name, "-rs"))
        random_init (atoi (value));
      else if (!strcmp (name, "-mlfqs"))
        thread_mlfqs = true;
#ifndef USERPROG
      /* Project #3. */
      else if (!strcmp (name, "-aging"))
        thread_prior_aging = true;
#endif
#ifdef USERPROG
      else if (!strcmp (name, "-ul"))
        user_page_limit = atoi (value);
#endif
```

src/threads/init.c

```c
  /* Enforce preemption. */
  if (++thread_ticks >= TIME_SLICE)
    intr_yield_on_return ();

#ifndef USERPROG
  /* Project #3. */
  thread_wake_up ();

  /* Project #3. */
  if (thread_prior_aging == true)
    thread_aging ();
#endif
```

src/threads/thread.c

Priority Scheduling - Aging

- **Replace tests to existing tests directory**
  - Extract threads_tests.tar and overwrite extracted directory to src/tests/threads

- How to implement aging
  - Check that **thread_prior_aging** is TRUE
  - If it is TRUE, increase the priority proportional to the time spent without occupying the CPU as tick is increased.

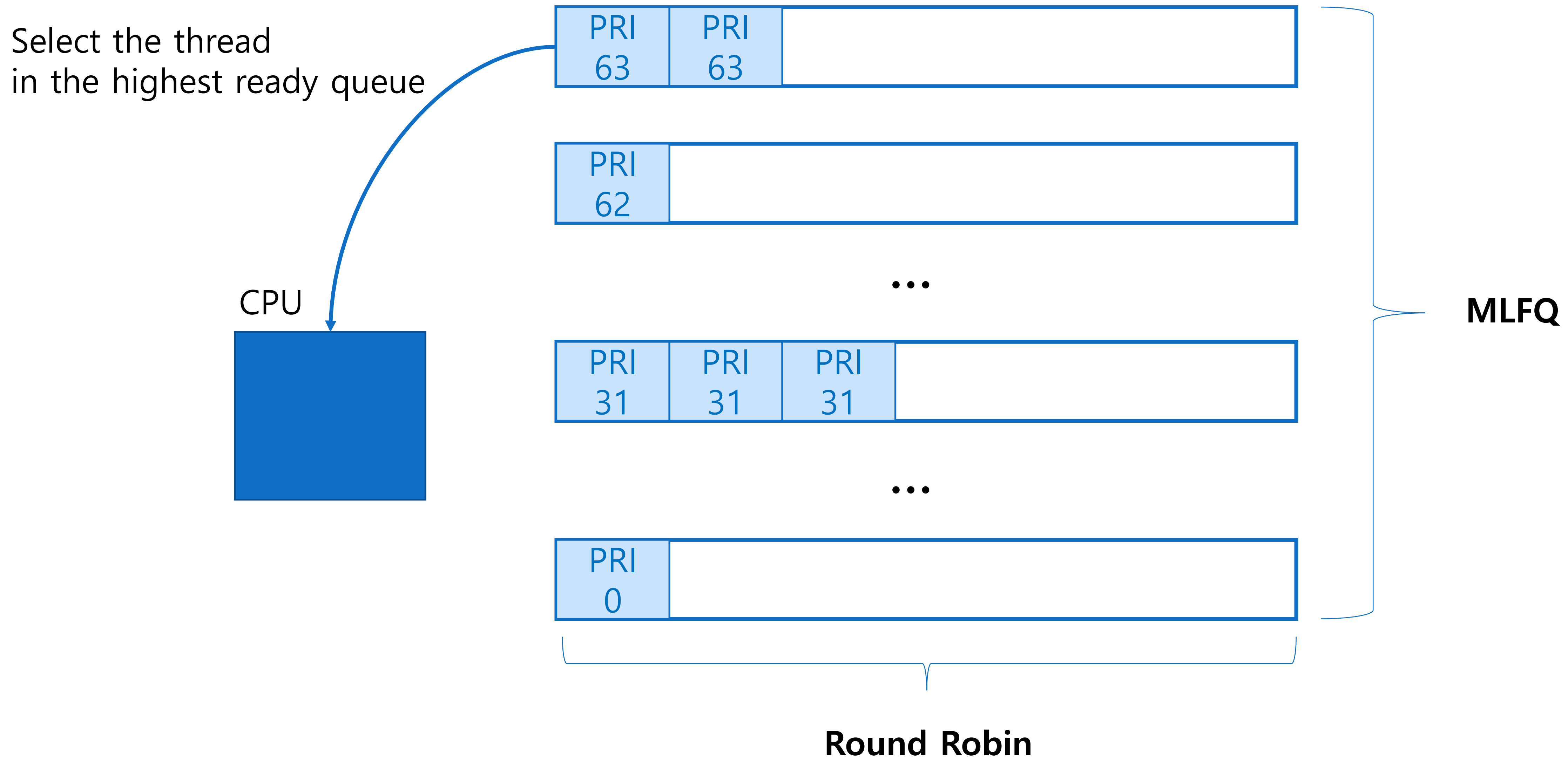
Advanced Scheduler - BSD Scheduler

- This is additional implementation of this project.
- You can find the information about this in Appendix B 4.4BSD Scheduler.

Advanced Scheduler - BSD Scheduler

- BSD scheduler is general purpose scheduler.
  - Multi-Level Feedback Queue (MLFQ) or Multi-Level Ready Queue (MLRQ) is generally used in general purpose scheduler.
  - Each priority has its own ready queue.
  - When schedule() is invoked, thread is selected from the highest priority queue.
  - Ready queue of each priority follows round robin policy.
- In this project, you can use MLFQs of 64 queues or MLFQ of 1 queue.
- MLFQs of 64 queues will be covered in this slide.

Advanced Scheduler - BSD Scheduler



Advanced Scheduler - Niceness

- Each thread in Pintos has **nice** value in the range from -20 to 20.
- Positive nice value lower the priority so that other threads can occupy CPU.
  - nice value 0 doesn't affect the priority.
- Initial nice value of the thread
  - If the thread is created initially, set nice value to 0.
  - If not, the thread starts with a nice value inherited from their parent thread.
- **Functions to implement**
  - int thread_get_nice (void)
    - Returns the current thread's nice value
  - void thread_set_nice (int new_nice)
    - Set the current thread's nice value to new_nice
    - Recalculates the thread's priority based on the new value
      - If the running thread no longer has the highest priority, yields

Advanced Scheduler - Calculating Priority

- Scheduler has priorities of 64 level.
  - Maximum priority: 63 (PRI_MAX)
  - Minimum priority: 0 (PRI_MIN)
  - 64 ready queues are generally used, but you can use only 1 ready queue.
- Calculating Priority
  - Initial priority is decided in thread_create()
  - Every 4 tick, priorities of all thread in the system are recalculated.
  - Formula for calculating priority
    - *priority* = PRI_MAX – (*recent_cpu* / 4) - (*nice* * 2)
    - *recent_cpu* : Estimate of the CPU time the thread has used recently
    - *nice:* nice value of the thread
    - Based on the formula of BSD scheduler, the thread that had much CPU time will get lower priority in the next scheduling.

Advanced Scheduler - Calculating recent_cpu

- *recent_cpu*
  - It estimates CPU time of the thread.
  - More recent CPU time should be weighted more heavily than less recent CPU time.
  - Initial recent_cpu value of the thread:
    - If it is created first, the value is 0.
    - If not, inherits value of the parent thread.
  - Whenever time interrupt is invoked, recent_cpu value of the thread in RUNNING state is increased by 1. (Except for idle thread)
- recent_cpu value of all thread (RUNNING, READY and BLOCKED) is recalculated every second.
  - $recent\_cpu = (2 * load\_avg) / (2 * load\_avg + 1) * recent\_cpu + nice$
  - *load_avg* : average of the number of thread in READY state
- **Functions to Implement**
  - Int thread_get_recent_cpu (void)
    - Returns 100 times the current thread's recent_cpu value
    - Rounded up to the nearest integer.

Advanced Scheduler - Calculating load_avg

- *load_avg*
  - System-wide value
  - Initialized to 0 when system is booted.
- load_avg value is updated every second.
  - *load_avg* = (59/60) * *load_avg* + (1/60) * *ready_threads*
  - *ready_threads* : number of thread in READY or RUNNING state (Except for idle thread)
- **Functions to Implement**
  - thread_get_load_avg (void)
    - Returns 100 times the current system load average,
    - Rounded to the nearest integer.

Advanced Scheduler - Summary

- Thread can manage nice value in range from -20 to 20.
- Range of priority: 0 (PRI_MIN) - 63 (PRI_MAX)
- Priority
  - Recalculate priority in every 4 ticks (same as TIME_SLICE)
    - *priority* = PRI_MAX – (*recent_cpu* / 4) - (*nice* * 2)
- *recent_cpu*
  - *recent_cpu* indicates recent CPU time of the thread.
  - recent_cpu value of the thread in RUNNING state is increased by 1 in every tick.
  - recent_cpu value of all thread is updated in every second (1sec = TIMER_FREQ)
    - *recent_cpu* = (2 * load_avg) / (2 * load_avg + 1) * *recent_cpu* + nice
- *load_avg*
  - Estimate the average of number of thread in READY state.
  - Initialized to 0 when it is booted.
  - load_avg value is updated in every second.
    - *load_avg* = (59/60) * *load_avg* + (1/60) * *ready_threads*

Advanced Scheduler - Fixed-Point Real Arithmetic

- Pintos kernel doesn't support floating point arithmetic.
- But in BSD scheduler, real numbers such as recent_cpu and load_avg are used.
- Fixed-point format is used instead of floating point arithmetic.
  - p.q format: p is integer and q is fraction
  - For 32-bit, 1 bit for sign, 17 bits for integer (p) and 14 bits for fraction (q)
- Example of fixed-point number
- 12.50 -> 1*2^3 + 1*2^2 + 1*2^(-1)
- Calculate 12.50 * 2^14 to represent 12.50 in fixed-point real arithmetic.

32 bit (4 Byte)

0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 . 1 0 0 0 0 0 0 0 0 0 0 0 0 0

1bit(sign) | 17 (p)bit | 14 (q)bit

Evaluation

- 13 tests will be graded.
  (Refer to the test case list in the next slide)
- Total score is 100 which consists of 80 for test cases and 20 for documentation.
- Refer to src/tests/threads/Grading, src/tests/threads/Rubric.alarm and src/tests/threads/Rubric.priority to check the points of each test.

Evaluation

- ✓alarm-single
- ✓alarm-multiple
- ✓alarm-simultaneous
- ✓alarm-priority
- ✓alarm-zero
- ✓alarm-negative
- ✓priority-change
- ✓priority-change-2
- ✓priority-fifo
- ✓**priority-lifo**
- ✓priority-preempt
- ✓priority-sema
- ✓priority-aging
- ✓Total : 13 tests

Evaluation

- priority-lifo can't be checked by make check
- Run the following command:
  - ✓ pintos –v -- -q run priority-lifo
- **Analyze the code and result of priority-lifo test in the documentation.**

Evaluation

- Additional Requirement
  - 5% additional point for BSD Scheduler implementation
    - Describe in the documentation where and how you implemented the BSD scheduler.
    - Mlfqs related tests will pass when implementing BSD Scheduler.

✓mlfqs-block
✓mlfqs-fair-2
✓mlfqs-fair-20
✓mlfqs-load-1
✓mlfqs-load-60
✓mlfqs-load-avg
✓mlfqs-nice-10
✓mlfqs-nice-2
✓mlfqs-recent-1
✓Total : 9 tests

Documentation

- Use the document file uploaded on e-class
- Documentation accounts for 20% of total score.
  (Development 80%, Documentation 20%)

Submission

- Before submission, check that you performed the following:
  1. **Make clean** before compressing **(in pintos/src directory)**
  2. Submission form (Refer to the next slide)
  3. Once you copy other's codes, you will get **F grade**

Submission

- Due date : **2019. 12. 8 23:59**
- Submission
  - The form of submission file is as follows:

Name of compressed file	Example (project 3, Group #7)
os_prj3_##.tar.gz	os_prj3_07.tar.gz

  - Only one person of group should submit the file.
  - **You should also submit the design document in hardcopy (AS916)**.
    (Due date of hardcopy is same as the compressed file)

Submission

- **Contents**
  ① Pintos source codes
  ② document: **document.doc** or **document.docx** (Other format is not allowed such as .hwp)

- **Form and way to submit**
  1) How to make tar.gz file
     - Run 'make clean' in pintos/src
     - Make new directory with your group number
     - Copy 'pintos' directory (not pintos/src) into the new directory
     - Copy the document file into the new directory
     - Compress the new directory into os_prj3_##.tar.gz **(tar -zcf os_prj3_[Group#].tar.gz ./[Group#])**
       ✓ **For example, if your group number is 7, tar -zcf os_prj3_07.tar.gz ./07**
       ✓ You should use -zcf options for using tar
  2) Way to submit: Upload the tar.gz file to e-class
     - **Submit Hardcopy to AS916 (You should submit softcopy and hardcopy both, if not 3% of point will be deducted)**
  3) Due date: 2019. 12. 8. 23:59

❖ **5% of point will be deducted for a wrong form and way to submit**
❖ **Late submission is allowed up to 3 days (~12/11) and 10% of point will be deducted per day**

Project Schedule

Projects	Points	Contents	Periods	Lectures
Project 0-1	1	Installing Pintos	9/16 – 9/22	Manual will be provided
Project 0-2	3	Pintos Data Structures	9/21 – 10/6	9/21 (Sat.)
Project 1	6	User Programs (1)	10/5 – 11/3	10/5 (Sat.)
Project 2	4	User Programs (2)	11/2 – 11/17	11/2 (Sat.)
Project 3	**6**	**Threads**	**11/16 – 12/8**	**11/16 (Sat.)**

※ Once you copy other's codes, you will get F grade