Project #3: Threads

Operating System (CSE4070) Project

Fall 2022

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Contents

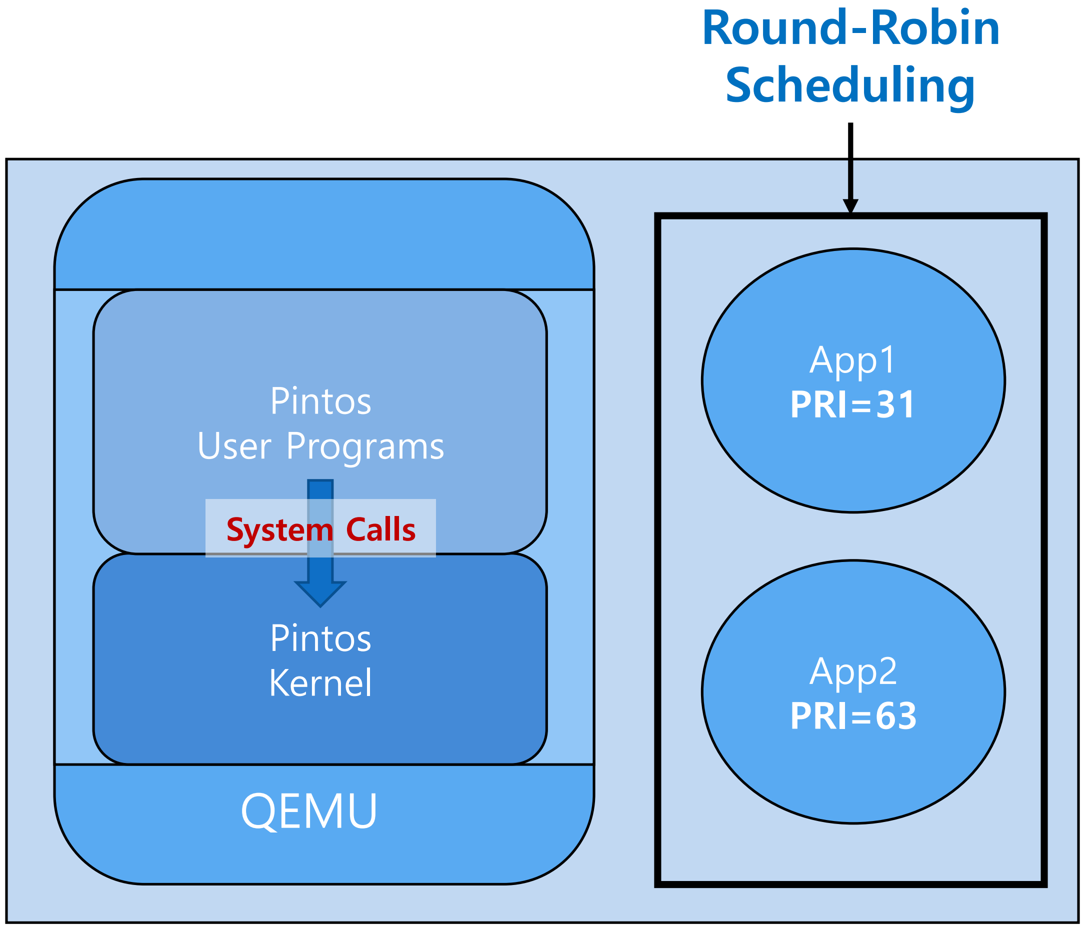
Notes

- "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 the class.
  - 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);
}
```

```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),
}
```

next_thread_to_run()
pops the first thread in the ready list

schedule() calls **next_thread_to_run()**
to find next thread to be run &
calls **switch_threads()** to switch process

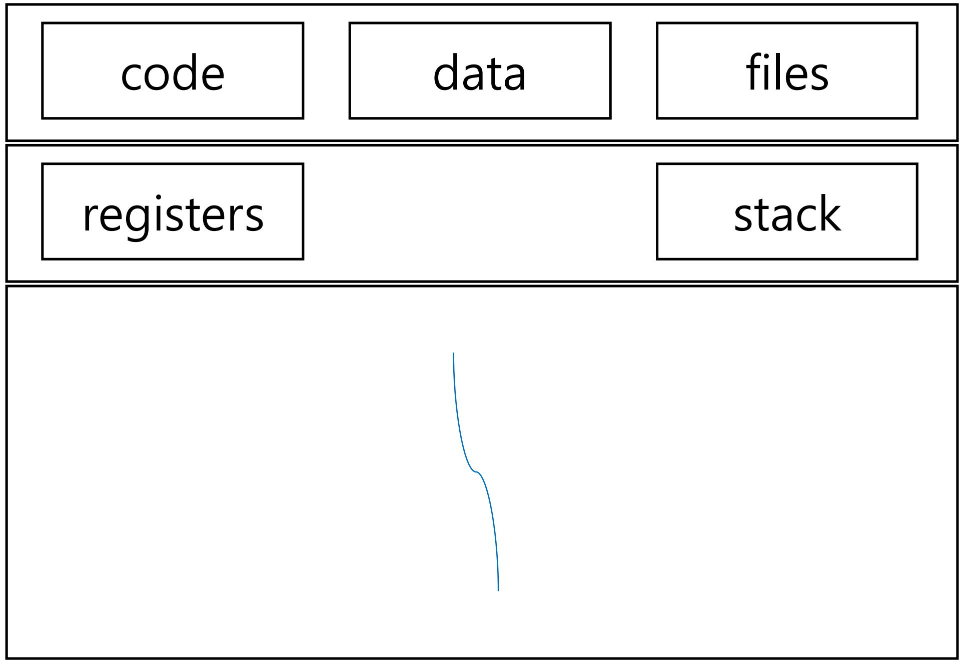
Schedulers

- Implement complex scheduler which considers thread's priority.
- Knowledge of threads and synchronization techniques are needed to improve scheduler.
- Threads are the objects of scheduling.
- Synchronization such as semaphores or locks should be used in the scheduler to organize order of thread execution.

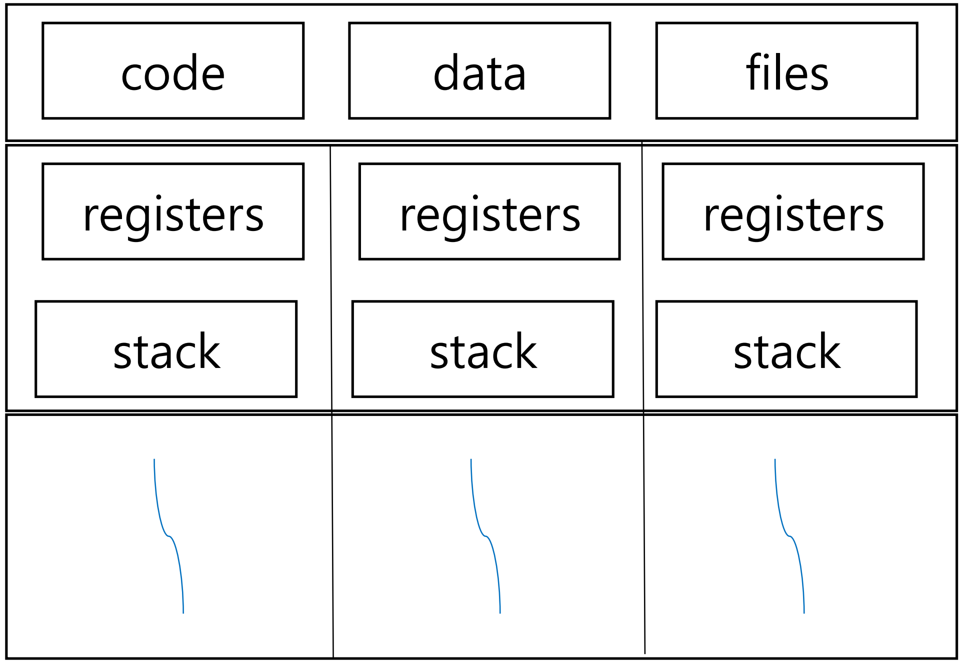
Threads

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

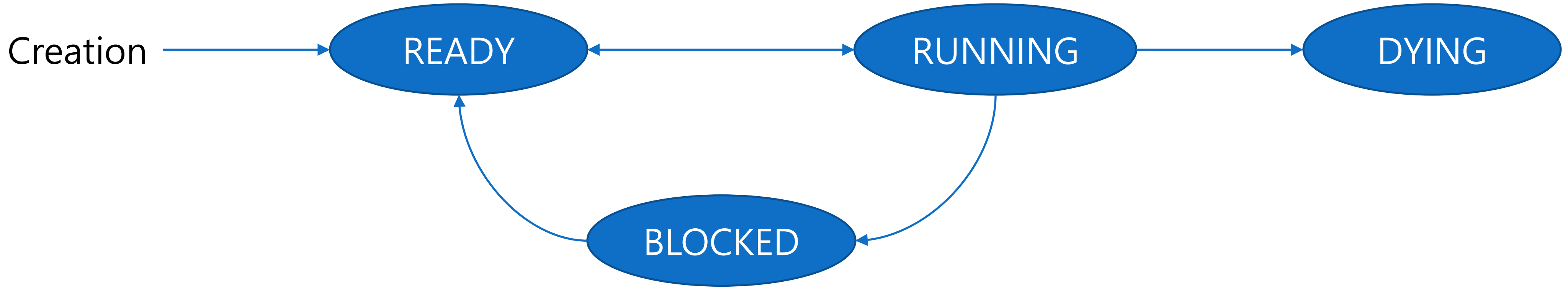


Multithreaded process

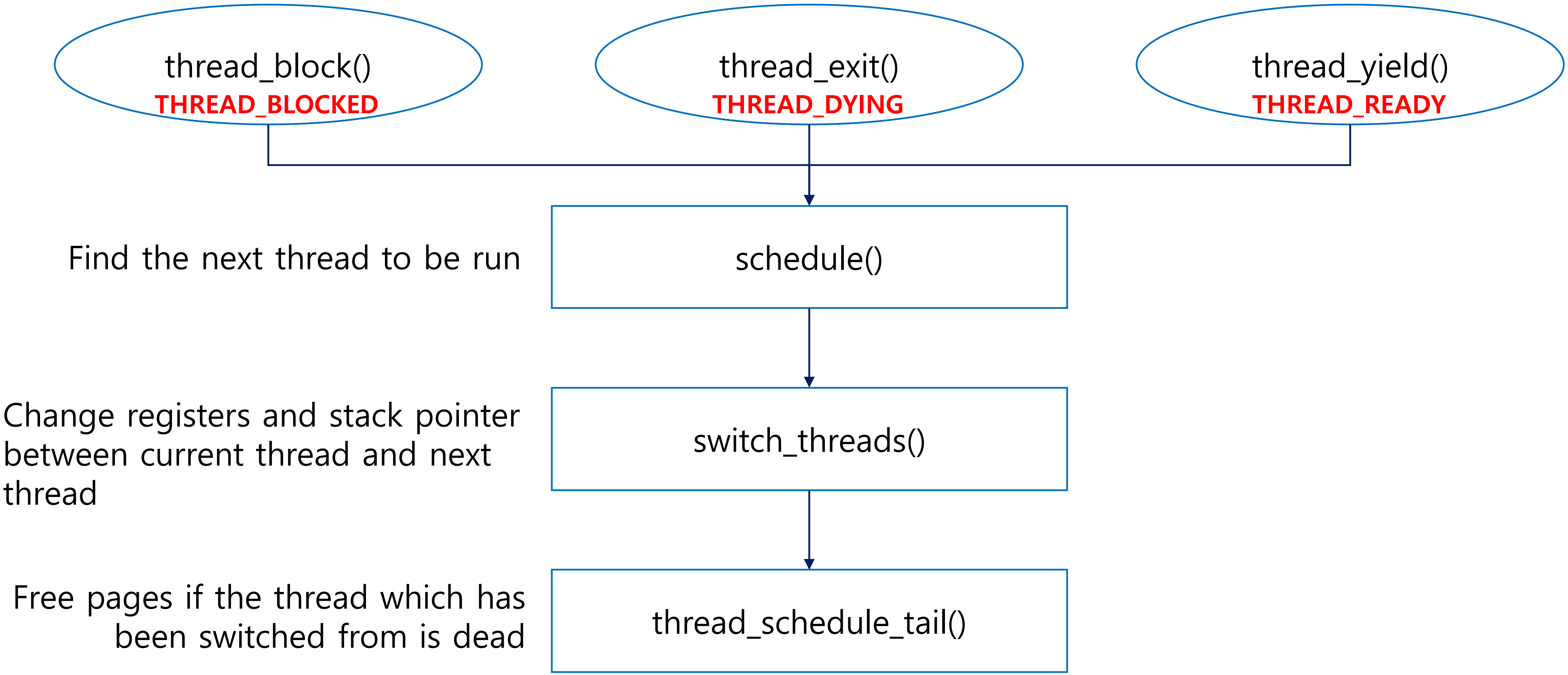
Thread Status

- 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);
}
```

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_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);
}
```

Semaphores

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- 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);
}
```

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

Requirements

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

Alarm Clock

- timer_sleep() is used to let the thread fall asleep.
- 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 inefficiency.

```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 inefficiency?
  - 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.
  - <u>**Find the threads that need to be woken up in this function.**</u>
  - If it is the case, insert it into ready queue.

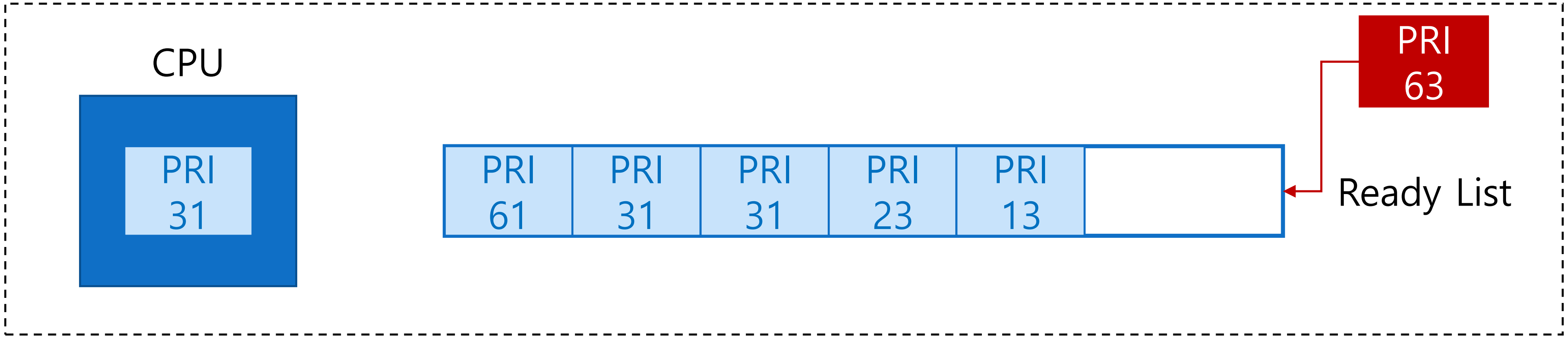
```c
/* Timer interrupt handler. */
static void
timer_interrupt (struct intr_frame *args UNUSED)
{
  ticks++;
  thread_tick ();
}
```

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.

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 the current thread, the current thread should immediately yield the CPU to new thread.



Priority Scheduler

Priority Scheduling

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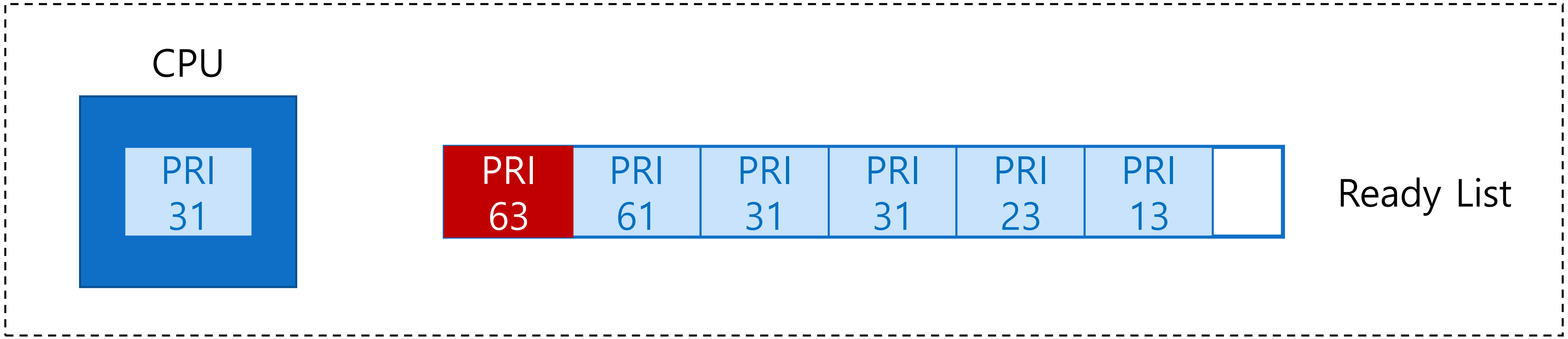

Priority Scheduler

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

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```
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
      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
/* 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
  /* 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 as the tick is increased.

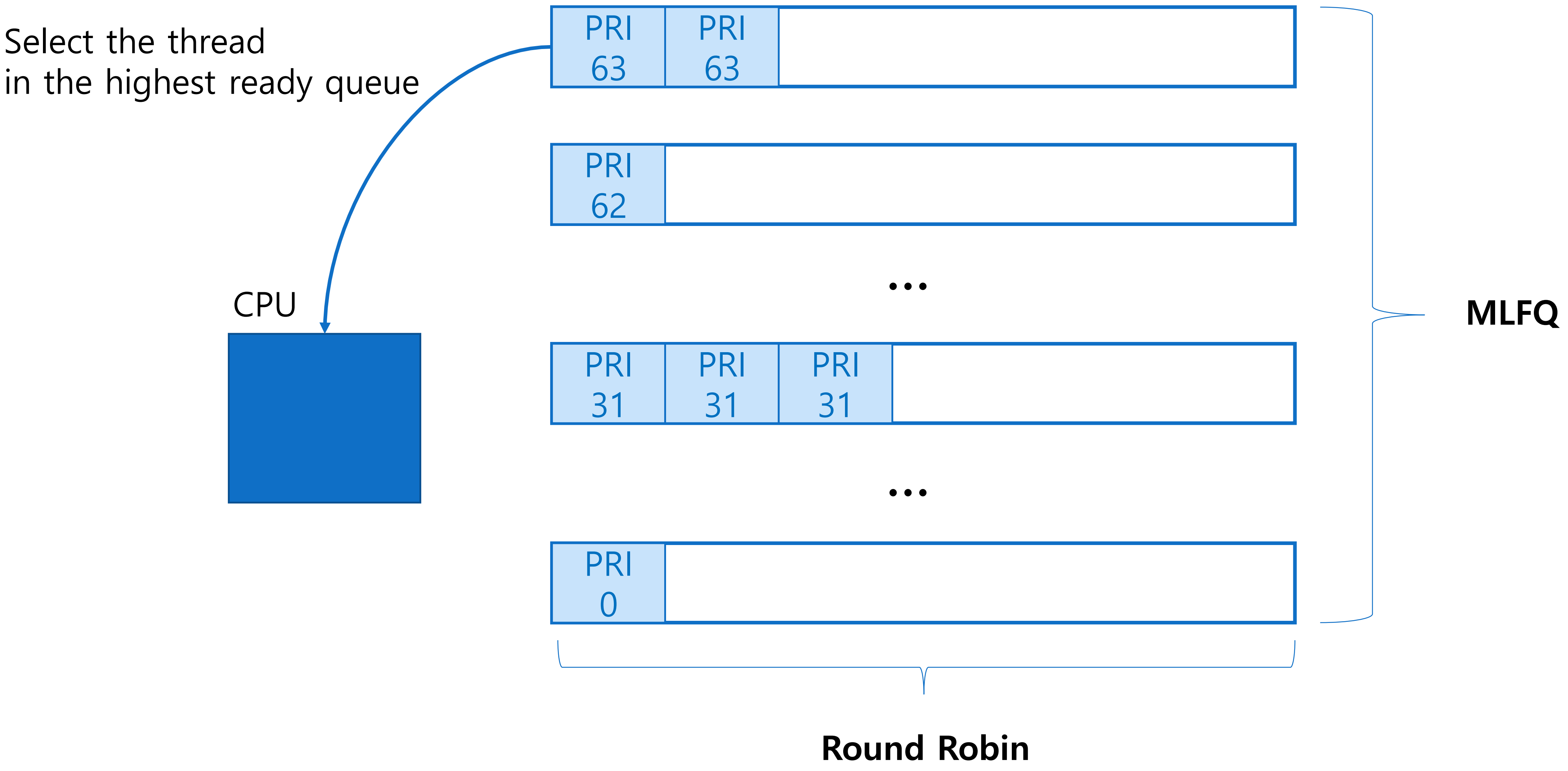
Advanced Scheduler - BSD Scheduler

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

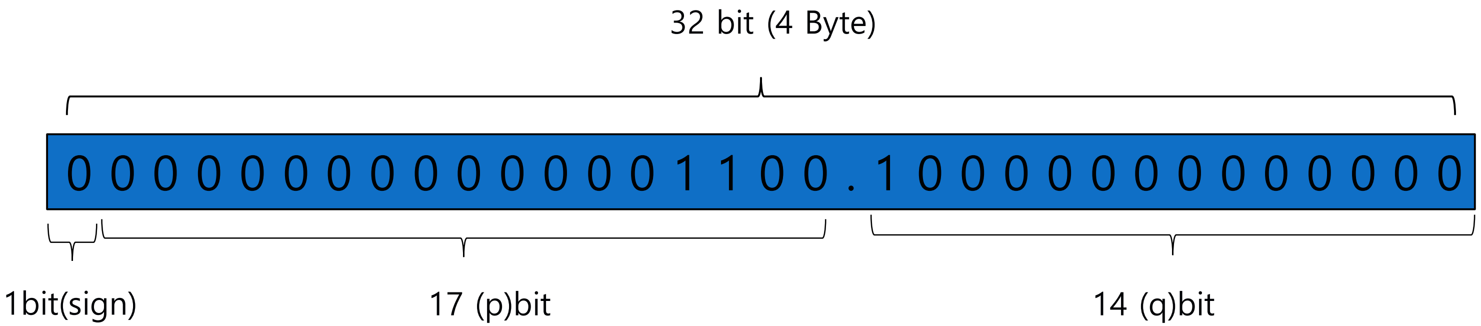
- load_avg
  - System-wide value
  - Initialized to 0 when system is booted.
- load_avg value is updated every second.
  - $load\_avg = (59/60) * load\_avg + (1/60) * ready\_threads$
  - *ready_threads* : number of thread in READY or RUNNING state (Except for idle thread)
- **Functions to Implement**
  - 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)



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
  - src/tests/threads/Rubric.priority

  to check the points of each test.

Evaluation

Alarm		
No.	**Test Case**	**Point**
1	alarm-single	4
2	alarm-multiple	4
3	alarm-simultaneous	4
4	alarm-priority	4
5	alarm-zero	1
6	alarm-negative	1
Total		18

Priority		
No.	**Test Case**	**Point**
1	priority-change	3
2	**priority-change2**	3
3	priority-fifo	3
4	priority-preempt	3
5	priority-sema	3
6	**priority-aging**	3
7	**priority-lifo**	3
Total		21

Evaluation

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

Evaluation

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

No.	Test Case	Point
1	mlfqs-load-1	5
2	mlfqs-load-60	5
3	mlfqs-load-avg	3
4	mlfqs-recent-1	5
5	mlfqs-fair-2	5
6	mlfqs-fair-20	3
7	mlfqs-nice-2	4
8	mlfqs-nice-10	2
9	mlfqs-block	5
Total		37

Documentation

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

Evaluation

- Total score:

$$\left(\frac{\mathbf{Alarm}}{\mathbf{18}} \times \mathbf{40} + \frac{\mathbf{Priority}}{\mathbf{21}} \times \mathbf{60} + \frac{\mathbf{Mlf}\boldsymbol{qs}}{\mathbf{37}} \times \mathbf{5}\right) / \mathbf{100} \times \mathbf{80}$$

Submission

- Make 'ID' directory and copy **'src' directory** in the pintos directory and the document file (**[ID].docx**).
- Compress 'ID' directory to '**os_prj3_[ID].tar.gz**'.
- We provide the script 'submit.sh' to make tar.gz file which contains 'src' directory and document file.
  학생들의 편의를 위해 pintos 디렉토리 내 submit.sh 스크립트를 제공합니다.
  이 스크립트는 src 디렉토리와 document file을 포함한 tar.gz 파일을 생성합니다.
- **Disclaimer**
  - **Any result produced from the 'submit.sh' script is at your own risk.**
  - **You must check the contents of the tar.gz file before submission.**
  - **'submit.sh' 스크립트로 생성된 결과의 모든 책임은 사용자에게 귀속됩니다.**
  - **제출하기 전, tar.gz 파일의 내용물을 반드시 다시 한 번 체크하기 바랍니다.**

Submission

- **Notice – ‘submit.sh’**
  - The ‘submit.sh’ script should be executed on a directory where ‘src’ folder is located.
    submit.sh 스크립트는 src 폴더가 위치한 디렉토리에서 실행되어야 합니다.
  - ‘ID’ folder should not be in the directory.
    해당 디렉토리에 ‘학번’ 폴더가 없어야 합니다.
  - ‘ID.docx’ file should be located in the directory.
    Also, report file with extensions other than ‘docx’ will not be compressed.
    해당 디렉토리에 ‘학번.docx’ 파일이 있어야 함께 압축됩니다.
    또한 ‘docx’ 이외의 확장자를 가진 보고서 파일은 압축되지 않습니다.
  - Be sure to backup your code in case of an unexpected situation.
    만일의 경우를 대비해 반드시 코드를 백업하여 주세요.

Submission

- It is a **personal project**.
- Due date : **2022. 12. 5 23:59**
- Submission
  - The form of submission file is as follows:

Name of compressed file	Example (ID: 20189999)
os_prj3_[ID].tar.gz	os_prj3_20189999.tar.gz

  - No hardcopy.
  - **Copy will get a penalty (1st time: 0 Point and downgrading, 2nd time: F grade)**

Submission

- **Contents**
  ① Pintos source codes (Only **'src' directory** in pintos directory)
  최소한의 용량을 위해 **src 디렉토리만** 압축파일에 포함합니다.
  ② Document: **[ID].docx** (e.g. 20189999.docx; Other format is not allowed such as .hwp)
- **How to submit**
  1) Make tar.gz file.
     - Copy the document file ([ID].docx) to pintos directory.
     - **Execute submit.sh script in the pintos directory and follow the instructions of the script.**
       pintos 디렉토리 내의 submit.sh 스크립트를 실행하고 스크립트의 지시를 따르십시오.
     - Check that **os_prj3_[ID].tar.gz** is created.
     - Decompress **os_prj3_[ID].tar.gz** and check the contents in it. ($ **tar -zxf os_prj3_[ID].tar.gz**)
       (Only **[ID].docx** and **src** directory should be contained in the tar.gz file.)
     - For example, if your ID is 20189999, os_prj3_20189999.tar.gz should be created.
       To decompress the tar.gz file, execute **tar -zxf os_prj3_20189999.tar.gz**
     - **Please check the contents of tar.gz file after creating it.**
  2) Upload the **os_prj3_[ID].tar.gz** file to e-class.