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Project 1: Threads

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SKK UNIVERSITY

Pintos Kernel (1)

- **The current Pintos kernel**
  - There is only one address space
  - There can be a number of threads running in the kernel mode
  - All the kernel threads share the same address space

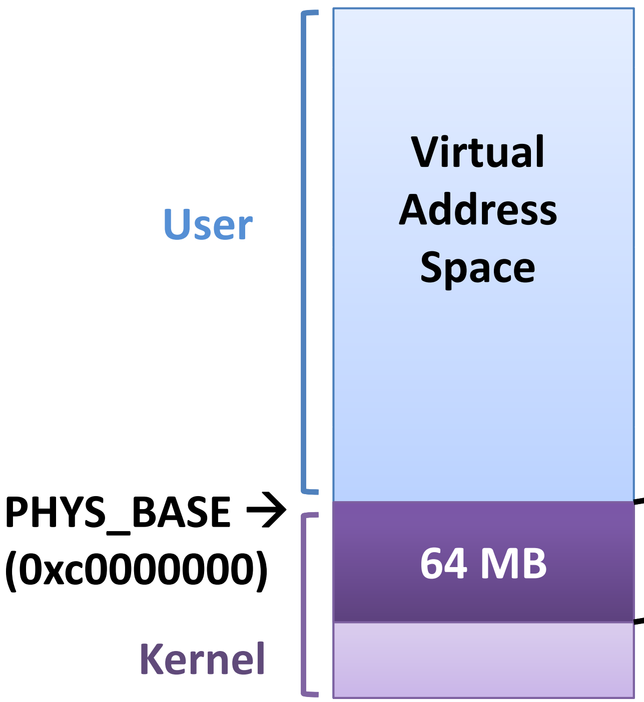
# threads per addr space: / # of addr spaces:	One	Many
One	MS/DOS Early Macintosh	Traditional UNIX
Many	**The current Pintos**	Mach, OS/2, Linux, Windows, Mac OS X, Solaris, HP-UX

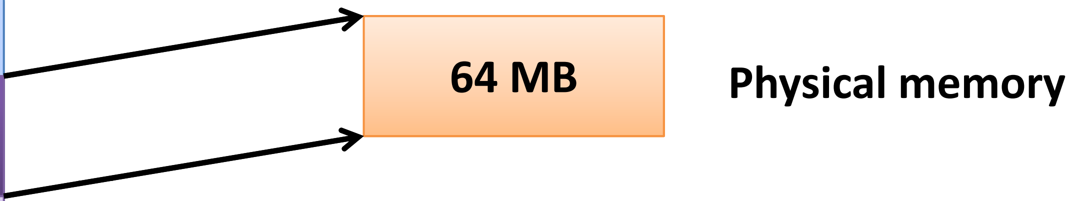
Pintos Kernel (2)

▪ Address space

- Up to 64MB of physical memory
- The kernel maps the physical memory at PHYS_BASE (`0xc0000 0000`)

```
static inline void *ptov (uintptr_t addr) {
    return (void *) (paddr + PHYS_BASE);
}
static inline uintptr_t vtop (void *addr) {
    return (uintptr_t) vaddr –
           (uintptr_t) PHYS_BASE;
}
```





Pintos Kernel (3)

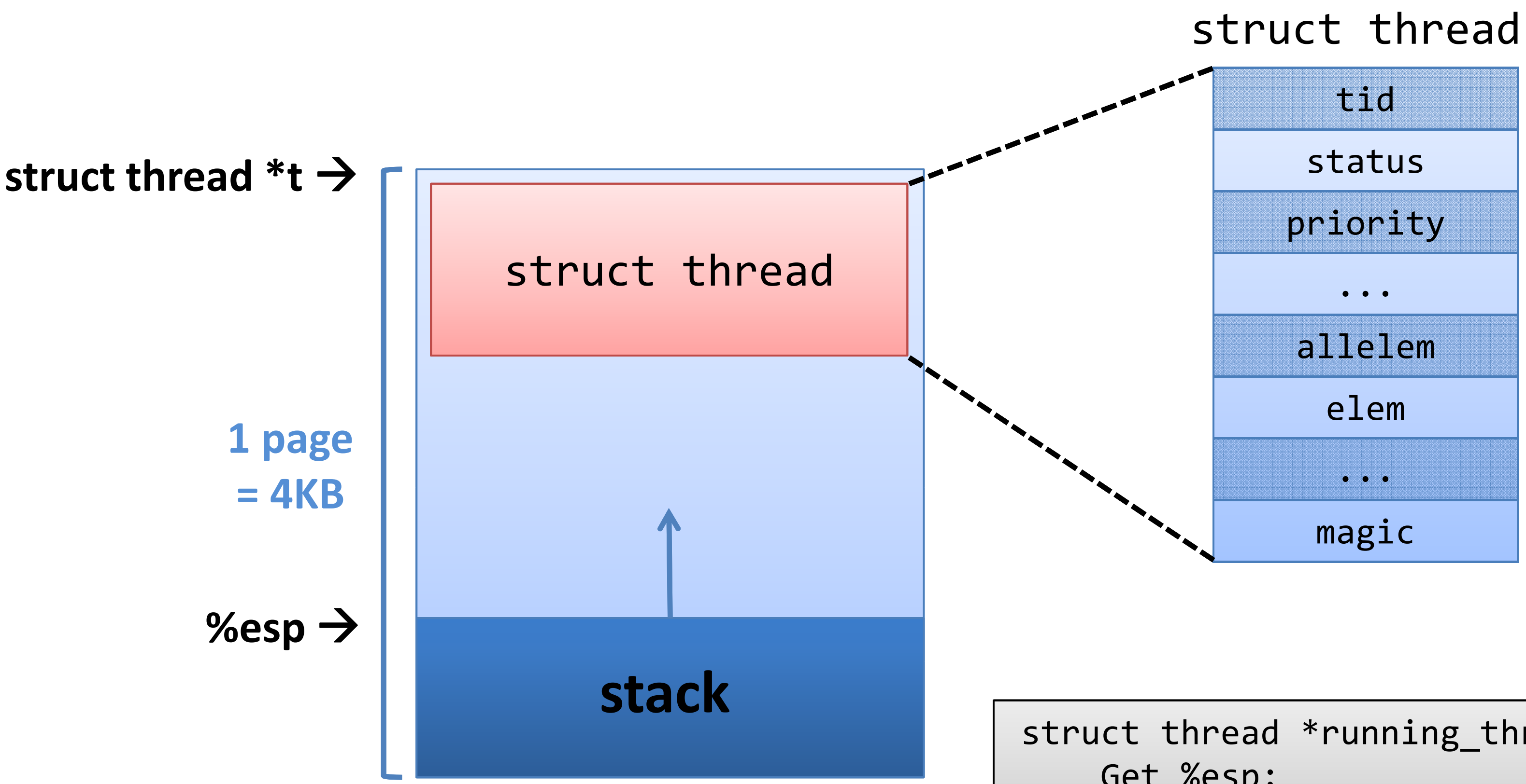
- **Kernel thread**
  - The kernel maintains a TCB (Thread Control Block) for each thread (`struct thread`)
  - Created using `thread_create()`

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

    – Allocate a page (4KB) for thread stack
    – Initialize TCB
    – Add TCB to the run queue
    – Return the corresponding `tid`
  - The function `running_thread()` returns the pointer to the TCB of the current thread

Pintos Kernel (4)

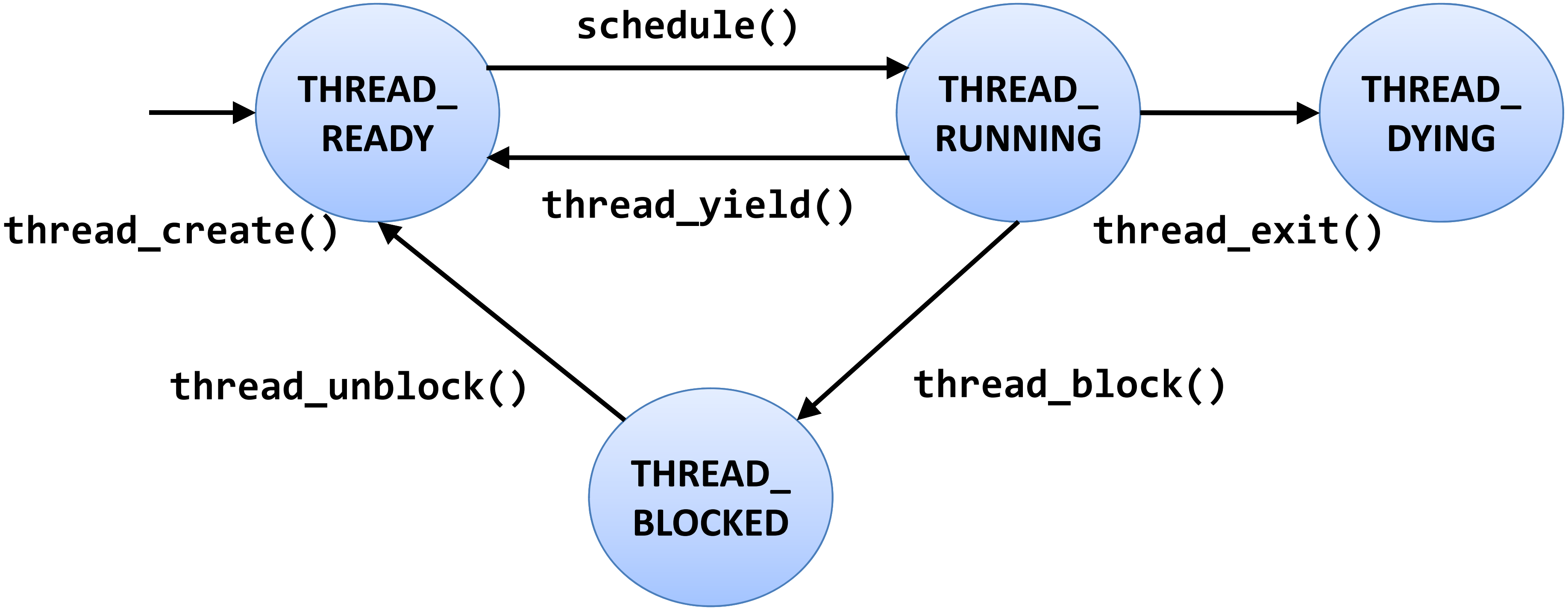
- TCB (Thread Control Block)




```
struct thread *running_thread() {
    Get %esp;
    return (%esp & 0xfffff000);
}
```

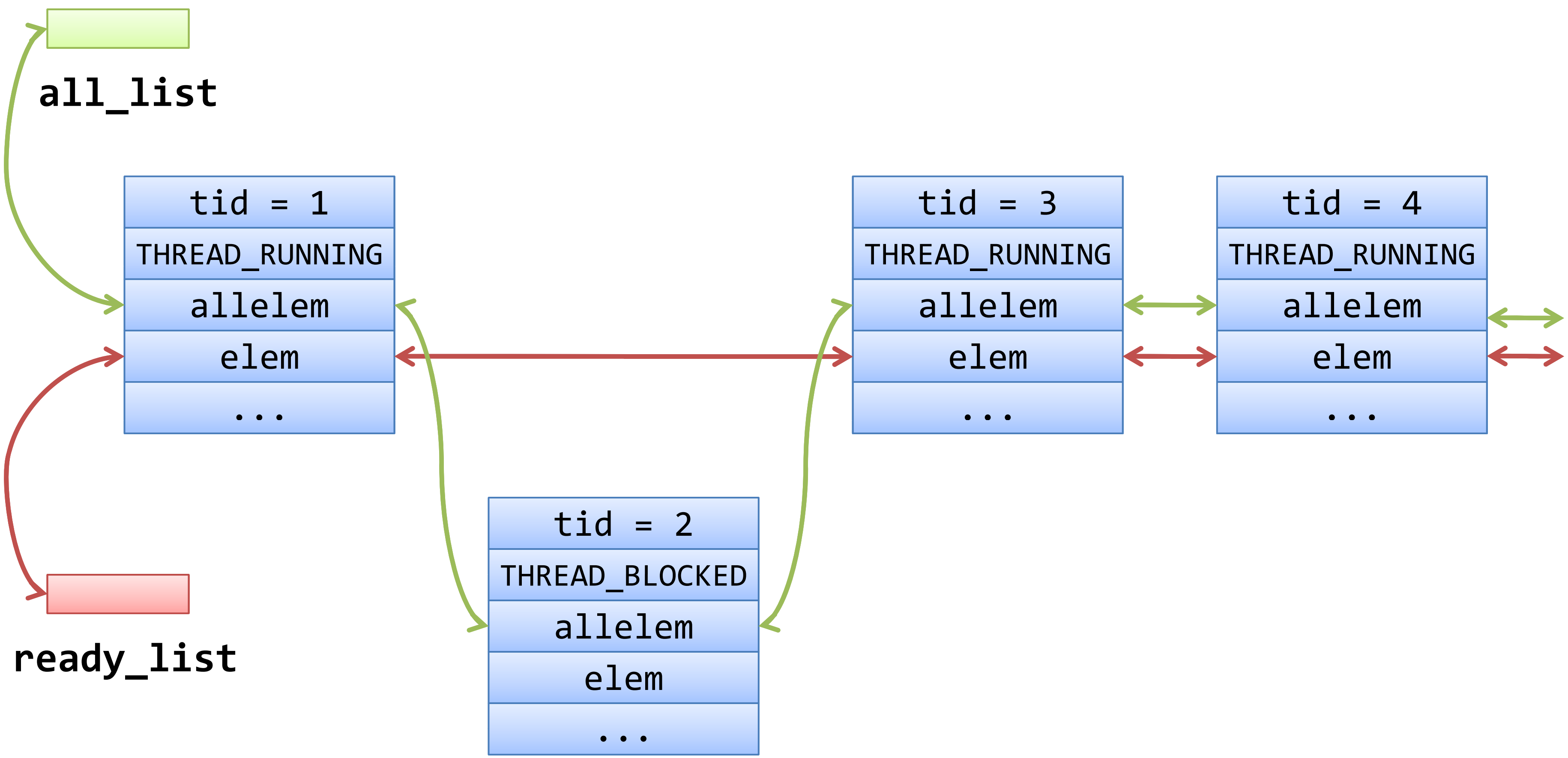
Pintos Kernel (5)

- **Thread states**
  - Refer to Appendix A.2: Threads



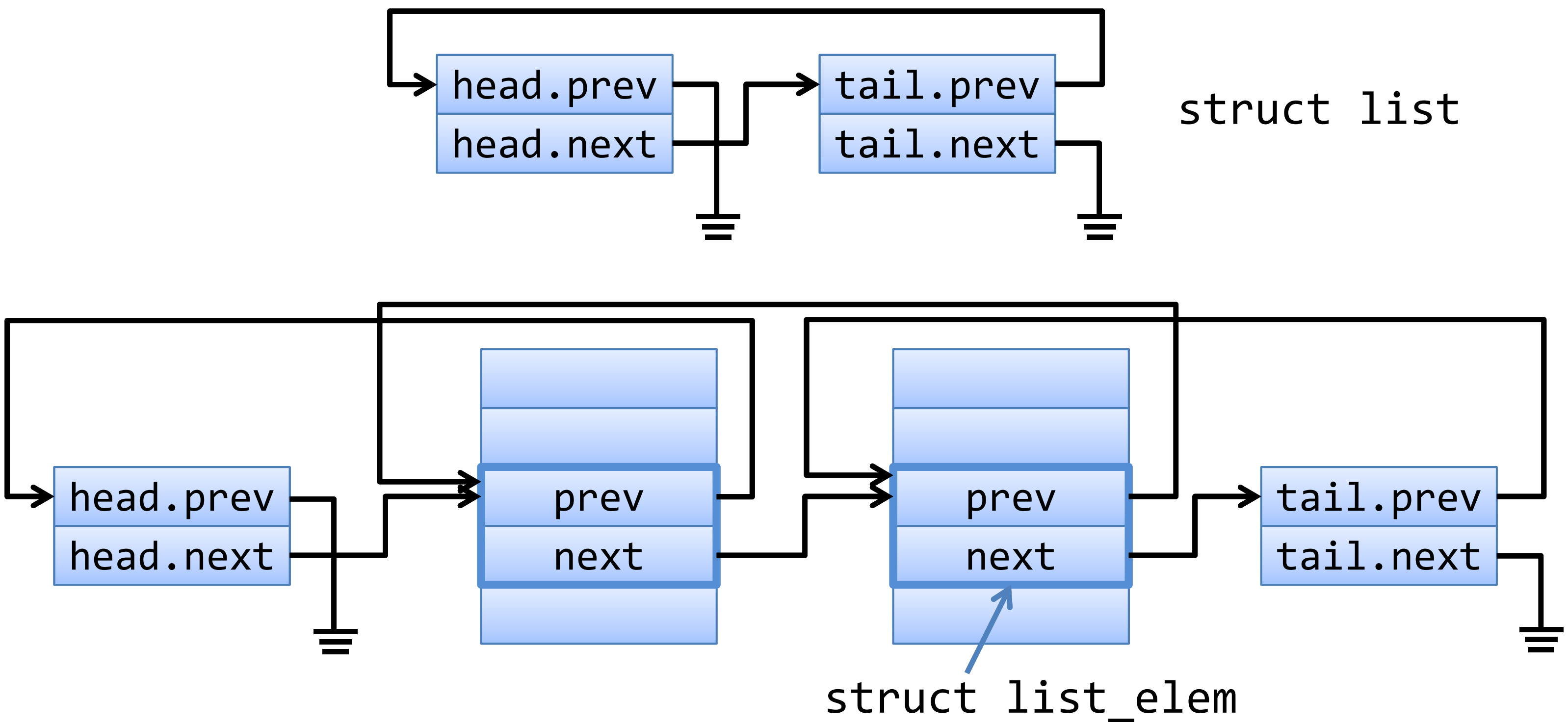
Pintos Kernel (6)

- Ready queue



Pintos Kernel (7)

- **List management in Pintos**
  - `#include <list.h>`   `/* src/lib/kernel/list.h */`
  - A type oblivious, easy-to-use, circularly-linked list



Pintos Kernel (8)

- **List management in Pintos (cont'd)**
  - `list_init (struct list *list);`
    - Initializes `list` as an empty list
  - `list_push_front (struct list *list, struct list_elem *elem);`
    `list_push_back (struct list *list, struct list_elem *elem);`
    - Inserts `elem` at the beginning (end) of `list`
  - `list_remove (struct list_elem *elem);`
    - Removes `elem` from its `list`
  - `list_pop_front (struct list *list);`
    `list_pop_back (struct list *list);`
    - Removes the front (back) element from `list` and returns it
  - `list_entry (LIST_ELEM, STRUCT, MEMBER);`
    - Converts pointer to list element `LIST_ELEM` into a pointer to the structure that `LIST_ELEM` is embedded inside.

Pintos Kernel (9)

- **List management example**
  - Display thread list (tid & name)

```
struct list all_list;

struct thread {
  tid_t tid;
  char name[16];
      ...
  struct list_elem allelem;
      ...
};
```

```
void list_thread ()
{
  struct list_elem *e;

  for (e = list_begin(&all_list);
       e != list_end(&all_list);
       e = list_next(e))
  {
    struct thread *t =
    list_entry (e, struct thread, allelem);
    printf (“%d: %s\n”, t->tid, t->name);
  }
}
```

  - (cf.) http://isis.poly.edu/kulesh/stuff/src/klist/

Project 1: Threads

- **Requirements**
  - Alarm clock
  - Priority scheduling
  - Priority donation
  - Note: Advanced scheduler is optional
- **Test cases to pass (total 18 tests)**
  - `alarm-single, alarm-multiple, alarm-simultaneous, alarm-priority, alarm-zero, alarm-negative, priority-change, priority-donate-one, priority-donate-multiple, priority-donate-multiple2, priority-donate-nest, priority-donate-sema, priority-donate-lower, priority-fifo, priority-preempt, priority-sema, priority-condvar, priority-donate-chain`

Alarm Clock (1)

- **Reimplement `timer_sleep()`**

```
void timer_sleep (int64 x);
```

  - Suspends execution of the calling thread until time has advanced at least x timer ticks
  - The current version simply "busy waits."
    - The thread spins in a loop checking the current time and calling `thread_yield()` until enough time has gone by.
  - Reimplement it to avoid busy waiting
  - You don't have to worry about the overflow of timer values.

Alarm Clock (2)

- **Time management in Pintos**
  - On every timer interrupt, the global variable `ticks` is increased by one
    - The variable `ticks` represent the number of timer ticks since the Pintos booted
    - Timer frequency: `TIMER_FREQ` (= 100) ticks per second (defined in `<src/devices/timer.h>`)
  - The time slice is set to `TIME_SLICE` (= 4) ticks for each thread (defined in `<src/threads/thread.c>`)
  - `timer_interrupt()`: Timer interrupt handler
    - Increase the `ticks` variable
    - If the current thread has exhausted its time slice, call `thread_yield()`.

Alarm Clock (3)

- **The current timer_sleep() implementation**
  - In <src/devices/timer.c>
  - timer_ticks() returns the current value of ticks

```
int64_t timer_elapsed (int64_t then)
{
   return timer_ticks () – then;
}

void timer_sleep (int64_t ticks)
{
   int64_t start = timer_ticks ();

   ASSERT (intr_get_level () == INTR_ON);

   while (timer_elapsed (start) < ticks)
     thread_yield ();
}
```

Alarm Clock (4)

- **Hints**
  - Make a new list of threads ("waiting_list")
  - Remove the calling thread from the ready list and insert it into the "waiting_list" changing its status to THREAD_BLOCKED
  - The thread waits in the "waiting_list" until the timer expires
  - When a timer interrupt occurs, move the thread back to the ready list if its timer has expired.
  - Use <list.h> for list manipulation

Priority Scheduling (1)

- **Scheduling**
  - The scheduling policy decides which thread to run next, given a set of runnable threads
- **The current Pintos scheduling policy: Round-robin (RR) scheduling**
  - The ready queue is treated as a circular FIFO queue
  - Each thread is given a time slice (or time quantum)
    - TIME_SLICE (= 4) ticks by default
  - If the time slice expires, the current thread is moved to the end of the ready queue
  - The next thread in the ready queue is scheduled
  - No priority: All the threads are treated equally

Priority Scheduling (2)

- The current Pintos scheduling

```
/* Yields the CPU.  The current thread is not put to sleep and
   may be scheduled again immediately at the scheduler's whim. */
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);
}
```

Priority Scheduling (3)

- **The current Pintos scheduling (cont'd)**

```c
/* Schedules a new process.  At entry, interrupts must be off and
   the running process's state must have been changed from
   running to some other state.  This function finds another
   thread to run and switches to it.

   It's not safe to call printf() until schedule_tail() has
   completed. */
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);
  schedule_tail (prev);
}
```

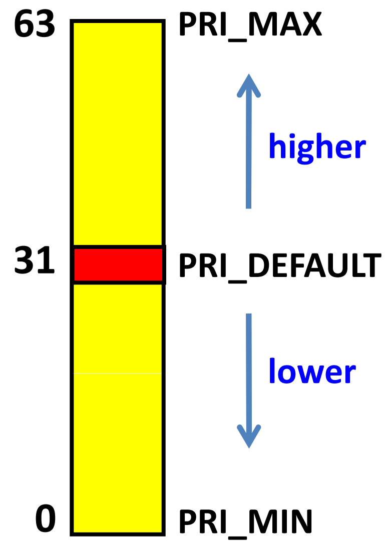
Priority Scheduling (4)

- **The current Pintos scheduling (cont'd)**

```
/* Chooses and returns the next thread to be scheduled.  Should
   return a thread from the run queue, unless the run queue is
   empty.  (If the running thread can continue running, then it
   will be in the run queue.)  If the run queue is empty, return
   idle_thread. */
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);
}
```

Priority Scheduling (5)

- **Priority scheduling**
  - Each thread is given a scheduling priority
  - The scheduler chooses the thread with the highest priority in the ready queue to run next
  - Thread priorities in Pintos
    - 64 priority levels (default = 31)
    - Lower numbers correspond to lower priorities
      - » Max priority = 63
      - » Min priority = 0
    - The initial priority is passed as an argument to `thread_create()`



Priority Scheduling (6)

- **Note**
  - When a thread is added to the ready list that has a higher priority than the currently running thread, the current thread should immediately yield the processor to the new thread.
  - A thread may raise or lower its own priority at any time, but lowering its priority such that it no longer has the highest priority must cause it to immediately yield the CPU.
  - When threads are waiting for a lock, semaphore, or condition variable, the highest priority waiting thread should be awakened first.

Synchronization (1)

- **Synchronization problem**
  - Accessing a shared resource by two concurrent threads creates a situation called **race condition**
    - The result is non-deterministic and depends on timing
  - We need "**synchronization**" mechanisms for controlling access to shared resources
  - **Critical sections** are parts of the program that access shared resources
  - We want to provide **mutual exclusion** in critical sections
    - Only one thread at a time can execute in the critical section
    - All other threads are forced to wait on entry
    - When a thread leaves a critical section, another can enter

Synchronization (2)

▪ Synchronization mechanisms in Pintos

- Locks
  - `void lock_init (struct lock *lock);`
  - `void lock_acquire (struct lock *lock);`
  - `void lock_release (struct lock *lock);`
- Semaphores
  - `void sema_init (struct semaphore *sema, unsigned value);`
  - `void sema_up (struct semaphore *sema);`
  - `void sema_down (struct semaphore *sema);`
- Condition variables
  - `void cond_init (struct condition *cond);`
  - `void cond_wait (struct condition *cond, struct lock *lock);`
  - `void cond_signal (struct condition *cond, struct lock *lock);`
  - `void cond_broadcast (struct condition *cond, struct lock *lock);`
- Refer to Appendix A.3: Synchronization

Synchronization (3)

- **Locks**
  - A lock is initially free
  - Call `lock_acquire()` before entering a critical section, and call `lock_release()` after leaving it
  - Between `lock_acquire()` and `lock_release()`, the thread holds the lock
  - `lock_acquire()` does not return until the caller holds the lock
  - At most one thread can hold a lock at a time
  - After `lock_release()`, one of the waiting threads should be able to hold the lock

Synchronization (4)

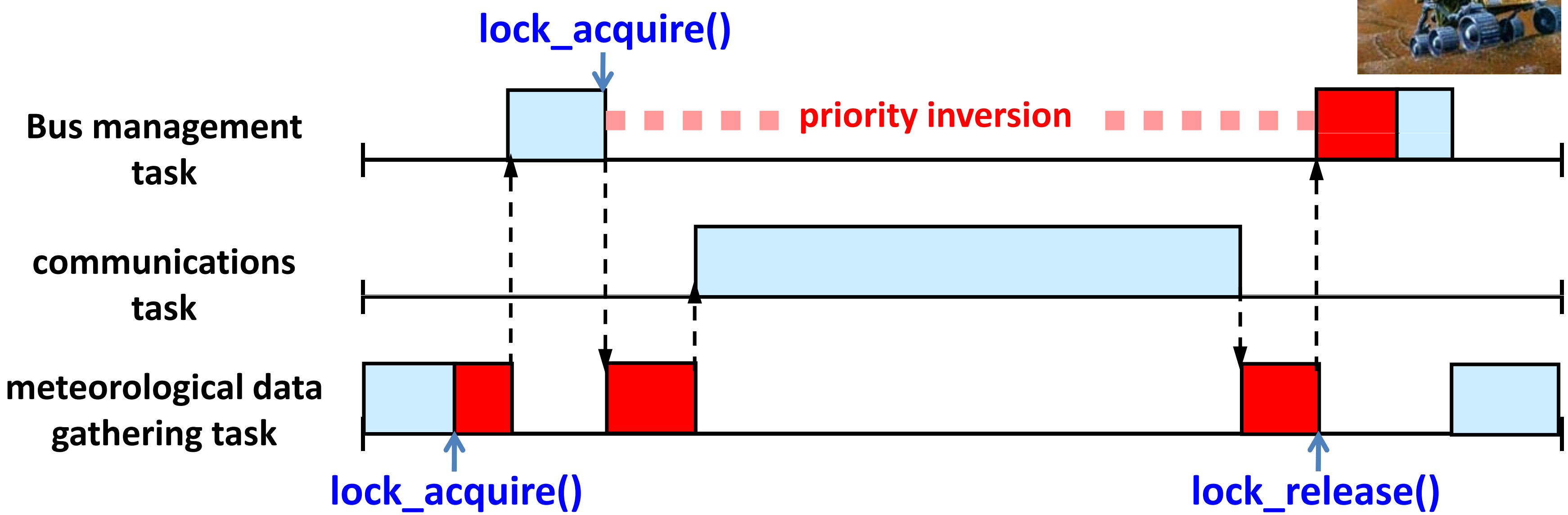
- **Semaphores**
  - A semaphore is a nonnegative integer with two operators that manipulate it atomically
  - `sema_down()` waits for the value to become positive, then decrement it
  - `sema_up()` increments the value and wakes up one waiting thread, if any
  - A semaphore initialized to 1 is similar to a lock
  - A semaphore initialized to N (> 1) represents a resource with many units available
    - Up to N threads can enter the critical section

Synchronization (5)

- **Condition variables**
  - Condition variables allow a thread in the critical section to wait for an event to occur
  - Condition variables are used with locks
  - `cond_wait()` atomically releases lock and waits for an event to be signaled by another thread.
    - Lock must be held before calling cond_wait()
    - After condition is signaled, reacquires lock before returning
  - `cond_signal()` wakes up one of threads that are waiting on condition
  - `cond_broadcast()` wakes up all threads, if any, waiting on condition

Priority Donation (1)

- **Priority inversion problem**
  - A situation where a higher-priority thread is unable to run because a lower-priority thread is holding a resource it needs, such as a lock.
  - *What really happened on Mars?*

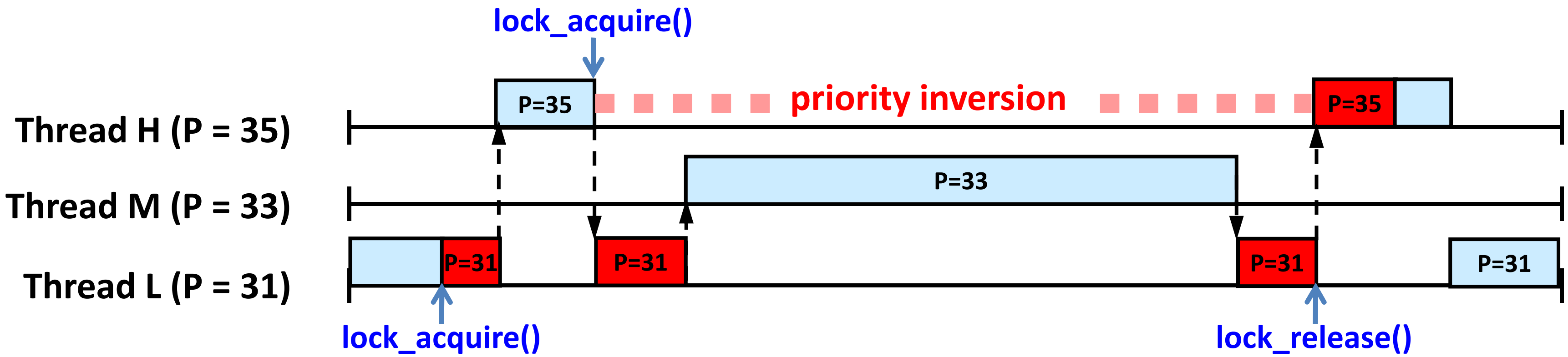


Priority Donation (2)

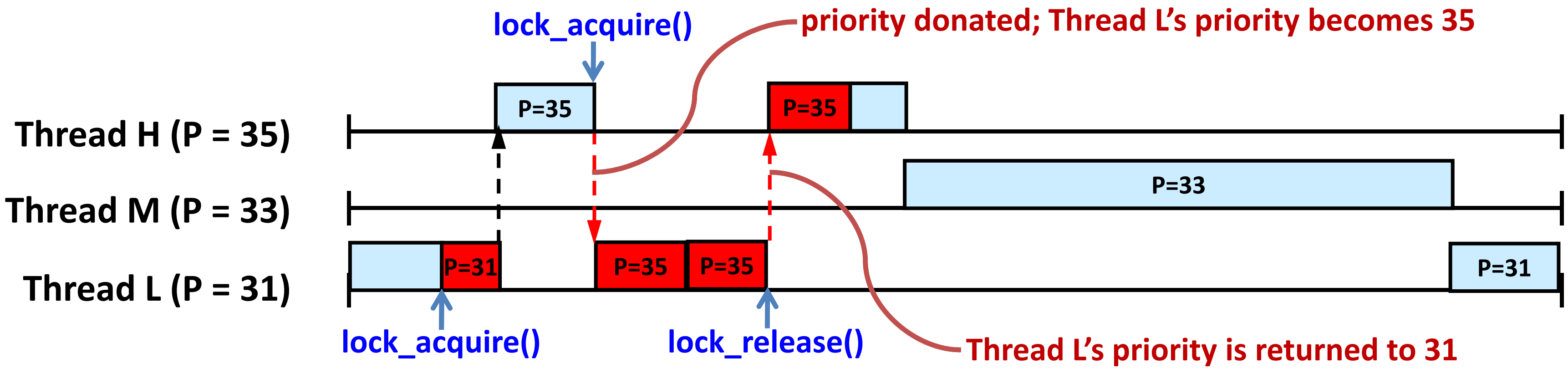
- **Priority donation (or priority inheritance)**
  - The higher-priority thread (donor) can donate its priority to the lower-priority thread (donee) holding the resource it requires.
  - The donee will get scheduled sooner since its priority is boosted due to donation
  - When the donee finishes its job and releases the resource, its priority is returned to the original priority

Priority Donation (3)

- **Before priority donation**



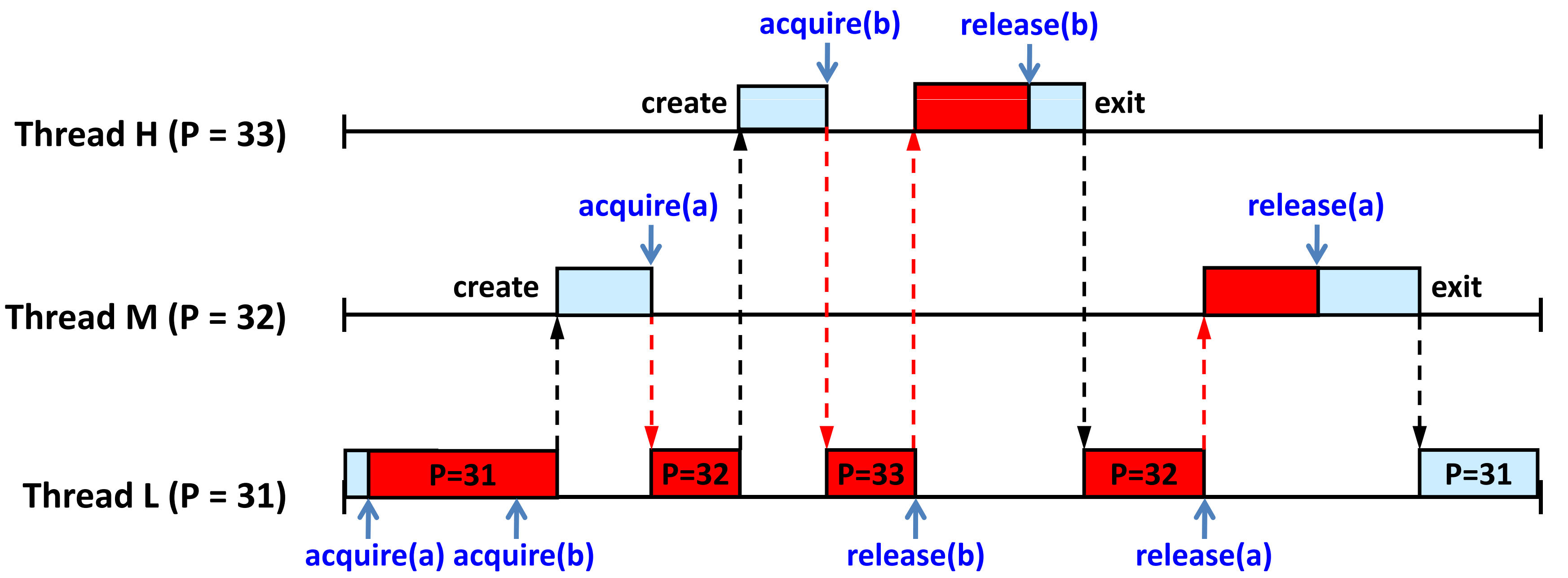
- **After priority donation**



Priority Donation (4)

▪ Multiple donations

- Multiple priorities are donated to a single thread



Priority Donation (5)

- **Multiple donations example**

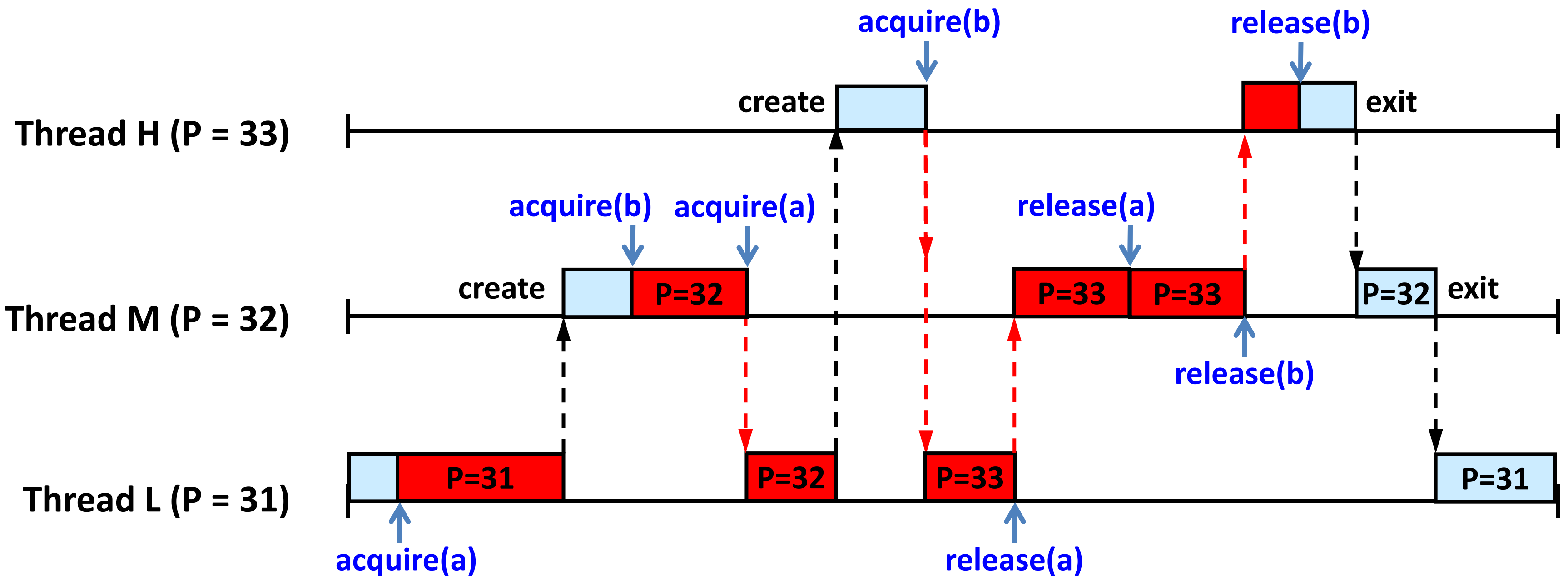
```
void
test_priority_donate_multiple (void)
{
  struct lock a, b;

  /* This test does not work with the MLFQS. */
  ASSERT (!thread_mlfqs);

  /* Make sure our priority is the default. */
  ASSERT (thread_get_priority () == PRI_DEFAULT);

  lock_init (&a);
  lock_init (&b);

  lock_acquire (&a);
  lock_acquire (&b);

  thread_create ("a", PRI_DEFAULT + 1, a_thread_func, &a);
  msg ("Main thread should have priority %d.  Actual priority: %d.",
       PRI_DEFAULT + 1, thread_get_priority ());

  thread_create ("b", PRI_DEFAULT + 2, b_thread_func, &b);
  msg ("Main thread should have priority %d.  Actual priority: %d.",
       PRI_DEFAULT + 2, thread_get_priority ());

  lock_release (&b);
  msg ("Thread b should have just finished.");
  msg ("Main thread should have priority %d.  Actual priority: %d.",
       PRI_DEFAULT + 1, thread_get_priority ());

  lock_release (&a);
  msg ("Thread a should have just finished.");
  msg ("Main thread should have priority %d.  Actual priority: %d.",
       PRI_DEFAULT, thread_get_priority ());
}
```

```
static void
a_thread_func (void *lock_)
{
  struct lock *lock = lock_;

  lock_acquire (lock);
  msg ("Thread a acquired lock a.");
  lock_release (lock);
  msg ("Thread a finished.");
}

static void
b_thread_func (void *lock_)
{
  struct lock *lock = lock_;

  lock_acquire (lock);
  msg ("Thread b acquired lock b.");
  lock_release (lock);
  msg ("Thread b finished.");
}
```

src/tests/threads/priority-donate-multiple.c

Priority Donation (6)

- **Nested donation**
  - If H is waiting on a lock that M holds and M is waiting on a lock that L holds, then both M and L should be boosted to H's priority



Priority Donation (7)

- Nested donation example

```c
void
test_priority_donate_nest (void)
{
  struct lock a, b;
  struct locks locks;

  /* This test does not work with the MLFQS. */
  ASSERT (!thread_mlfqs);

  /* Make sure our priority is the default. */
  ASSERT (thread_get_priority () == PRI_DEFAULT);

  lock_init (&a);
  lock_init (&b);

  lock_acquire (&a);

  locks.a = &a;
  locks.b = &b;
  thread_create ("medium", PRI_DEFAULT + 1, medium_thread_func, &locks);
  thread_yield ();
  msg ("Low thread should have priority %d.  Actual priority: %d.",
       PRI_DEFAULT + 1, thread_get_priority ());

  thread_create ("high", PRI_DEFAULT + 2, high_thread_func, &b);
  thread_yield ();
  msg ("Low thread should have priority %d.  Actual priority: %d.",
       PRI_DEFAULT + 2, thread_get_priority ());

  lock_release (&a);
  thread_yield ();
  msg ("Medium thread should just have finished.");
  msg ("Low thread should have priority %d.  Actual priority: %d.",
       PRI_DEFAULT, thread_get_priority ());
}
```

```c
static void
medium_thread_func (void *locks_)
{
  struct locks *locks = locks_;

  lock_acquire (locks->b);
  lock_acquire (locks->a);

  msg ("Medium thread should have priority %d.  Actual priority: %d.",
       PRI_DEFAULT + 2, thread_get_priority ());
  msg ("Medium thread got the lock.");

  lock_release (locks->a);
  thread_yield ();

  lock_release (locks->b);
  thread_yield ();

  msg ("High thread should have just finished.");
  msg ("Middle thread finished.");
}

static void
high_thread_func (void *lock_)
{
  struct lock *lock = lock_;

  lock_acquire (lock);
  msg ("High thread got the lock.");
  lock_release (lock);
  msg ("High thread finished.");
}
```

src/tests/threads/priority-donate-nest.c

Priority Scheduling/Donation

- **Hints**
  - Remember each thread's base priority
  - When you schedule a new thread, find the thread with the highest priority among candidates
  - The "effective" priority of a thread can be greater than the base priority due to priority donation
  - The "effective" priority should be adjusted properly on `lock_acquire()` and `lock_release()`
  - You don't have to implement priority donation for semaphores or condition variables

Submission (1)

- **Due**
  - October 13, 11:59PM
  - Fill out the design document (`threads.tmpl`) and put it in your source tree under the name `pintos/src/threads/DESIGNDOC`
  - Tar and gzip your Pintos source codes

```
$ cd pintos
$ (cd src/threads; make clean)
$ tar cvzf TeamName.tar.gz ./src
```

  - Send it to the instructor via e-mail
  - The submission status will be posted in the course homepage.

Submission (2)

- **Submitting your report**
  - Hand in the printed version of your design document (`DESIGNDOC` file) in the following class on October 14.
  - In addition, your report should contain the following information:
    - The percentage of contribution for each member
    - The list of specific tasks done by each member
  - Your report should be signed by all team members
  - Good luck!