Pintos Internals

main()

```
int main (void)
{
  ram_init ();
  argv = read_command_line ();
  argv = parse_options (argv);

①/* make ourselves as a thread */
  thread_init ();
  console_init ();

  printf ("Pintos booting with %'zu"
"kB RAM.\n", ram_pages*PGSIZE/1024);

②/* initialize memory system */
  palloc_init ();
  malloc_init ();
  paging_init ();

#ifdef USERPROG
  tss_init ();   /* Segmentation */
  gdt_init ();
#endif

③intr_init (); /* intr handlers */
  timer_init ();
  kbd_init ();
  input_init ();

#ifdef USERPROG
  exception_init ();
  syscall_init ();
#endif

④/* start thread scheduler */
  thread_start ();
  serial_init_queue ();
  timer_calibrate ();

#ifdef FILESYS
  disk_init ();
  filesys_init (format_filesys);
#endif

  printf ("Boot complete.\n");

⑤/* run tests or user programs */
  run_actions (argv);

  if (power_off_when_done)
    power_off ();
  thread_exit ();
}
```

1. THE INITIAL THREAD

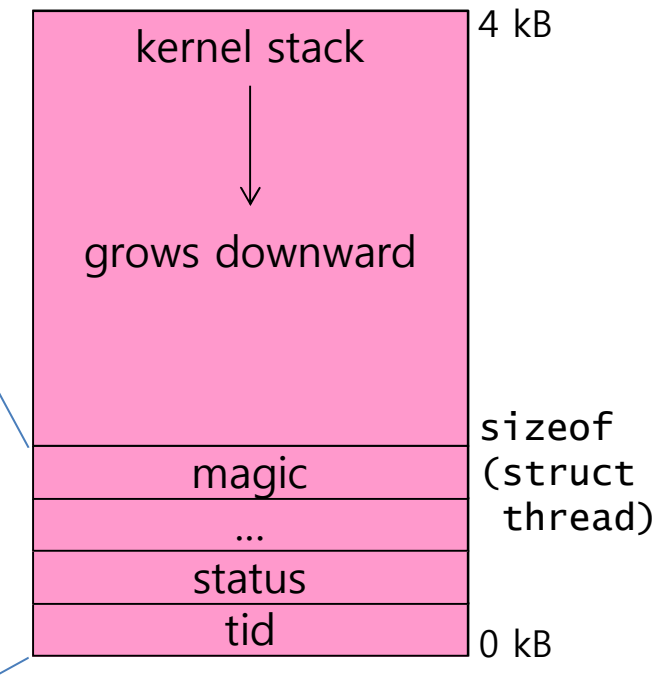
The Initial Thread

- Create a `struct thread` for the initial thread by transforming the code that's currently running into a thread

```
/* Initial thread, the thread running init.c:main(). */
static struct thread *initial_thread;

void thread_init (void)
{
  ASSERT (intr_get_level () == INTR_OFF);

  lock_init (&tid_lock);
  list_init (&ready_list);   /* initialze ready queue */

  /* Set up a thread structure for the running thread. */
  initial_thread = running_thread ();
  init_thread (initial_thread, "main", PRI_DEFAULT);
  initial_thread->status = THREAD_RUNNING;
  initial_thread->tid = allocate_tid ();
}
```

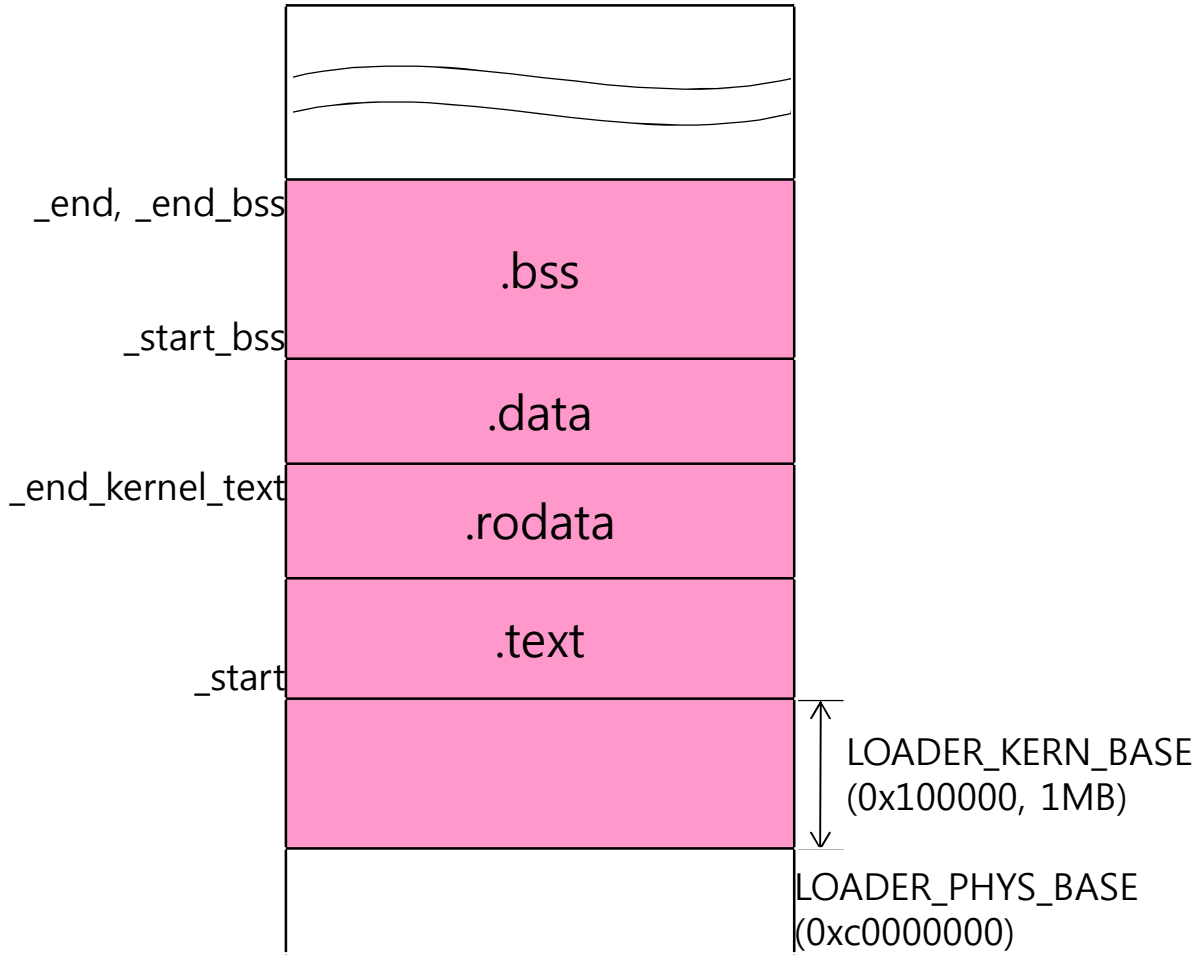
`struct thread` – pintos의 process control block

```
struct thread
  {
    /* Thread identifier. */
    tid_t tid;
    /* Thread state. */
    enum thread_status status;
    /* Name *
    char name[16];
    /* Saved stack pointer. */
    uint8_t *stack;
    /* Priority. */
    int priority;
    /* List element. */
    struct list_elem elem;
#ifdef USERPROG
    /* Page directory. */
    uint32_t *pagedir;
#endif
    /* Detects stack overflow. */
    unsigned magic;
  };
```

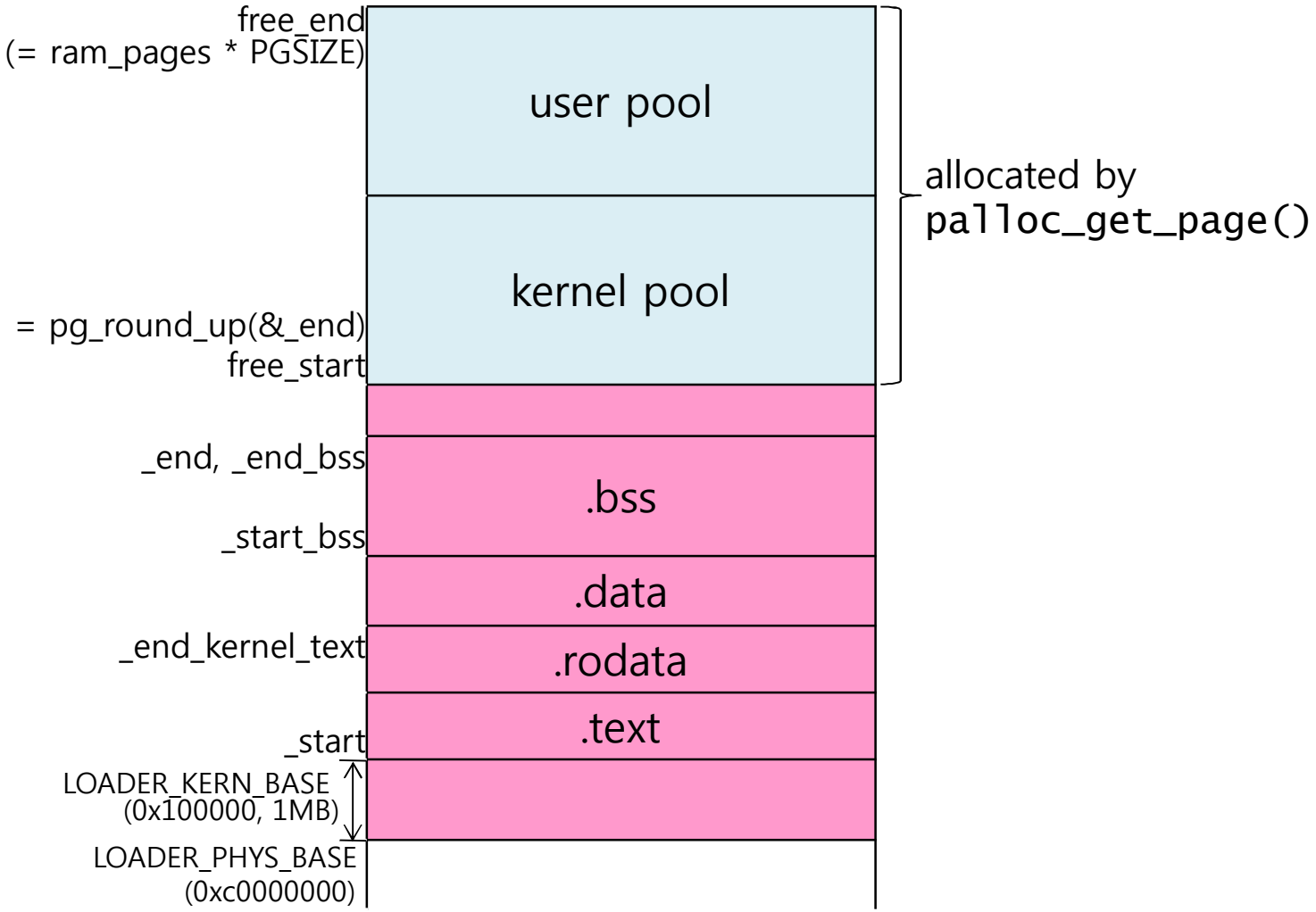


2. INITIALIZING MEMORY

부팅 직후 최초 메모리 (in kernel linker script kernel.lds.s)



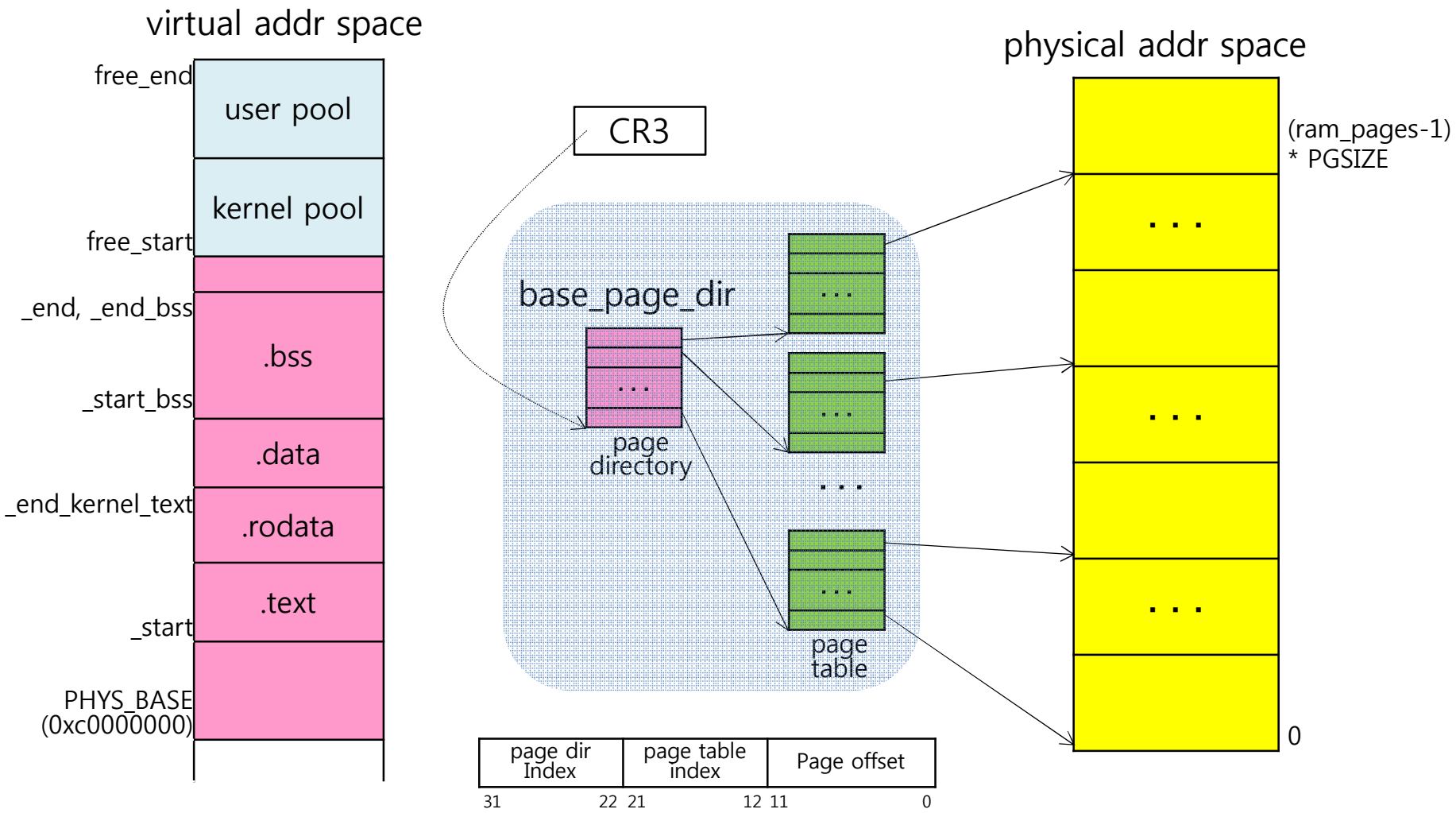
동적 메모리 할당 영역 초기화
palloc_init()



페이징 시스템 초기화
paging_init ()

```
static void paging_init (void)
{
  uint32_t *pd, *pt;
  size_t page;
  extern char _start,
_end_kernel_text;

  pd = base_page_dir =
    palloc_get_page (PAL_ASSERT |
                     PAL_ZERO);
  pt = NULL;
  for(page=0;page<ram_pages;page++) {
    uintptr_t paddr=page*PGSIZE;
    char *vaddr = ptov(paddr);
    size_t pde_idx= pd_no(vaddr);
    size_t pte_idx= pt_no(vaddr);
    bool in_kernel_text =
      &_start <= vaddr && vaddr
      < &_end_kernel_text;
    if (pd[pde_idx] == 0) {
      pt=palloc_get_page(PAL_ASSERT
                         | PAL_ZERO);
      pd[pde_idx] = pde_create (pt);
    }

    pt[pte_idx] = pte_create_kernel
            (vaddr, !in_kernel_text);
  }

  asm volatile ("movl %0, %%cr3" : :
         "r" (vtop (base_page_dir)));
}
```

Virtual Address Translation



3. INITIALIZING INTERRUPT HANDLING

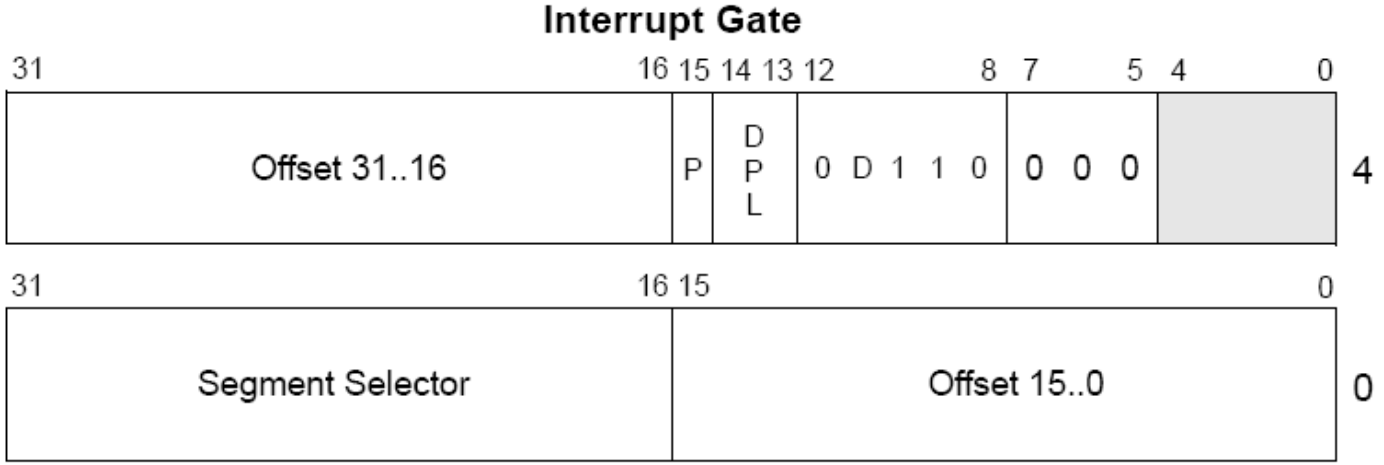
Internal vs. External Interrupts

- Internal interrupts (trap 등의 SW interrupt)
  - Interrupts caused directly by CPU instructions
  - System calls, invalid memory access, divide by zero, ...
  - Internal interrupts are **synchronous**, meaning that their delivery is synchronized with CPU instructions
  - `intr_disable`() does not disable internal interrupts
  - 내부 인터럽트 처리 중에는 아무 짓이나 할 수 있으며, 따라서 다른 커널 코드/다른 인터럽트와의 동기화 필요
- External interrupts (I/O interrupt)
  - Interrupts originating outside the CPU
  - H/W devices such as timer, keyboard, disks, ...
  - External interrupts are **asynchronous**, meaning that their delivery is NOT synchronized with CPU instructions
  - Handling of external interrupts can be postponed with `intr_disable`()
  - 외부인터럽트 처리 중에는 sleep/yield 할 수 없으며, 따라서 다른 인터럽트는 발생하지 않도록 하고,
  - 가능한 빨리 처리를 마무리

Interrupt Descriptor Table

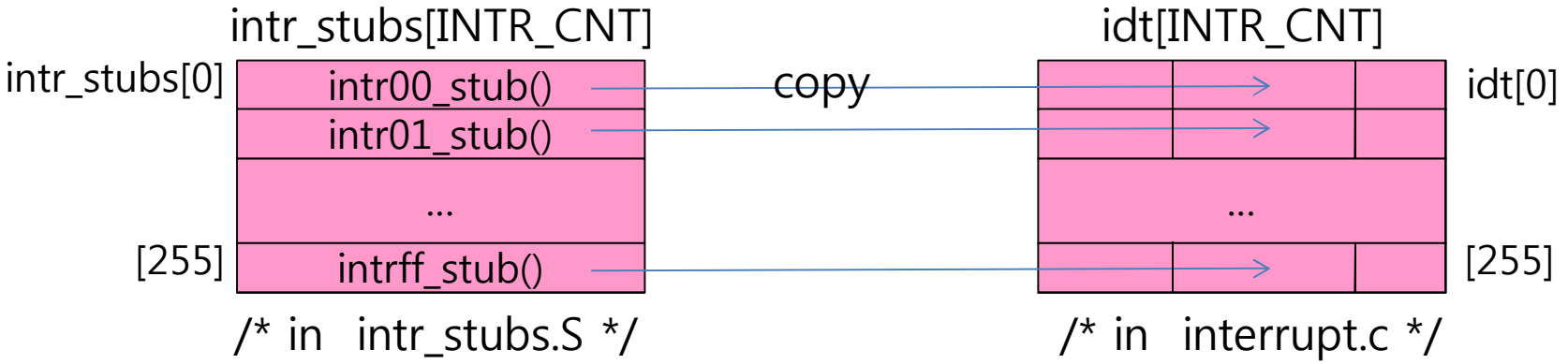
- Interrupt Descriptor Table (IDT)
  - Pointed by special register `idtr`

- IDT descriptors
  - Task-gate descriptor
  - Interrupt-gate descriptor
  - Trap-gate descriptor



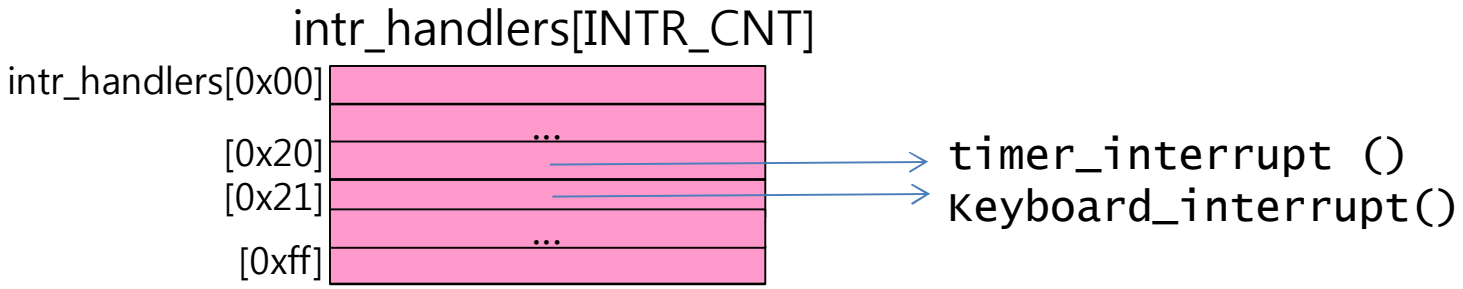
Interrupt Infrastructure

```
void intr_init (void)
{

  pic_init (); /* Initialize interrupt controller. */

  /* Initialize IDT. */
  for (i = 0; i < INTR_CNT; i++)
    idt[i] = make_intr_gate (intr_stubs[i], 0);

  /* Load IDT register. */
  idtr_operand = make_idtr_operand (sizeof idt - 1, idt);
  asm volatile ("lidt %0" : : "m" (idtr_operand));

}
```

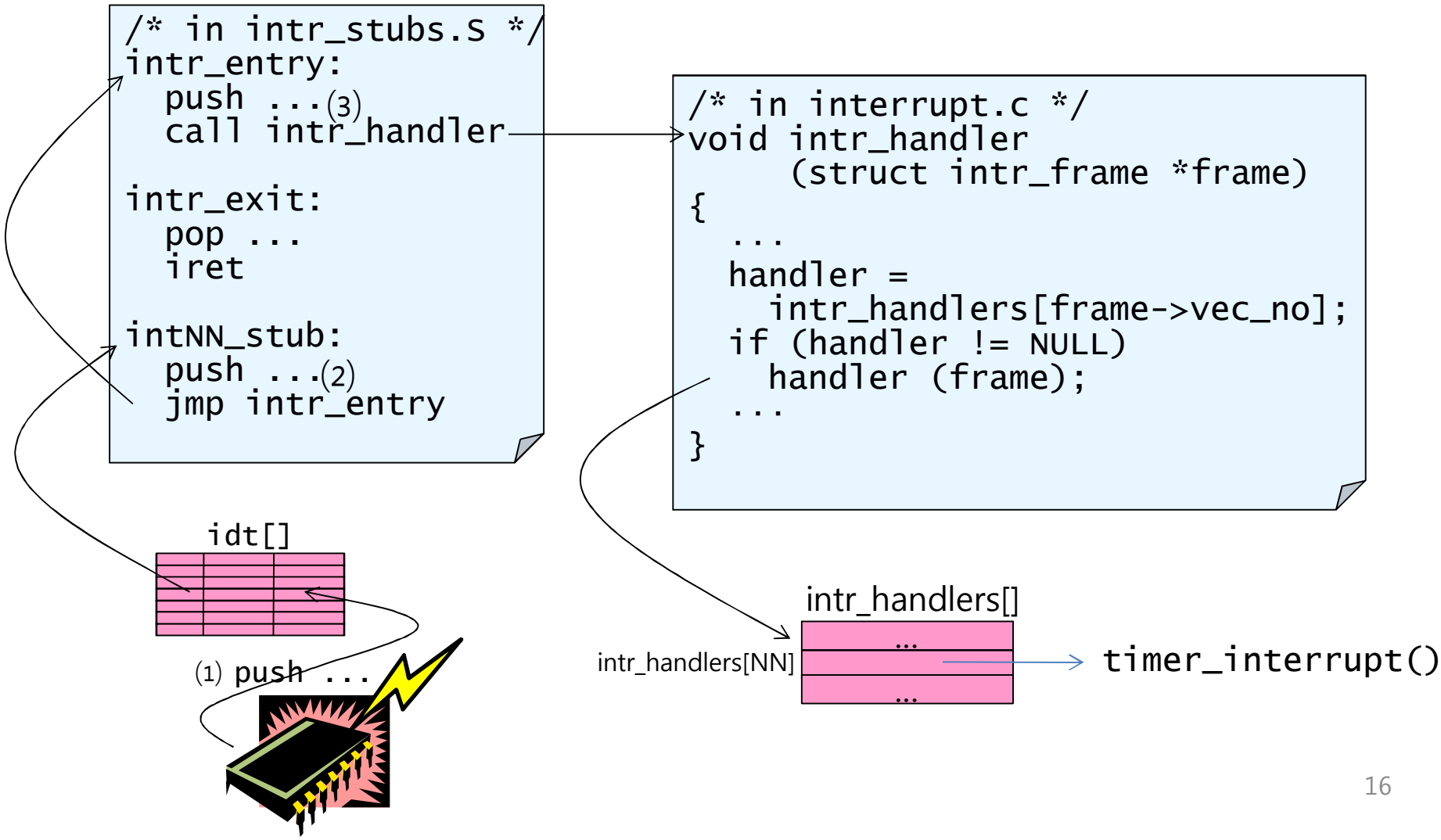


Interrupt Initialization

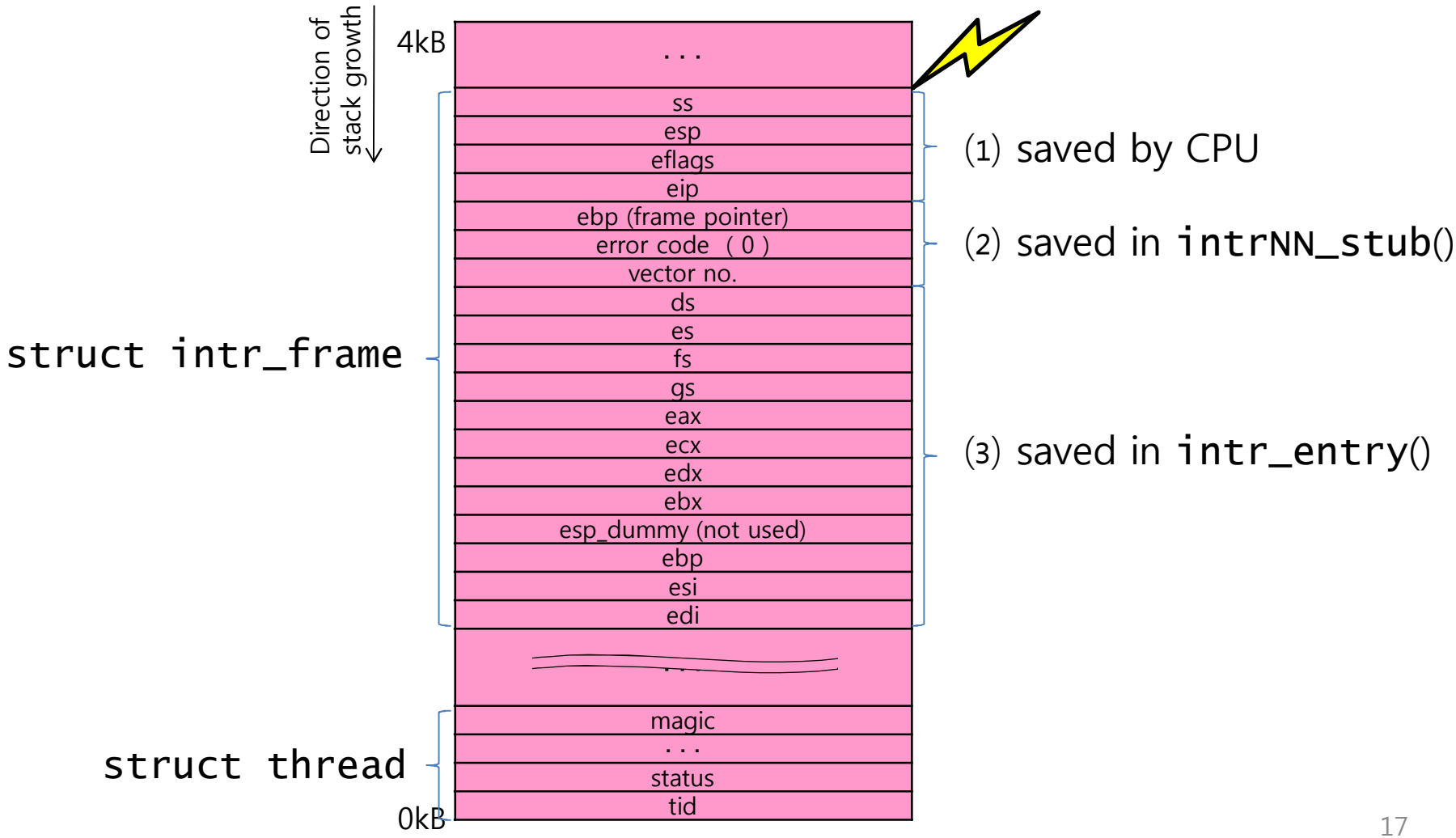
```
Void timer_init (void)
{
  uint16_t count = (1193180 + TIMER_FREQ / 2) / TIMER_FREQ;
  outb (0x43, 0x34);
  outb (0x40, count & 0xff);
  outb (0x40, count >> 8);
  intr_register_ext (0x20, timer_interrupt, "8254 Timer");
}

Void kbd_init (void)
{
  intr_register_ext (0x21, keyboard_interrupt, "8042 Keyboard");
}
```



Interrupt Handling



Interrupt Frame on Interrupted Thread's Stack



intr_handler()

```
/* Handler for all interrupts, faults,
   and exceptions. This function is
   called by the assembly language
   interrupt stubs in intr-stubs.S.
   FRAME describes the interrupt & the
   interrupted thread's registers. */
void intr_handler (struct intr_frame
*frame)
{
  bool external;
  intr_handler_func *handler;

  /* External interrupts are special.
     We only handle one at a time (so
     interrupts must be off) and they
     need to be acknowledged on the
     PIC (see below). An external
    interrupt handler cannot sleep. */
  external = frame->vec_no >= 0x20 &&
             frame->vec_no < 0x30;
  if (external) {
    ASSERT(intr_get_level()==INTR_OFF);
    ASSERT (!intr_context ());
    in_external_intr = true;
    yield_on_return = false;
  }

  /* Invoke the interrupt handler */
  handler=intr_handlers[frame->vec_no];
  if (handler != NULL) handler(frame);
  else if (frame->vec_no == 0x27 ||
           frame->vec_no == 0x2f) {
    /* There is no handler, but this
       interrupt can trigger spuriously
       due to a h/w fault or
       h/w race condition. Ignore it. */
  }
  else {
    /* No handler & not spurious. Invoke
       the unexpected interrupt handler*/
    intr_dump_frame (frame);
    PANIC ("Unexpected interrupt");
  }

  /* Complete the processing of an
     external interrupt. */
  if (external) {
    ASSERT(intr_get_level() == INTR_OFF);
    ASSERT (intr_context ());
    in_external_intr = false;
    pic_end_of_interrupt(frame->vec_no);
    if (yield_on_return)
      thread_yield ();
  }
}
```

4. STARTING THREAD SCHEDULER

Starting Thread Scheduling

```
void thread_start (void)
{
  /* Create the idle thread. */
  struct semaphore idle_started;

  sema_init (&idle_started, 0);
  thread_create("idle",
                PRI_MIN,
                idle,
                &idle_started);

  /* Start preemptive thread
     scheduling. */
  intr_enable ();

  /* Wait for the idle thread
  to initialize idle_thread. */
  sema_down (&idle_started);
}
```

```
static void
idle (void *idle_started_ UNUSED)
{
  struct semaphore *idle_started
                  = idle_started_;

  idle_thread = thread_current();
  sema_up (idle_started);

  for (;;) {
    intr_disable ();
    thread_block ();

    asm volatile ("sti;
             hlt" : : : "memory");
  }
}
```

Thread Creation

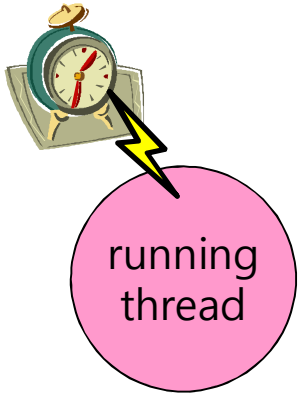
```
tid_t thread_create (
        const char *name,
        int priority,
        thread_func *function,
        void *aux)
{
  struct thread *t;
  struct kernel_thread_frame *kf;
  struct switch_entry_frame *ef;
  struct switch_threads_frame *sf;
  tid_t tid;

  ASSERT (function != NULL);

  /* Allocate thread. */
  t = palloc_get_page(PAL_ZERO);
  if (t == NULL) return TID_ERROR;

  /* Initialize thread. */
  init_thread (t,name,priority);
  tid = t->tid = allocate_tid ();

  /* Stack frame for
     kernel_thread(). */
  kf = alloc_frame(t, sizeof *kf);
  kf->eip = NULL;
  kf->function = function;
  kf->aux = aux;

  /* Stack frame for
     switch_entry(). */
  ef = alloc_frame(t, sizeof *ef);
  ef->eip = (void (*) (void))
            kernel_thread;

  /* Stack frame for
     switch_threads(). */
  sf = alloc_frame(t, sizeof *sf);
  sf->eip = switch_entry;

  /* Add to run queue. */
  thread_unblock (t);

  return tid;
}
```

allocate struct thread (and stack), and initialize it

creates some **fake stack frames** for switch_threads() and kernel _thread()

Thread Switching – Case I

- thread_yield()




```
intr_handler ()
{
  ...
  handler();
  ...
  if (external) {
    ...
    if (yield_on_return)
      thread_yield ();
  }
}
```

```
timer_interrupt ()
{
  ticks++;
  ...
  /* Enforce preemption. */
  if (++thread_ticks
        >= TIME_SLICE)
    intr_yield_on_return ();
}
```

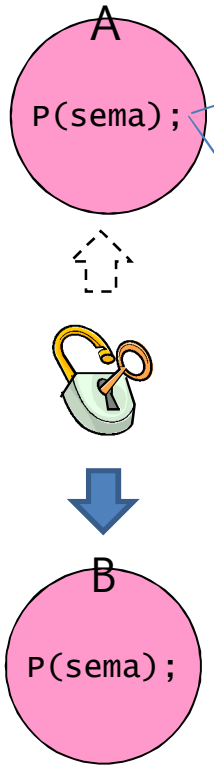
yield_on_return ← 1

thread_yield()

```
/* 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);
}
```

Thread Switching – Case II

- thread_block()




```
void sema_down (struct semaphore *sema)
{
  ...
  while (sema->value == 0)
    {
      list_push_back (&sema->waiters,
                      &thread_current ()->elem);
      thread_block ();
    }
  ...
}
```

thread_block()

```
/* Puts the current thread to sleep.  It will not be scheduled
   again until awoken by thread_unblock().

   This function must be called with interrupts turned off.  It
   is usually a better idea to use one of the synchronization
   primitives in synch.h. */
void
thread_block (void)
{
  ASSERT (!intr_context ());
  ASSERT (intr_get_level () == INTR_OFF);

  thread_current ()->status = THREAD_BLOCKED;
  schedule ();
}
```

Thread Switching – Case Ⅲ

- `thread_exit()`

```
/* Function used as the basis for a kernel thread. */
static void
kernel_thread (thread_func *function, void *aux)
{
  ASSERT (function != NULL);

  intr_enable ();       /* The scheduler runs with
                           interrupts off. */
  function (aux);       /* Execute the thread function. */
  thread_exit ();       /* If function() returns,
                           kill the thread. */
}
```

thread_exit()

```
/* Deschedules the current thread and destroys it.  Never
   returns to the caller. */
Void thread_exit (void)
{
  ASSERT (!intr_context ());

#ifdef USERPROG
  process_exit ();
#endif

  /* Just set our status to dying and schedule another process.
     We will be destroyed during the call to schedule_tail(). */
  intr_disable ();
  thread_current ()->status = THREAD_DYING;
  schedule ();
  NOT_REACHED ();
}
```

schedule()

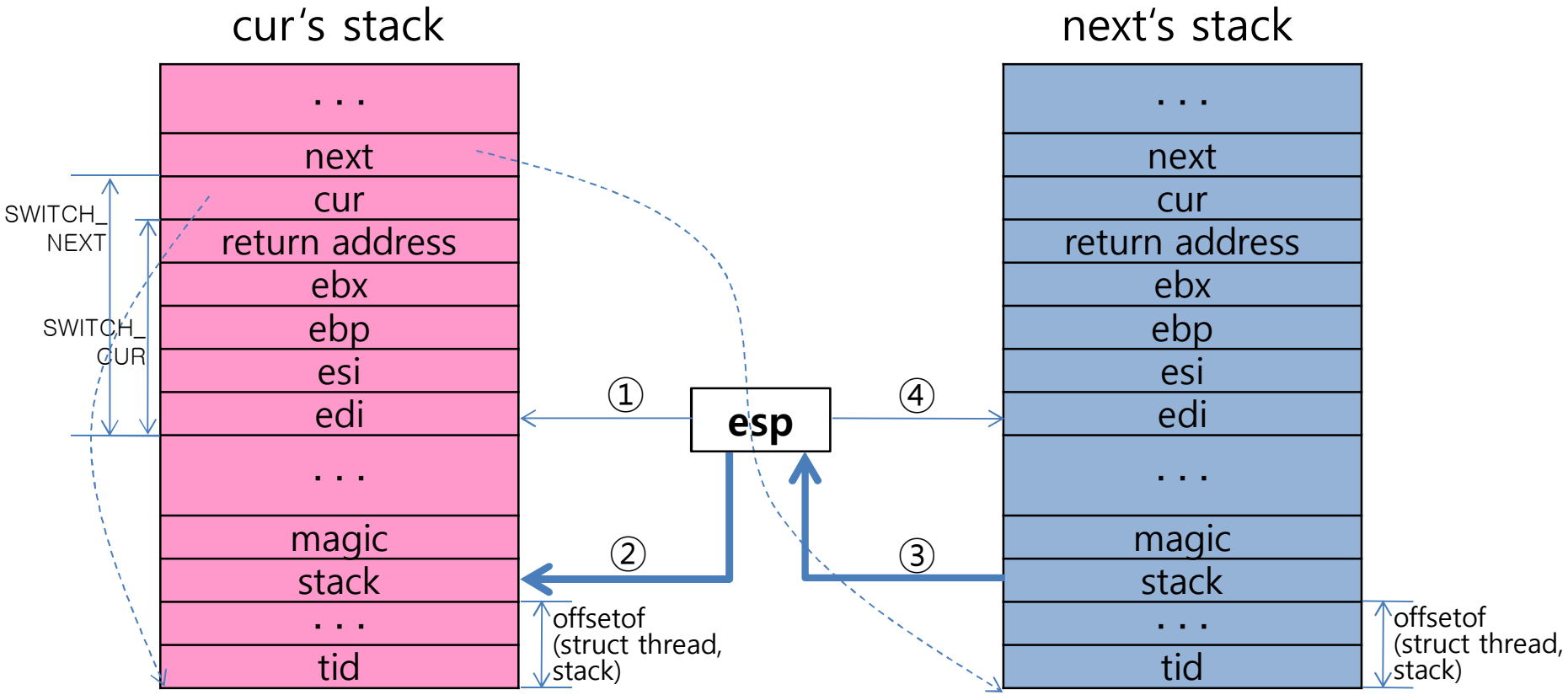
```
/* Schedules a new process.  At entry, interrupts must be off and
   the running process's state must have been changed from
   running to some other state.  This function finds another
   thread to run and switches to it. It's not safe to call
   printf() until schedule_tail() has completed. */
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);
}
```

switch_threads()

```
.globl switch_threads
.func switch_threads
switch_threads:
  # Save caller's register state.
  #
  # Note that the SVR4 ABI allows us
  # to destroy %eax, %ecx, %edx,
  # but requires us to preserve
  # %ebx, %ebp, %esi, %edi.  See
  # [SysV-ABI-386] pages 3-11 and
  # 3-12 for details.

  # This stack frame must match the
  # one set up by thread_create()
  # in size.

  pushl %ebx
  pushl %ebp
  pushl %esi
  pushl %edi

 # Get offsetof (struct thread,
                 stack).
```

```
.globl thread_stack_ofs

  mov thread_stack_ofs, %edx

  # Save current stack pointer to
  # old thread's stack, if any.
  movl SWITCH_CUR(%esp), %eax
  movl %esp, (%eax,%edx,1)

  # Restore stack pointer from new
  # thread's stack.
  movl SWITCH_NEXT(%esp), %ecx
  movl (%ecx,%edx,1), %esp

  # Restore caller's register state.
  popl %edi
  popl %esi
  popl %ebp
  popl %ebx
        ret

.endfunc
```

Context Switch

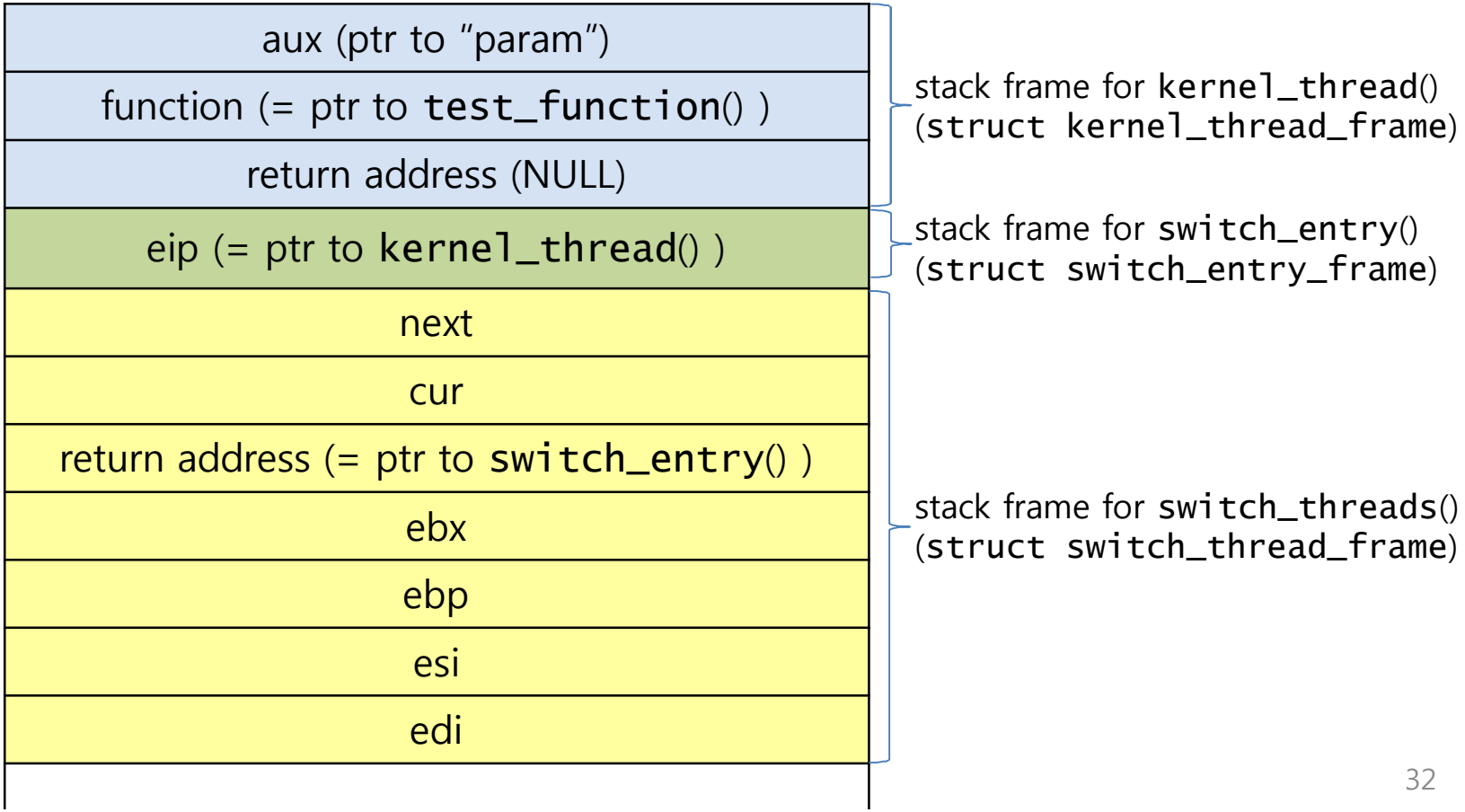


schedule_tail()

```
void schedule_tail (struct thread *prev)
{
  struct thread *cur = running_thread ();
  ASSERT (intr_get_level () == INTR_OFF);
  cur->status = THREAD_RUNNING; /* Mark us as running. */
  thread_ticks = 0; /* Start new time slice. */
#ifdef USERPROG
  process_activate (); /* Activate the new address space. */
#endif

  /* If the thread we switched from is dying, destroy its struct
     thread. This must happen late so that thread_exit() doesn't
     pull out the rug under itself. (We don't free initial_thread
     because its memory was not obtained via palloc().) */
  if (prev!=NULL &&
      prev->status==THREAD_DYING &&
      prev!=initial_thread) {
    ASSERT (prev != cur);
    palloc_free_page (prev);
  }
}
```

Special Case – When a Thread Is Newly Created

thread_create ("test", PRI_DEFAULT, test_function, "param");



switch_entry()

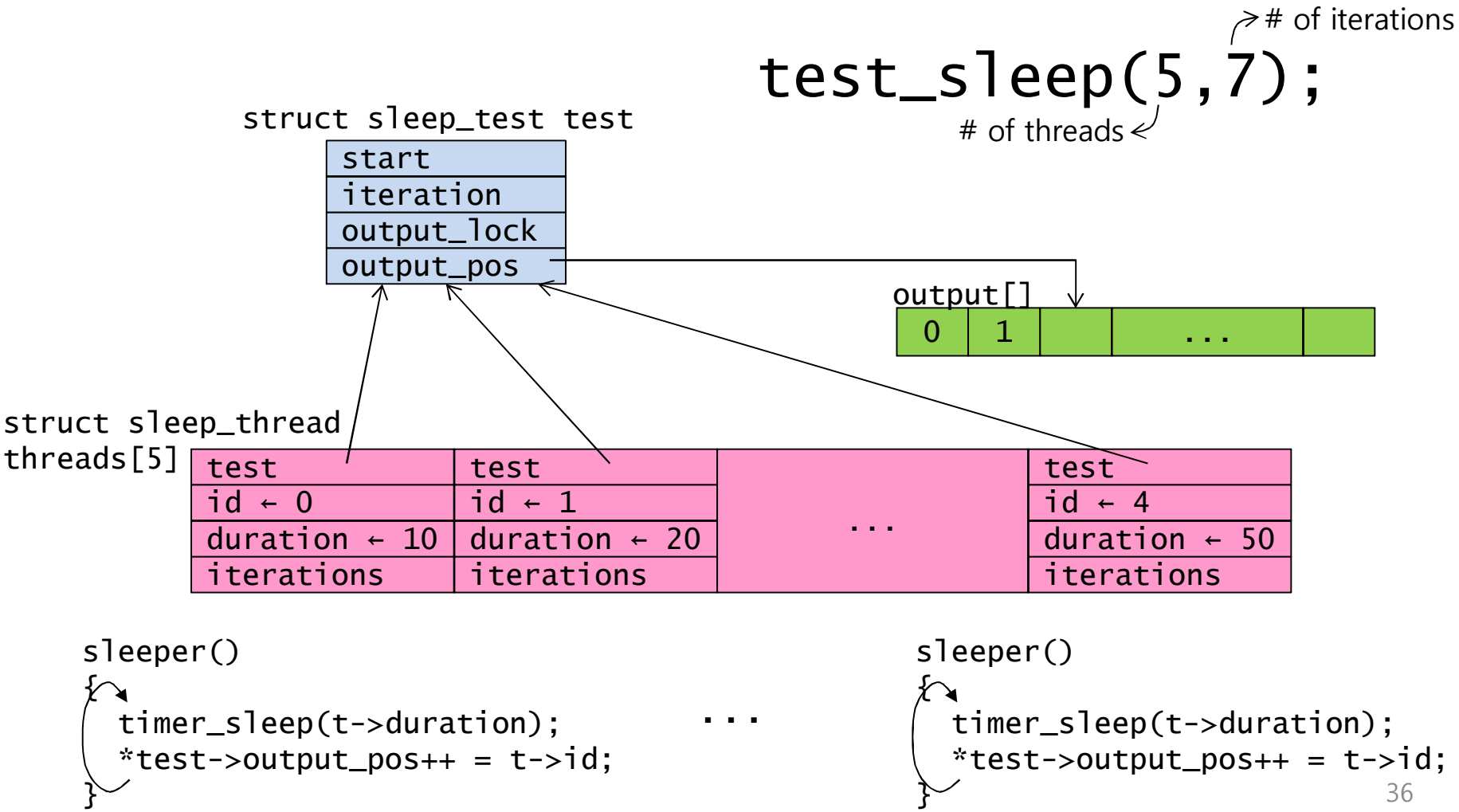
```
.globl switch_entry
.func switch_entry
switch_entry:
        # Discard switch_threads() arguments.
        addl $8, %esp

        # Call schedule_tail(prev).
        pushl %eax
.globl schedule_tail
        call schedule_tail
        addl $4, %esp

        # Start thread proper.
        ret
.endfunc
```

kernel_thread()

```
/* Function used as the basis for a kernel thread. */
static void
kernel_thread (thread_func *function, void *aux)
{
  ASSERT (function != NULL);

  /* The scheduler runs with interrupts off. */
  intr_enable ();

  /* Execute the thread function. */
  function (aux);

  /* If function() returns, kill the thread. */
  thread_exit ();
}
```

5. RUNNING TESTS

Running Kernel Command Line – `alarm-multiple`



Output of `alarm-multiple`