P1: Implement a Multi-Threading Package (in user space)

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Implement the following interface:

void thread_init();

- initialize the user-level threading module (process becomes a thread)

void thread_create(void (*f)(void *arg), void *arg, unsigned int stack_size);

- create another thread that executes f(arg)

void thread_yield();

- yield to another thread (*thread scheduling is non-preemptive*)

void thread_exit();

- thread terminates and yields to another thread or terminates entire process

Example usage

```
static void test_code(void *arg){
    int i;

    for (i = 0; i < 10; i++) {
        printf("%s here: %d\n", arg, i);
        thread_yield();
    }
    printf("%s done\n", arg);
}

int main(int argc, char **argv){
    thread_init();
    thread_create(test_code, "thread 1", 16 * 1024);
    thread_create(test_code, "thread 2", 16 * 1024);
    test_code("main thread");
    thread_exit();
    return 0;
}
```

You’ll need to understand stacks *really well*

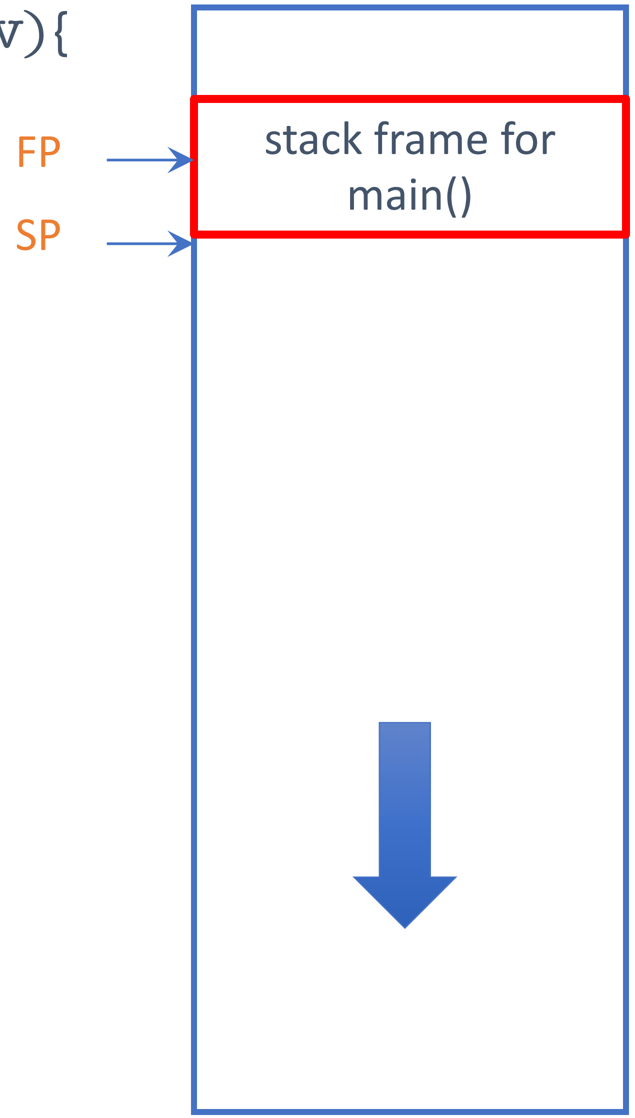
Review: stack (aka call stack)

PC/IP

```
int main(argc, argv){
        ...
        f(3.14)
        ...
}

int f(x){
        ...
        g();
        ...
}

int g(y){
        ...
}
```



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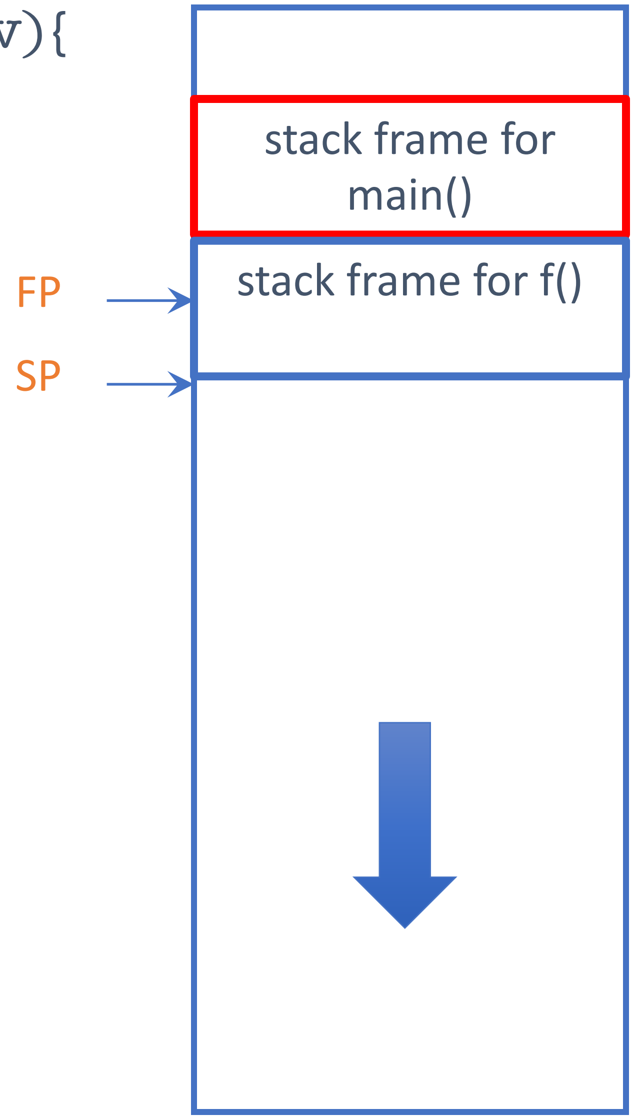

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PC/IP → ...
        g();
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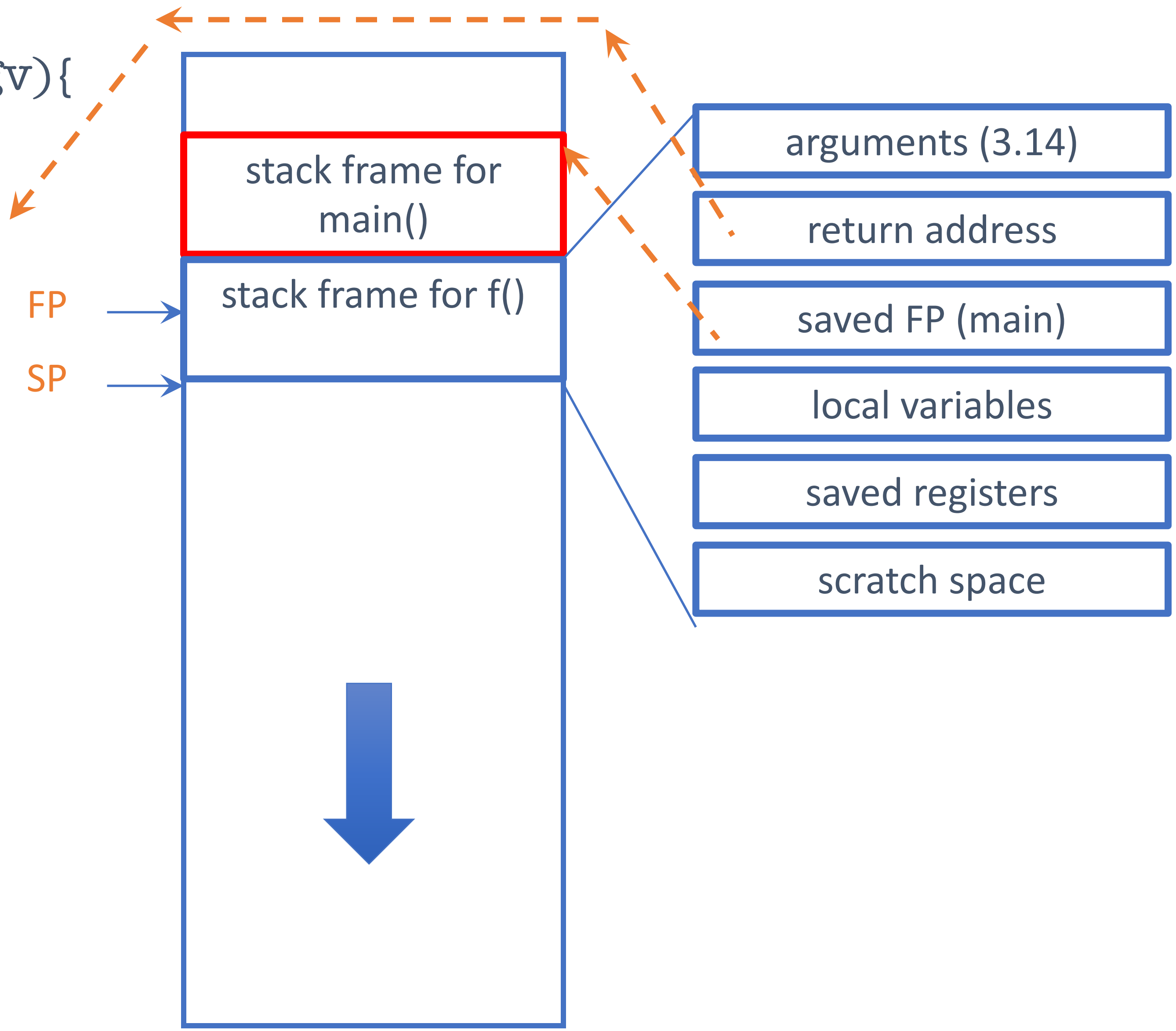

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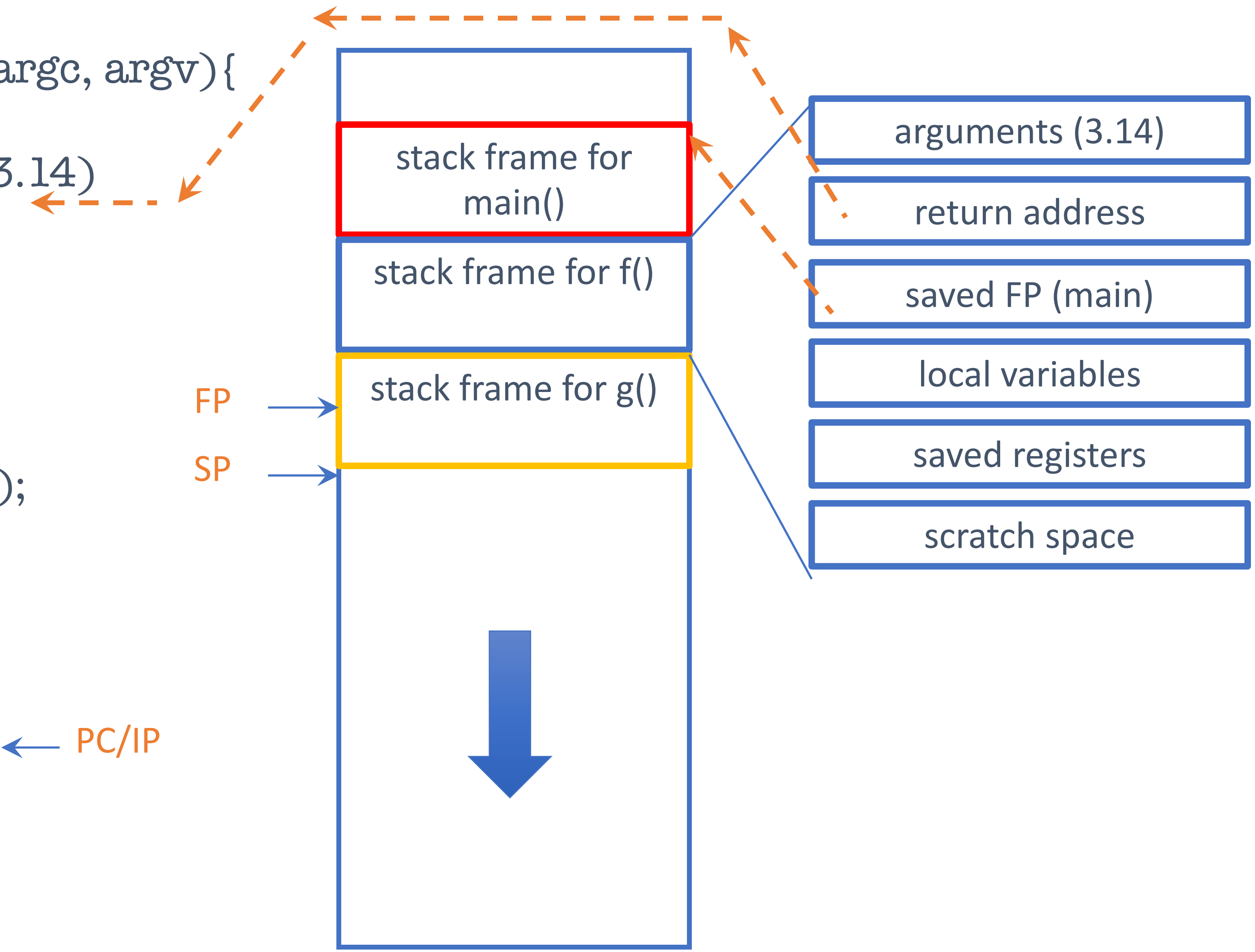

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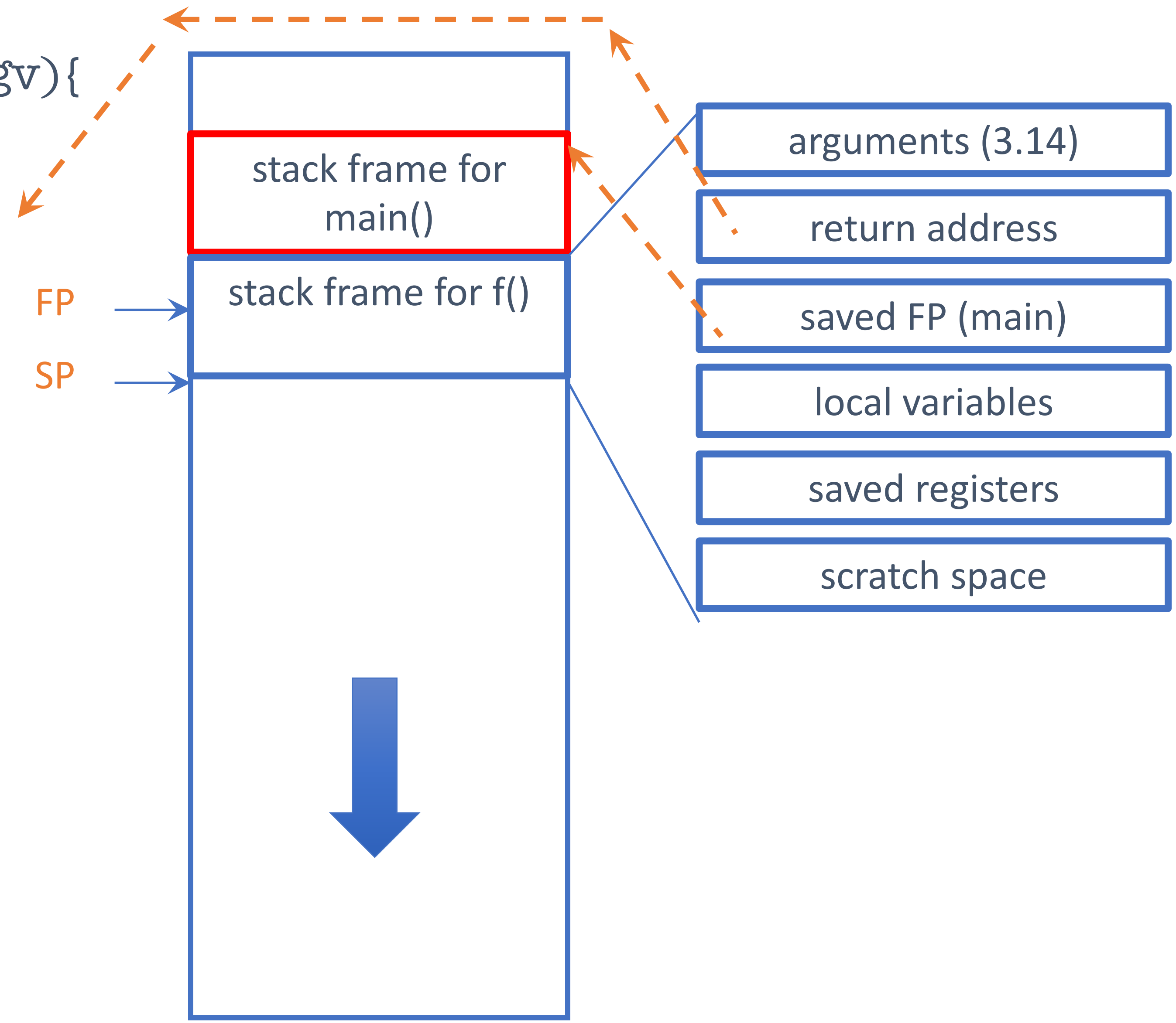

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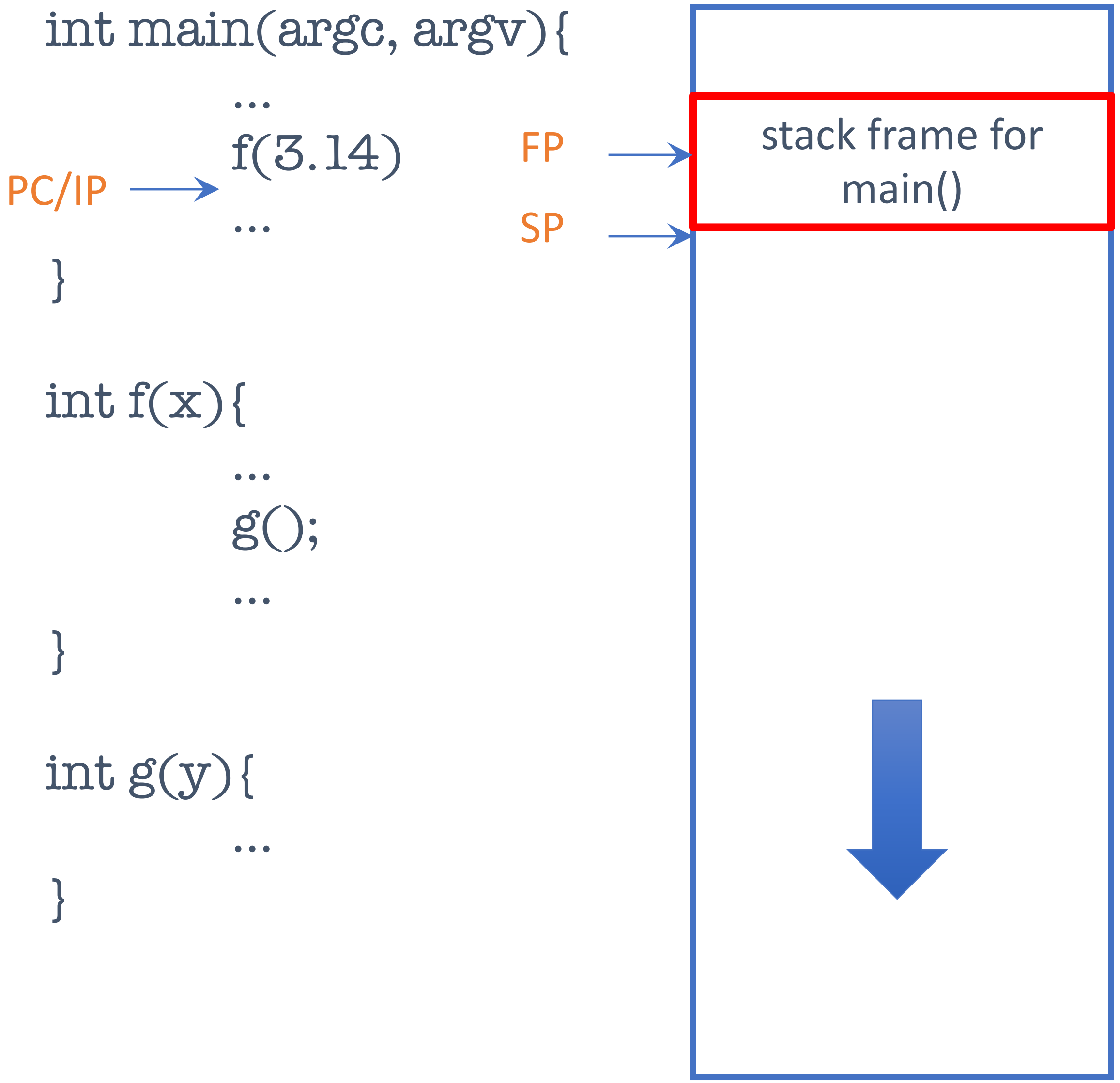

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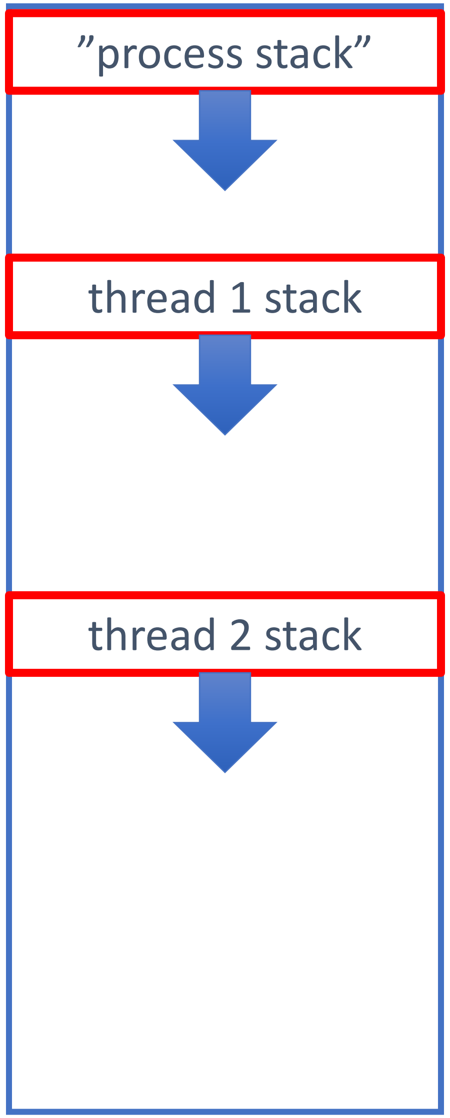
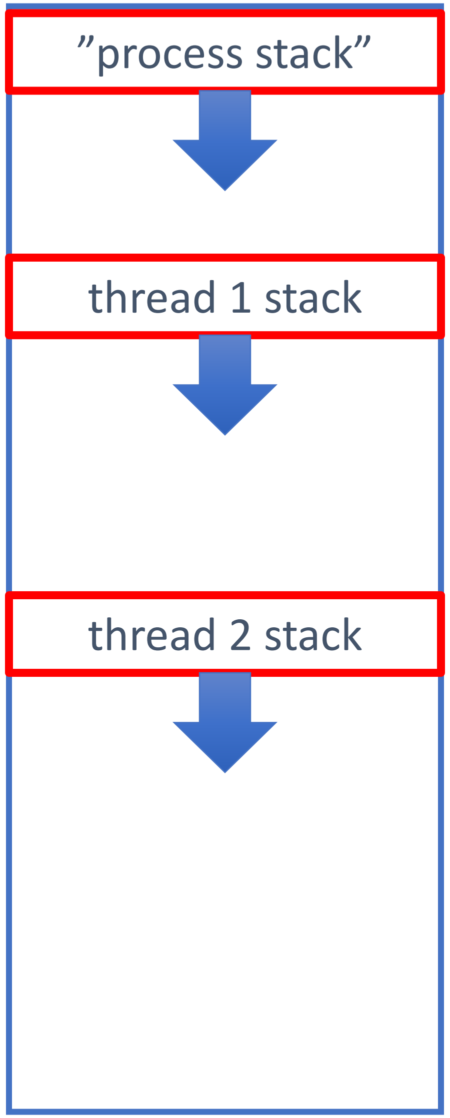


Each thread has its own stack!!

- And its own PC (aka IP), SP, FP, general purpose registers



But we have only one CPU, one core

- And the process has only one stack

We need some magic…

(where's the thread?)

We run one thread at a time

- and save the state of the other threads in a secret location
- The state of a thread (aka *context*) consists of
  - its registers (including PC, SP, and FP)
  - its stack
  - possibly more stuff (scheduling state)

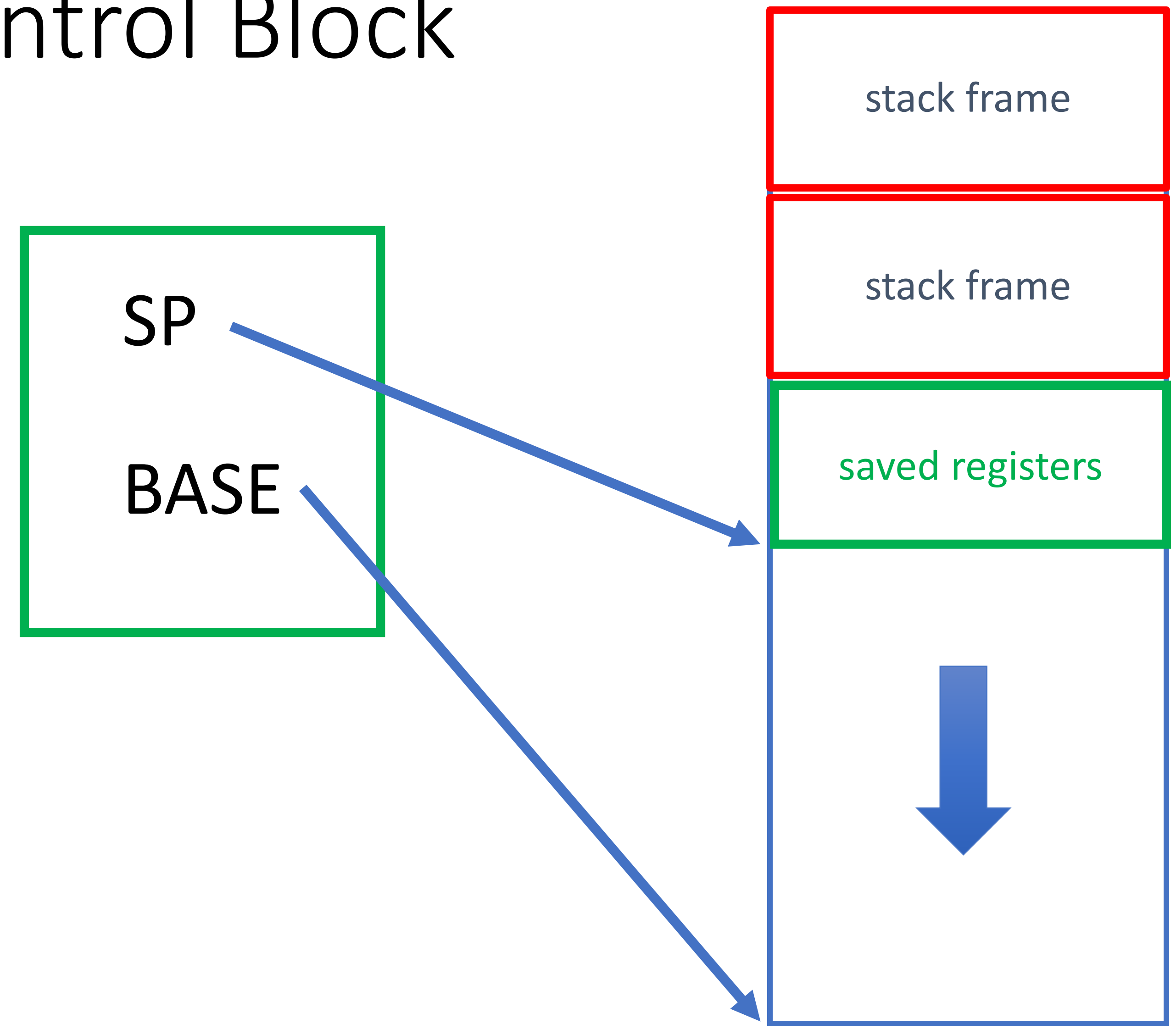
Context Switching

- When a thread exist (thread_exit) or yields (thread_yield) another thread, if any, gets to run
- If a thread yields, we need to save its context
- We need to be able to restore another context

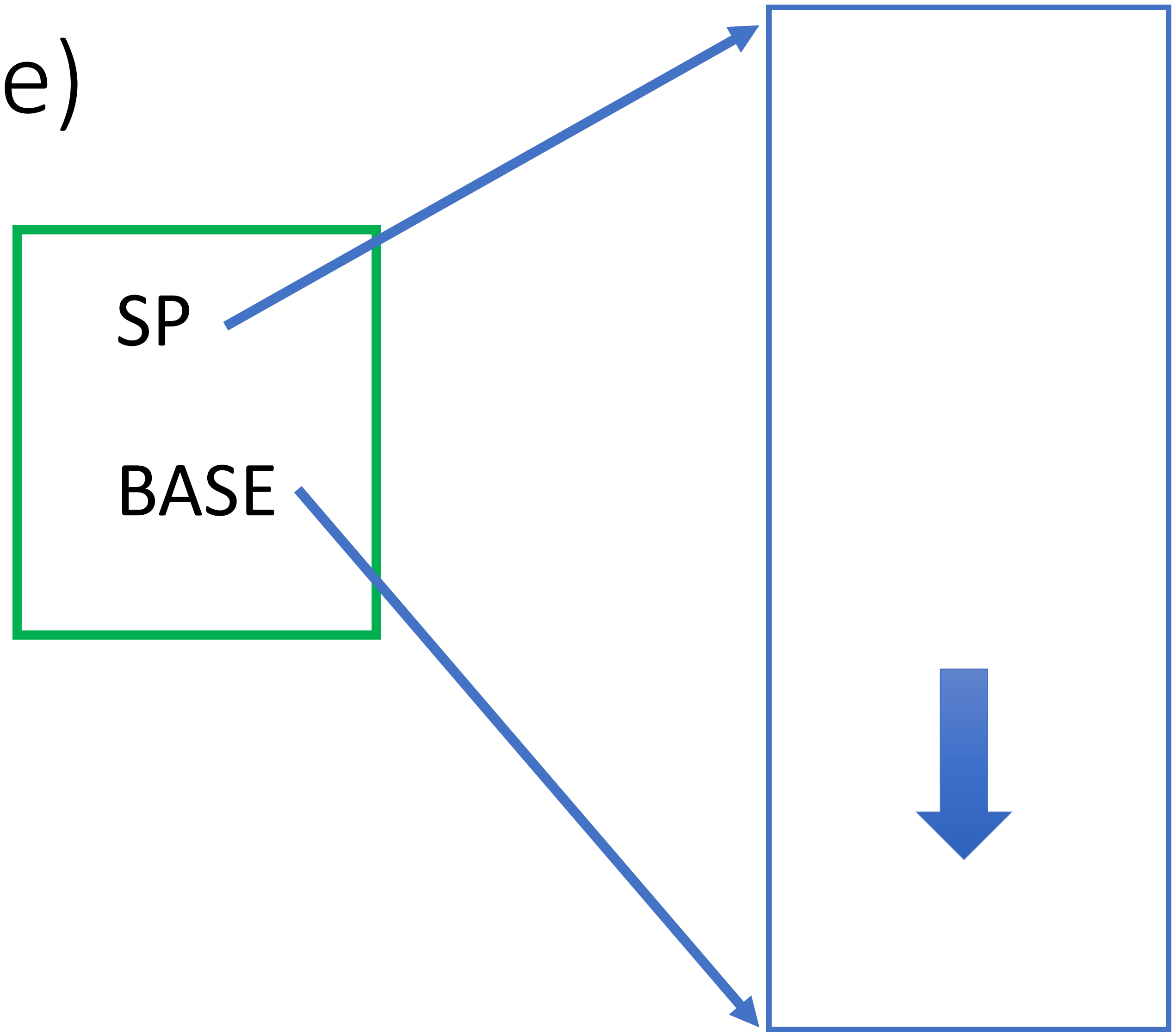
Where to store the context of a thread?

- Convenient to push a thread’s registers onto the stack
  - but you can’t save the stack pointer on the stack…
- Keep the stack pointer in a *Thread Control Block*
  - one TCB per thread

Thread Control Block



Thread Control Block (initial state)



Scheduling State of a Thread

- Running
  - currently running
- Runnable (aka Ready)
  - TCB on the run queue (aka ready queue)
- Terminated
  - TCB marked as having terminated

thread_init()

- Initializes thread package
- Maintains *run queue* and *current thread*
- Allocates a TCB, but *not* a stack
  - because process already has one in use
- Set TCB->*base* to NULL to mark no stack has been allocated
- Initial run queue is empty
- Current thread points to allocated TCB

thread_create(f, arg, stack_size)

- Create a new thread
- Allocates a TCB and a stack (of the given size)
    - set TCB->*base* to “bottom”, and TCB->*sp* to “top”
- May or may not immediately switch to the new thread
    - I think it’s easier if you switch immediately

thread_yield()

- See if the run queue is empty
  - if so, we're done
- Get next TCB of the run queue
- Put current TCB on the run queue
- **Switch contexts**
  - Save registers on the stack
  - Save sp in current TCB
  - Restore sp of next TCB
  - Restore registers from the stack

thread_exit()

- See if the run queue is empty
  - if so, exit from the process using exit(0)
- Mark TERMINATED in TCB
- Get next TCB of the run queue
- **Switch contexts**
  - Save registers on the stack
  - Save sp in current TCB
  - Restore sp of next TCB
  - Restore registers from the stack
- Next thread cleans up last thread

ctx_switch(&old_sp, new_sp)

```
ctx_switch:  // ip already pushed!
    pushq   %rbp
    pushq   %rbx
    pushq   %r15
    pushq   %r14
    pushq   %r13
    pushq   %r12
    pushq   %r11
    pushq   %r10
    pushq   %r9
    pushq   %r8
    movq    %rsp,  (%rdi)
    movq    %rsi,  %rsp
    popq    %r8
    popq    %r9
    popq    %r10
    popq    %r11
    popq    %r12
    popq    %r13
    popq    %r14
    popq    %r15
    popq    %rbx
    popq    %rbp
    retq
```

USAGE:

```
struct tcb *current, *next;

void yield(){
        assert(current->state == RUNNING);
        current->state = RUNNABLE;
        runQueue.add(current);
        next = scheduler();
        next->state = RUNNING;
        ctx_switch(&current->sp, next->sp)
        current = next;
}
```

Starting a *new* process

```
ctx_start:
   pushq   %rbp
   pushq   %rbx
   pushq   %r15
   pushq   %r14
   pushq   %r13
   pushq   %r12
   pushq   %r11
   pushq   %r10
   pushq   %r9
   pushq   %r8
   movq    %rsp, (%rdi)
   movq    %rsi, %rsp
   callq   ctx_entry
```

```
void thread_create( func ){
        current->state = RUNNABLE;
        runQueue.add(current);
        next = malloc(…);
        next->func = func;
        next->stack  = malloc(…)
        next->state = RUNNING;
        ctx_start(&current->sp,  top_of_stack)
        current = next;
}

void ctx_entry(){
        current = next;
        (*current->func)();
        current->state = FINISHED;
        finishedQueue.add(current);
        next = scheduler();
        next->state = RUNNING;
        ctx_switch(&current->sp, next->sp)
        // this location cannot be reached
}
```

Synchronization Primitives

Semaphores

- We’re not teaching general semaphores in CS4410 anymore
- A semaphore is a kind of counter:

```
struct sema;
void sema_init(struct sema *sema, unsigned int count);
void sema_dec(struct sema *sema);
void sema_inc(struct sema *sema);
bool sema_release(struct sema *sema);
```

Semaphore interface

`void sema_init(struct sema *sema, unsigned int count)`

- Initialize the semaphore to the given counter

`void sema_dec(struct sema *sema)`

- Wait until sema > 0, then decrement semaphore

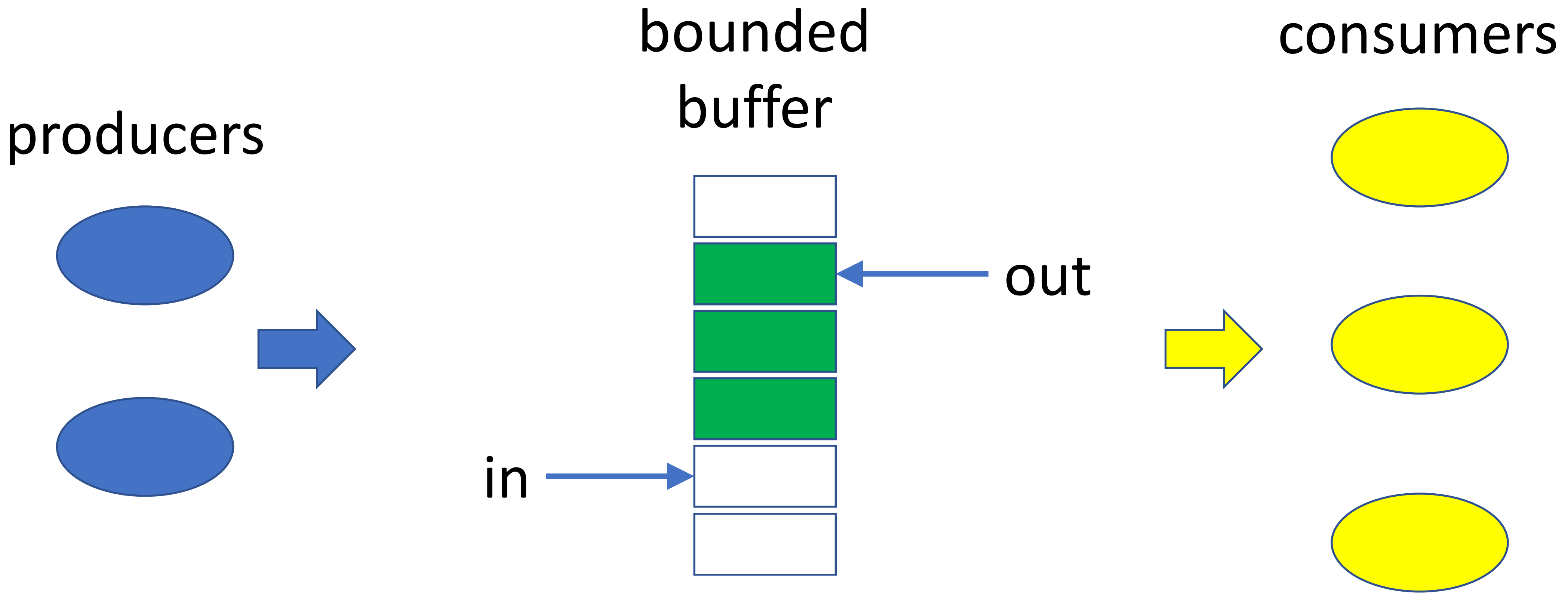
`void sema_inc(struct sema *sema)`

- Increment the semaphore

`bool sema_release(struct sema *sema)`

- Release the semaphore

Example usage: Producer/Consumer



Producers block
when buffer is full

Consumers block
when buffer is empty

Example usage: Producer/Consumer

```
#define NSLOTS    3

static struct sema s_empty, s_full, s_lock;
static unsigned int in, out;
static char *slots[NSLOTS];

int main(int argc, char **argv){
    thread_init();
    sema_init(&s_lock, 1);
    sema_init(&s_full, 0);
    sema_init(&s_empty, NSLOTS);

    thread_create(consumer, "consumer 1", 16 * 1024);
    producer("producer 1");
    return 0;
}
```

Example usage: Producer/Consumer

```
static void producer(void *arg){
    for (;;) {
        // first make sure there's an empty slot.
        sema_dec(&s_empty);

        // now add an entry to the queue
        sema_dec(&s_lock);
        slots[in++] = arg;
        if (in == NSLOTS) in = 0;
        sema_inc(&s_lock);

        // finally, signal consumers
        sema_inc(&s_full);
    }
}
```

Example usage: Producer/Consumer

```
static void consumer(void *arg){
    unsigned int i;

    for (i = 0; i < 5; i++) {
        // first make sure there's something in the buffer
        sema_dec(&s_full);

        // now grab an entry to the queue
        sema_dec(&s_lock);
        void *x = slots[out++];
        printf("%s: got '%s'\n", arg, x);
        if (out == NSLOTS) out = 0;
        sema_inc(&s_lock);

        // finally, signal producers
        sema_inc(&s_empty);
    }
}
```

Semaphore implementation

- Associate a queue with the semaphore
- If thread tries to decrement a zero semaphore, put its TCB on the queue
- If thread increments a semaphore with a non-empty queue, don’t increment the semaphore but move one TCB from the semaphore’s queue to the read queue

EGOS (Earth and Grass O.S.)

Overview

- Runs as a process in user space on Linux, Mac OS X, …
  - as long as it supports mmap()
- Architecture:
  - Earth: a virtual machine monitor (like VMWare, VirtualBox, KVM, …)
  - Grass: a microkernel operating system
    - microkernel: file system etc. runs mostly in user space

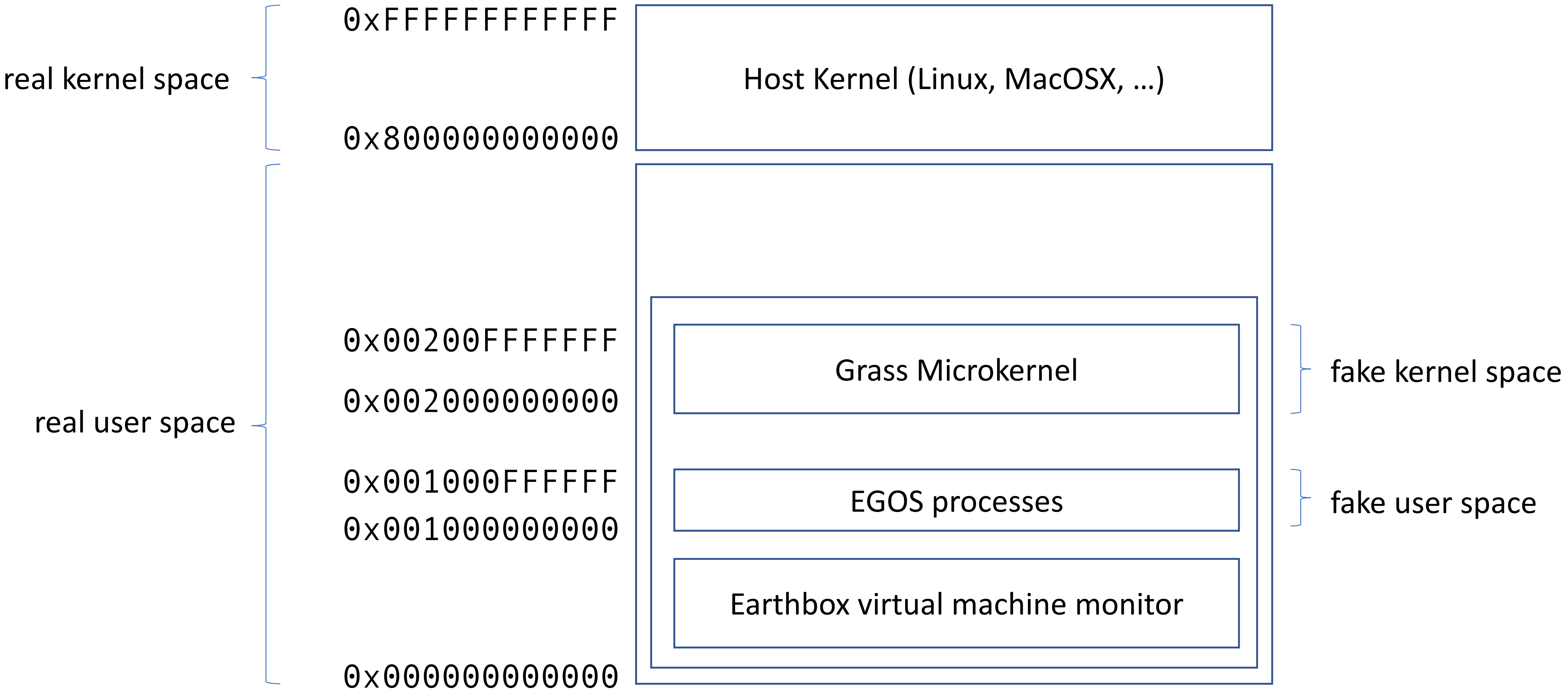
Earthbox

- Emulates a computer
  - Interrupts
  - TLB
  - Devices (disks, tty, clock, etc.)
- Sets up the address spaces for Grass kernel and EGOS processes
- Then context switches to Grass kernel

Grass Microkernel

- Organized as a collection of processes
  - processes communicate through exchanging messages
  - process can only block by waiting for a message
- Some are purely kernel processes, some support user space
- Device drivers are implemented as kernel processes
  - invoke Earth's virtual devices
- Main file system implemented in user space
  - a simple file system implemented in kernel space for booting

Address Space Regions



Very very small system call interface

- sys_getpid()
- sys_recv(&message)
- sys_send(message)
- sys_rpc(request, &response)
- sys_exit(status)
- sys_gettime()
- sys_print(string)

Other O.S. services

- spawn a process:
  - send request to kernel spawn server
- read/write/create a file:
  - send request to one of the file servers
- print something:
  - send request to kernel tty server
- read from keyboard:
  - send request to kernel tty server
- …