CS 318 Principles of Operating Systems

Fall 2022

Lecture 4: Thread

JOHNS HOPKINS
WHITING SCHOOL
of ENGINEERING

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Administrivia

Lab 0 due today

Fill out project group form

- If you don't have a group yet, you can fill the form to request team matching

Lab 1 released

- Lab 1 overview session next Tuesday
- Read the requirements now (can start with Alarm Clock)

GitHub classroom invitation link

- Used for the following lab assignments

Processes

Recall that a process includes many things

- An address space (defining all the code and data pages)
- OS resources (e.g., open files) and accounting information
- Execution state (PC, SP, regs, etc.)

Creating a new process is costly

- because of all of the data structures that must be allocated and initialized
  - recall struct proc in Solaris

Communicating between processes is also costly

- because most communication goes through the OS
  - overhead of system calls and copying data

Concurrent Programs

Recall our Web server example (or any parallel program)…

- forks off copies of itself to handle multiple simultaneous requests

To execute these programs we need to

- Create several processes that execute in parallel
- Cause each to map to the same address space to share data
  - They are all part of the same computation
- Have the OS schedule these processes in parallel (logically or physically)

This situation is very inefficient

- Space: PCB, page tables, etc.
- Time: create data structures, fork and copy addr space, etc.

Rethinking Processes

What is similar in these cooperating processes?

- They all share the same code and data (address space)
- They all share the same privileges
- They all share the same resources (files, sockets, etc.)

What don't they share?

- Each has its own execution state: PC, SP, and registers

Idea: Why not separate the process concept from its execution state?

- Process: address space, privileges, resources, etc.
- Execution state: PC, SP, registers

Exec state also called thread of control, or thread

Threads

Modern OSes separate the concepts of processes and threads

- The thread defines a sequential execution stream within a process (PC, SP, registers)
- The process defines the address space and general process attributes

A thread is bound to a single process

- Processes, however, can have multiple threads

Threads become the unit of scheduling

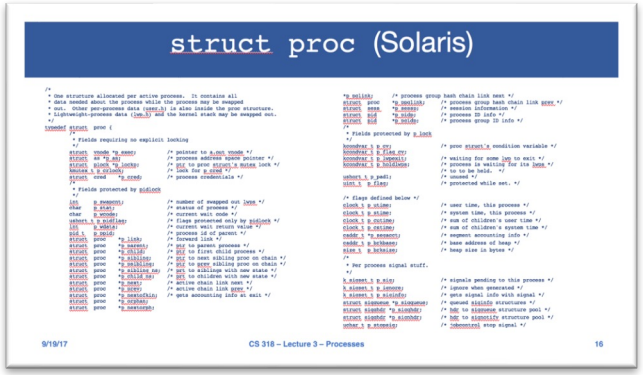
- Processes are now the containers in which threads execute
- Processes become static, threads are the dynamic entities

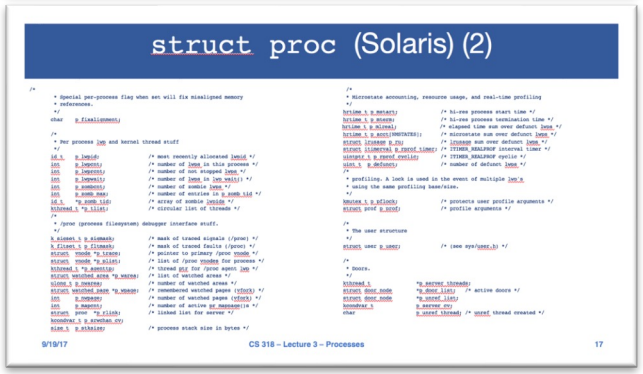
Data structure: *Thread Control Block* (TCB)

Small and Fast…

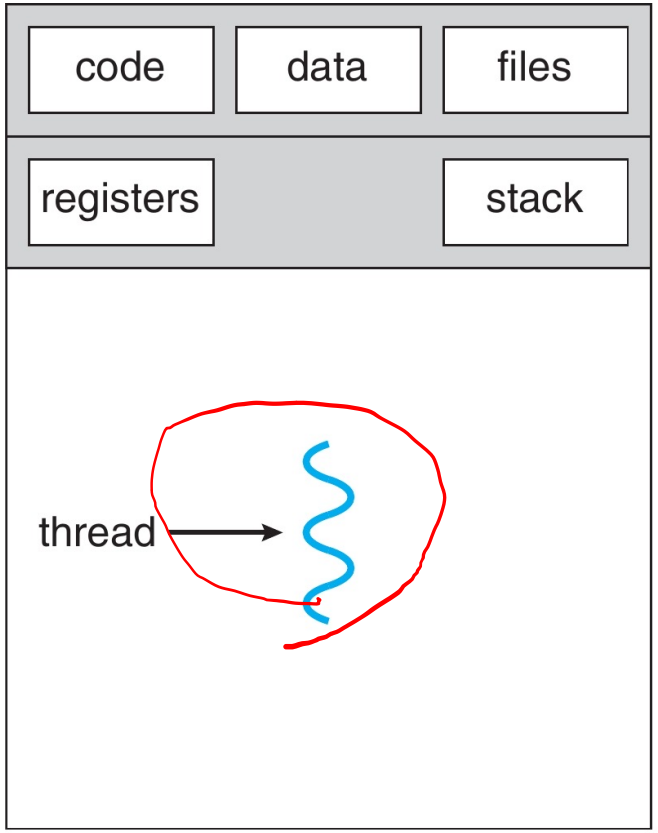
Pintos thread class

```
struct thread {
    tid_t tid;                          /* Thread identifier. */
    enum thread_status status;          /* Thread state. */
    char name[16];                      /* Name (for debugging purposes). */
    uint8_t *stack;                     /* Saved stack pointer. */
    int priority;                       /* Priority. */
    struct list_elem allelem;           /* List element for all threads list. */
    struct list_elem elem;              /* List element. */
    unsigned magic;                     /* Detects stack overflow. */
};
```

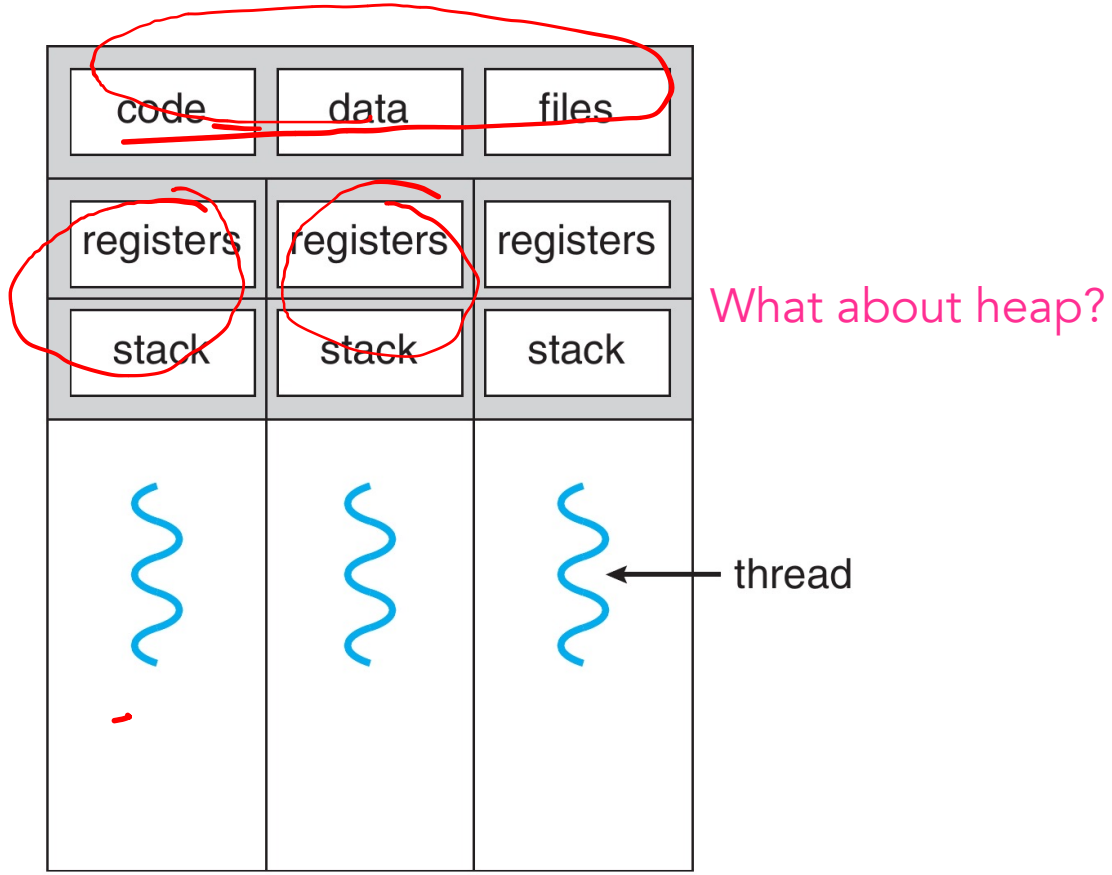




Threads in a Process



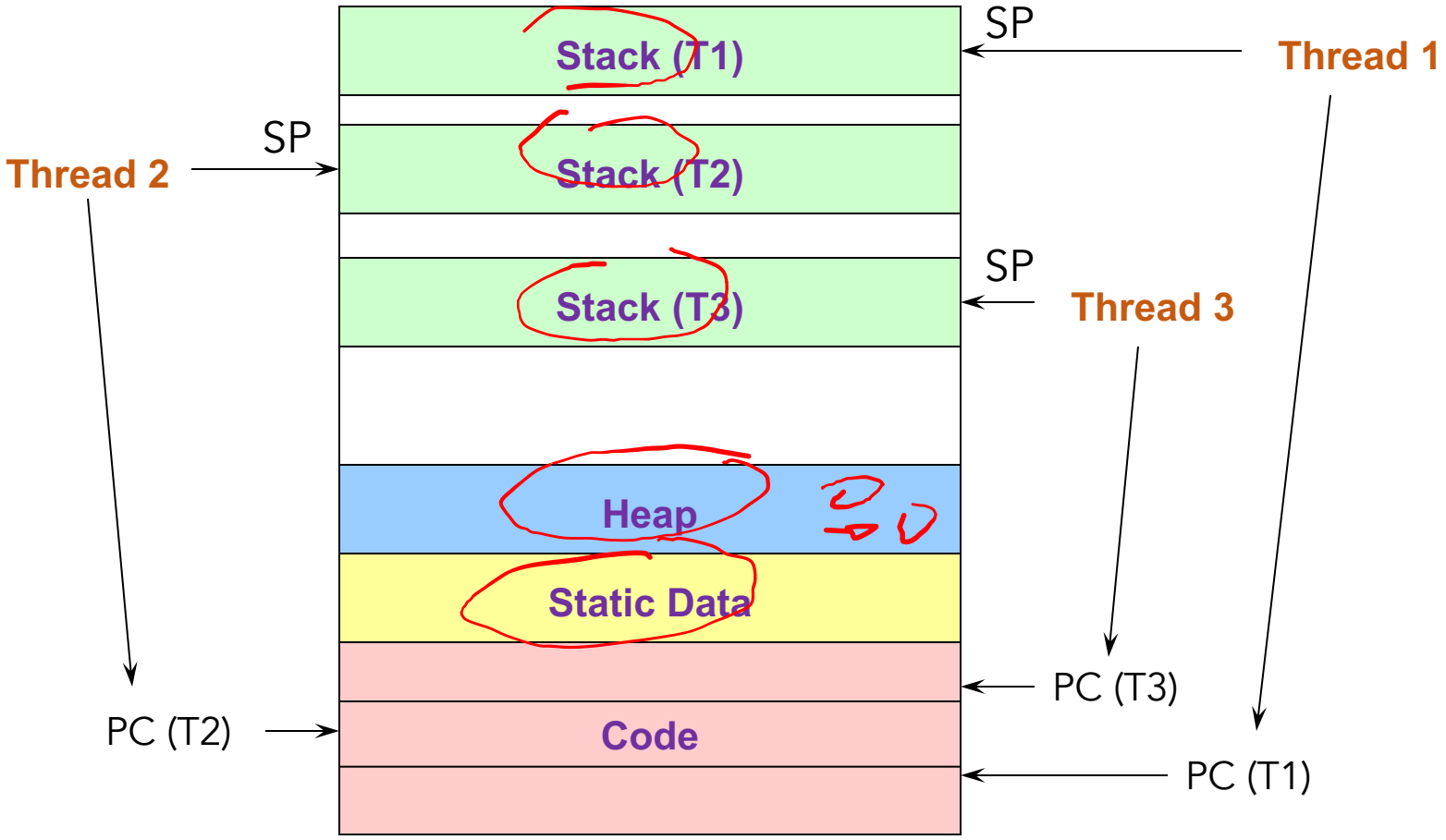
single-threaded process



multithreaded process

What about heap?

Threads in a Process



Process/Thread Separation

Easier to support multithreaded applications

- Concurrency does not require creating new processes

Concurrency (multithreading) can be very useful

- Improving program structure
- Allowing one process to use multiple CPUs/cores
- Handling concurrent events (e.g., Web requests)
- Allowing program to overlap I/O and computation

So multithreading is even useful on a uniprocessor

- Although today even cell phones are multicore

But, brings a whole new meaning to Spaghetti Code

- Forcing OS students to learn about synchronization…

Threads: Concurrent Servers

`fork()` to create new processes to handle requests is overkill

Recall our forking Web server:

```
while (1) {
  int sock = accept();
  if ((child_pid = fork()) == 0) {
    // Handle client request
    // Close socket and exit
  } else {
    // Close socket
  }
}
```

Threads: Concurrent Servers

Instead, we can create a new thread for each request

```
web_server() {
    while (1) {
        int sock = accept();
        thread_fork(handle_request, sock);
    }
}

handle_request(int sock) {
    Process request
    close(sock);
}
```

Thread Package API

```
tid thread_create (void (*fn) (void *), void *);
```

- Create a new thread, run fn with arg

```
void thread_exit ();
```

- Destroy current thread

```
void thread_join (tid thread);
```

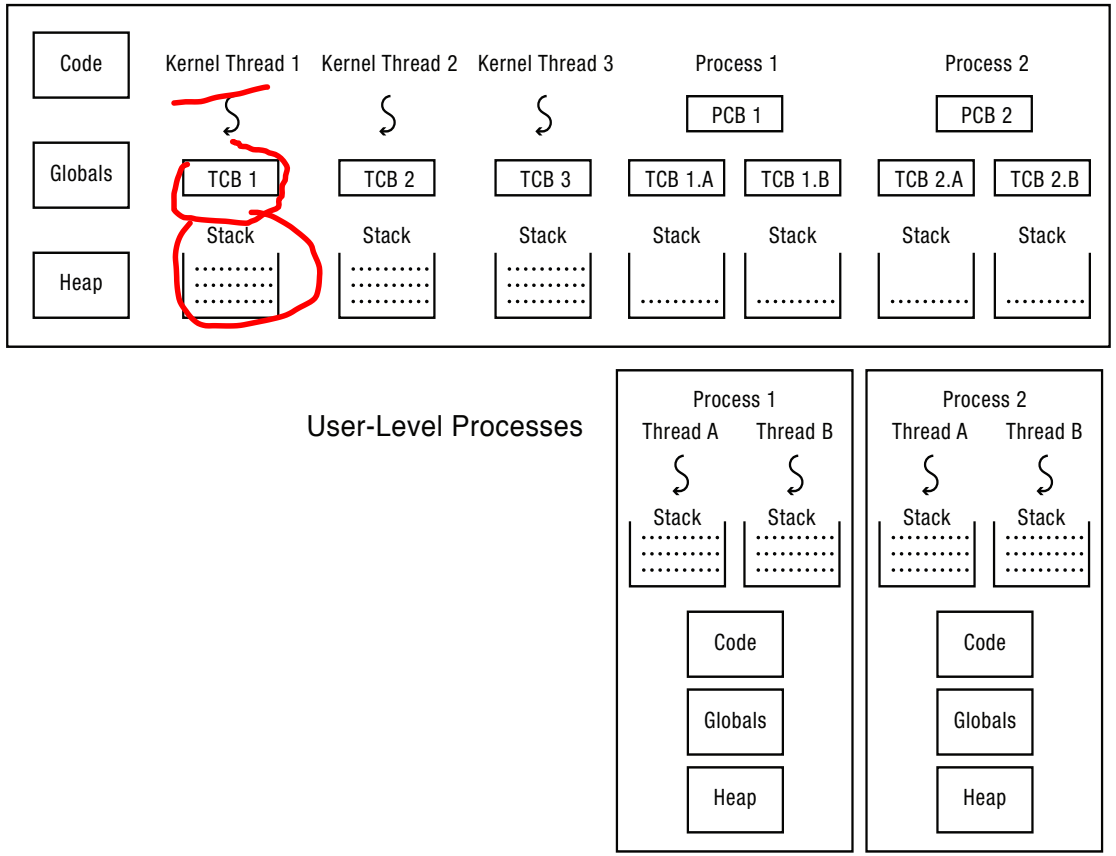
- Wait for thread thread to exit

See Birrell for good introduction

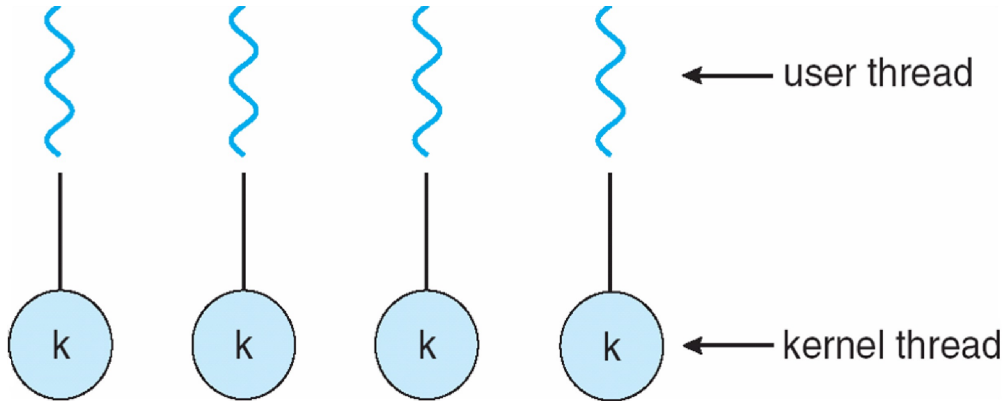
Implementing Threads

`thread_create(fun, args)`

- Allocate **Thread Control Block (TCB)**
- Allocate stack
- Build stack frame for base of stack
- Put func, args on stack
- Put thread on ready list



Kernel-Level Threads



All thread operations are implemented in the kernel

The OS schedules all the threads in the system

Also known as lightweight processes

- Windows: threads
- Solaris: lightweight processes (LWP)
- POSIX Threads (pthreads): PTHREAD_SCOPE_SYSTEM

Kernel Thread Limitations

Every thread operation must go through kernel

- create, exit, join, synchronize, or switch for any reason
- On my laptop: syscall takes 100 cycles, fn call 5 cycles
- Result: threads 10x-30x slower when implemented in kernel

One-size fits all thread implementation

- Kernel threads must please all people
- Maybe pay for fancy features (priority, etc.) you don't need

General heavy-weight memory requirements

- e.g., requires a fixed-size stack within kernel
- other data structures designed for heavier-weight processes

Alternative: User-Level Threads

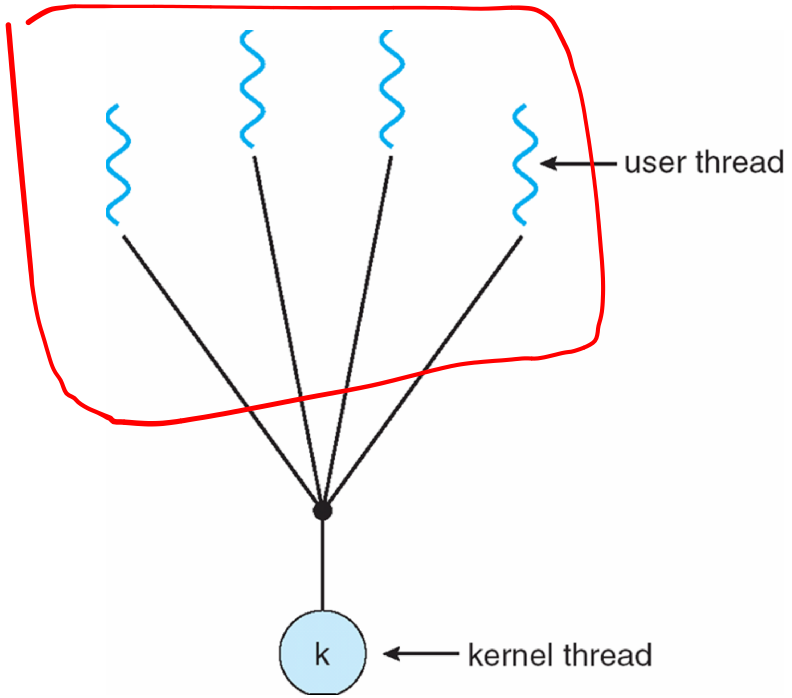
Implement as user-level library (a.k.a. green threads)

- One kernel thread per process
- `thread_create`, `thread_exit`, etc., just library functions
- library does thread context switch

User-level threads are small and fast

- pthreads: PTHREAD_SCOPE_PROCESS
- Java: Thread

n : 1



User-Level Thread Limitations

Can't take advantage of multiple CPUs or cores

User-level threads are invisible to the OS

- They are not well integrated with the OS

As a result, the OS can make poor decisions

- Scheduling a process with idle threads
- A blocking system call (e.g., disk `read`) blocks all threads
  - Even if the process has other threads that can execute
- Unscheduling a process with a thread holding a lock

How to solve this?

- communication between the kernel and the user-level thread manager (Windows 8)
  - Scheduler Activation

Kernel vs. User Threads

Kernel-level threads

- Integrated with OS (informed scheduling)
- Slower to create, manipulate, synchronize

User-level threads

- Faster to create, manipulate, synchronize
- Not integrated with OS (uninformed scheduling)

Understanding their differences is important

- Correctness, performance

Kernel and User Threads

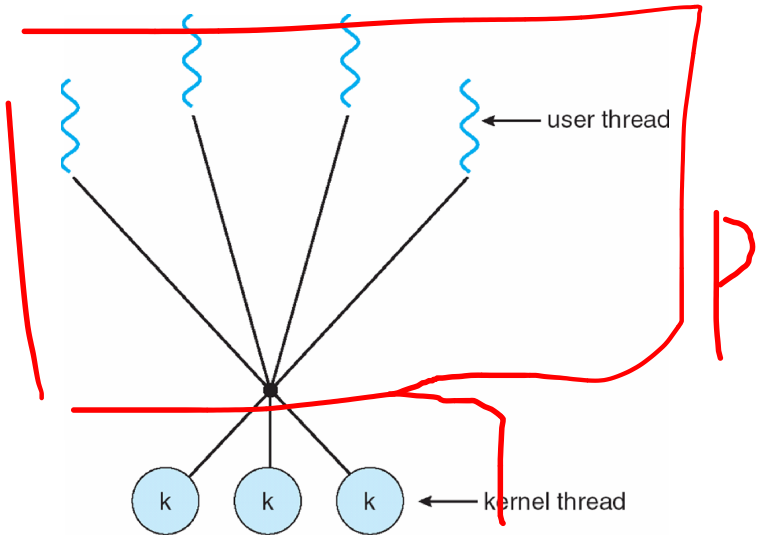
Or use both kernel and user-level threads

- Can associate a user-level thread with a kernel-level thread
- Or, multiplex user-level threads on top of kernel-level threads

Java Virtual Machine (JVM) (also C#, others)

- Java threads are user-level threads
- On older Unix, only one "kernel thread" per process
  - Multiplex all Java threads on this one kernel thread
- On modern OSes
  - Can multiplex Java threads on multiple kernel threads
  - Can have more Java threads than kernel threads
  - Why?

User Threads on Kernel Threads



User threads implemented on kernel threads

- Multiple kernel-level threads per process
- `thread_create`, `thread_exit` still library functions as before

Sometimes called n : m threading

- Have n user threads per m kernel threads (Simple user-level threads are n : 1, kernel threads 1 : 1)

Implementing User-Level Threads

Allocate a new stack for each `thread_create`

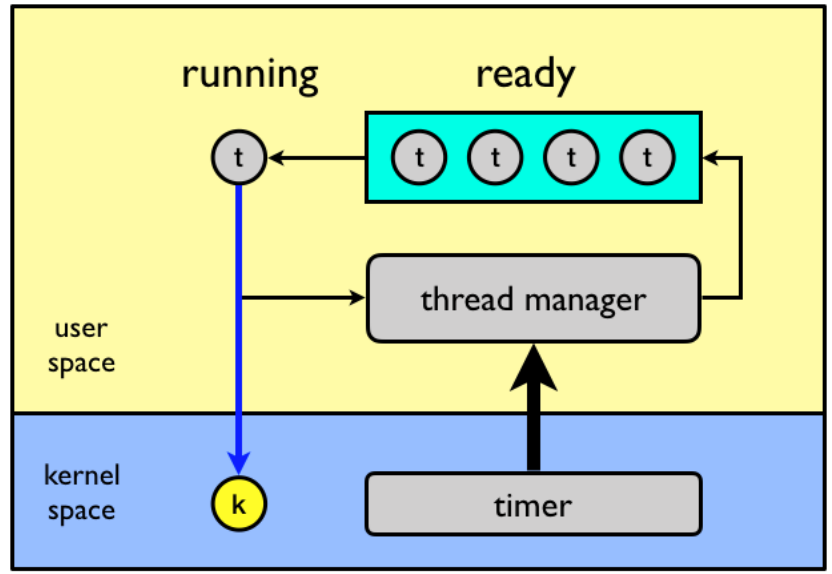
Keep a queue of runnable threads

Schedule periodic timer signal (`setitimer`)

- Switch to another thread on timer signals (preemption)

Replace blocking system calls (`read`/`write`/etc.) to non-blocking calls

- If operation would block, switch and run different thread



User-Level Thread Scheduling

The thread scheduler determines when a thread runs

It uses queues to keep track of what threads are doing

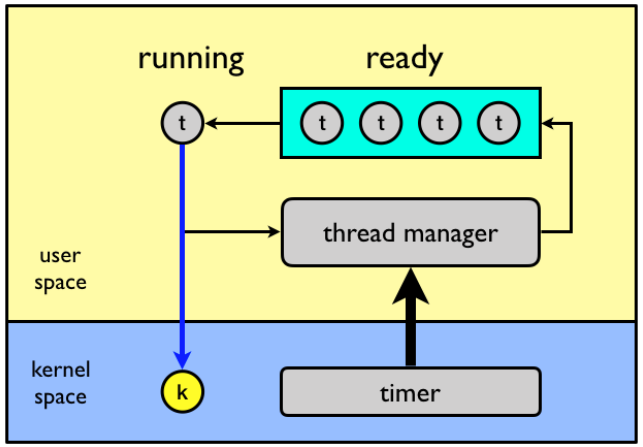
- Just like the OS and processes
- But it is implemented at user-level in a library

Run queue: Threads currently running (usually one)

Ready queue: Threads ready to run

Are there wait queues?

- How might you implement sleep(time)?



Non-Preemptive Thread Scheduling

Threads voluntarily give up the CPU with `yield`

Ping Thread

```
while (1) {
 printf("ping\n");
 yield();
}
```

Pong Thread

```
while (1) {
 printf("pong\n");
 yield();
}
```

What is the output of running these two threads?

yield()

Wait a second. How does yield() work?

The semantics of yield are that it gives up the CPU to another thread

- In other words, it context switches to another thread

So what does it mean for yield to return?

- It means that *another thread* called yield!

Execution trace of ping/pong

- `printf("ping\n");`
- `yield();`
- `printf("pong\n");`
- `yield();`
- …

Preemptive Thread Scheduling

Non-preemptive threads have to voluntarily give up CPU

- A long-running thread will take over the machine
- Only voluntary calls to yield, sleep, or finish cause a context switch

Preemptive scheduling causes an involuntary context switch

- Need to regain control of processor asynchronously
- Use timer interrupt
- Timer interrupt handler forces current thread to "call" yield

Thread Context Switch

The context switch routine does all of the magic

- Saves context of the currently running thread (old_thread)
  - Push all machine state onto its stack
- Restores context of the next thread
  - Pop all machine state from the next thread's stack
- The next thread becomes the current thread
- Return to caller as new thread

This is all done in assembly language

- It works **at** the level of the procedure calling convention, so it cannot be implemented using procedure calls

Background: Calling Conventions (1)

What

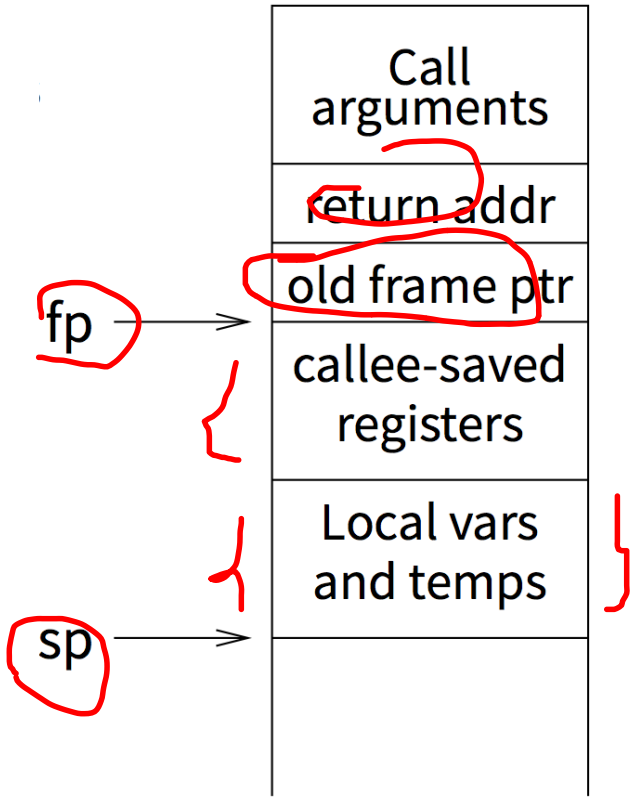
- a standard on how functions should be implemented and called by the *machine*
- how a function call in C or C++ gets converted into assembly language
  - how arguments are passed to a func, how return values are passed back out of a function, how the func is called, and how the func manages the stack and its stack frame, etc.
- Compilers need to obey this standard in compiling code into assembly
  - set up the stack and registers properly

Why

- A program calls functions across many object files and libraries
- For these codes to be interfaced together, we need a standardization for calls

Background: Calling Conventions (2)

x86 calling convention stack setup




```
int compute(int a, int b)
{
  int i, result;
  result = 0;
  for (i = 0; i < a; i++)
    result = result + b - i;
  return result;
}
void foo()
{
  int x, y, z;
  x = 3;
  y = 5;
  z = compute(x, y);
  printf("compute(%d, %d)=%d\n", x, y, z);
}
```

Background: Calling Conventions

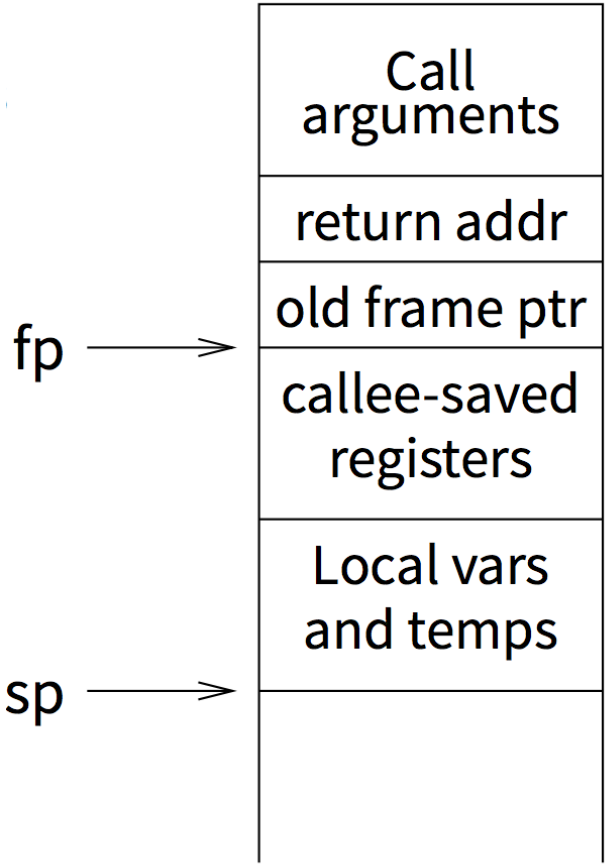
Registers divided into 2 groups

- caller-saved regs: callee function free to modify
  - on x86, %eax [return val], %edx, & %ecx
- callee-saved regs: callee function must restore to original value upon return
  - on x86, %ebx, %esi, %edi, plus %ebp and %esp

- save active caller registers
- call `compute` (pushes pc)

- restore caller registers

- save used callee registers
- ...do stuff...
- restore callee saved registers
- jump back to calling function



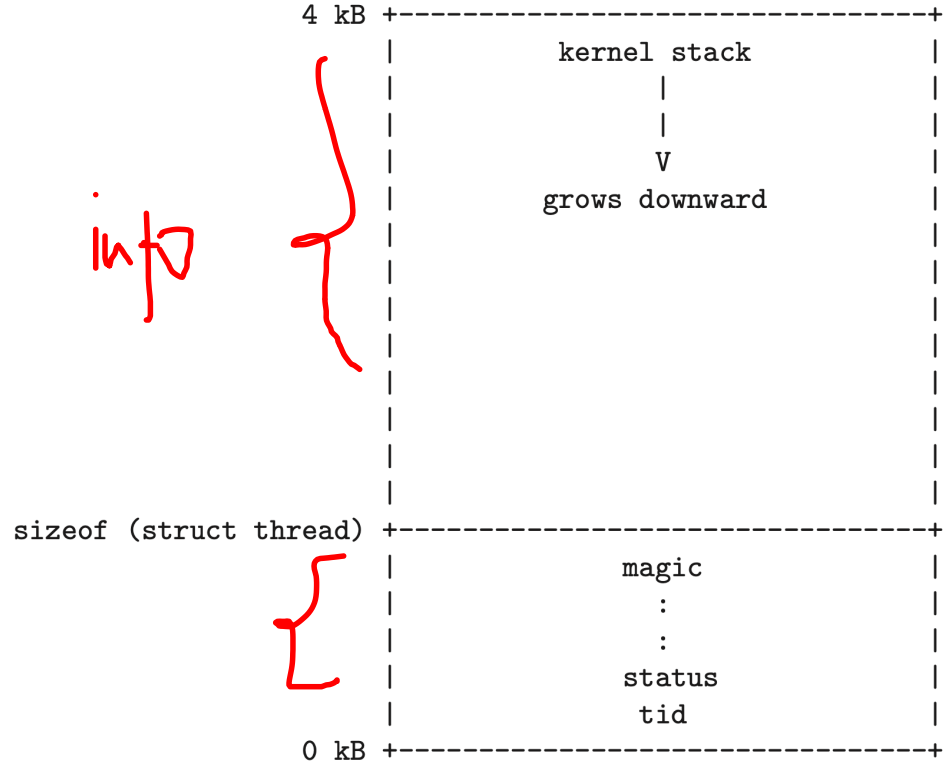
Pintos Thread Implementation

Thread control block structure

```
struct thread {
  tid_t tid;
  enum thread_status status;
  char name[16];
  uint8_t *stack; /* Saved stack pointer. */
  struct list_elem allelem;
  struct list_elem elem;
  unsigned magic; /* Detects stack overflow. */
};

uint32_t thread_stack_ofs =
         offsetof(struct thread, stack);
```

/* Each thread structure is stored in its own 4 kB page. The thread structure itself sits at the very bottom of the page (at offset 0). The rest of the page is reserved for the thread's kernel stack, which grows downward from the top of the page (at offset 4 kB) */



Pintos `switch_threads`

C declaration for thread switch function:

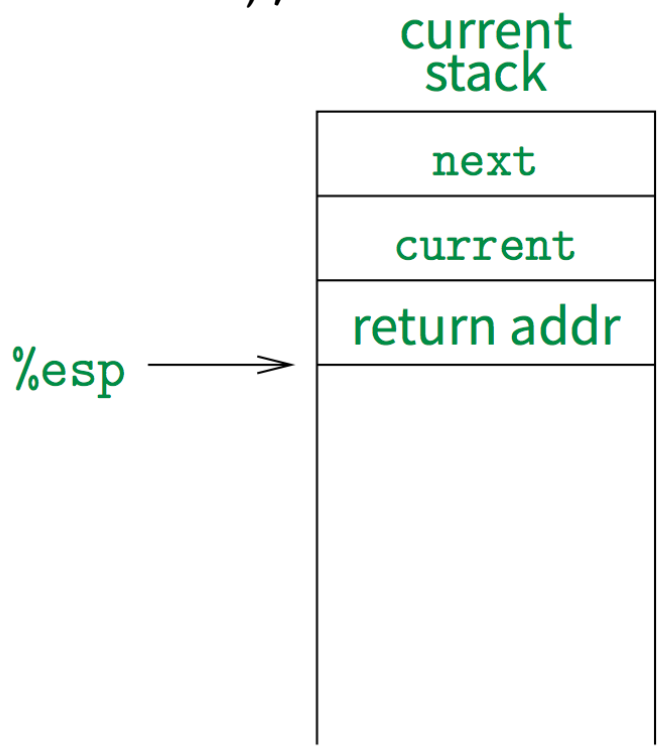
```
- struct thread *switch_threads (struct thread *cur, struct thread *next);
```

Actual implementation is in i386 assembly

i386 switch_threads

```
struct thread *switch_threads (struct thread *cur, struct thread *next);
```

```
pushl %ebx; pushl %ebp      # Save callee-saved regs
pushl %esi; pushl %edi
mov thread_stack_ofs, %edx # %edx = offset of stack field
                           # in thread struct
movl 20(%esp), %eax        # %eax = cur
movl %esp, (%eax,%edx,1)   # cur->stack = %esp
movl 24(%esp), %ecx        # %ecx = next
movl (%ecx,%edx,1), %esp   # %esp = next->stack
popl %edi; popl %esi       # Restore calle-saved regs
popl %ebp; popl %ebx
ret                        # Resume execution
```

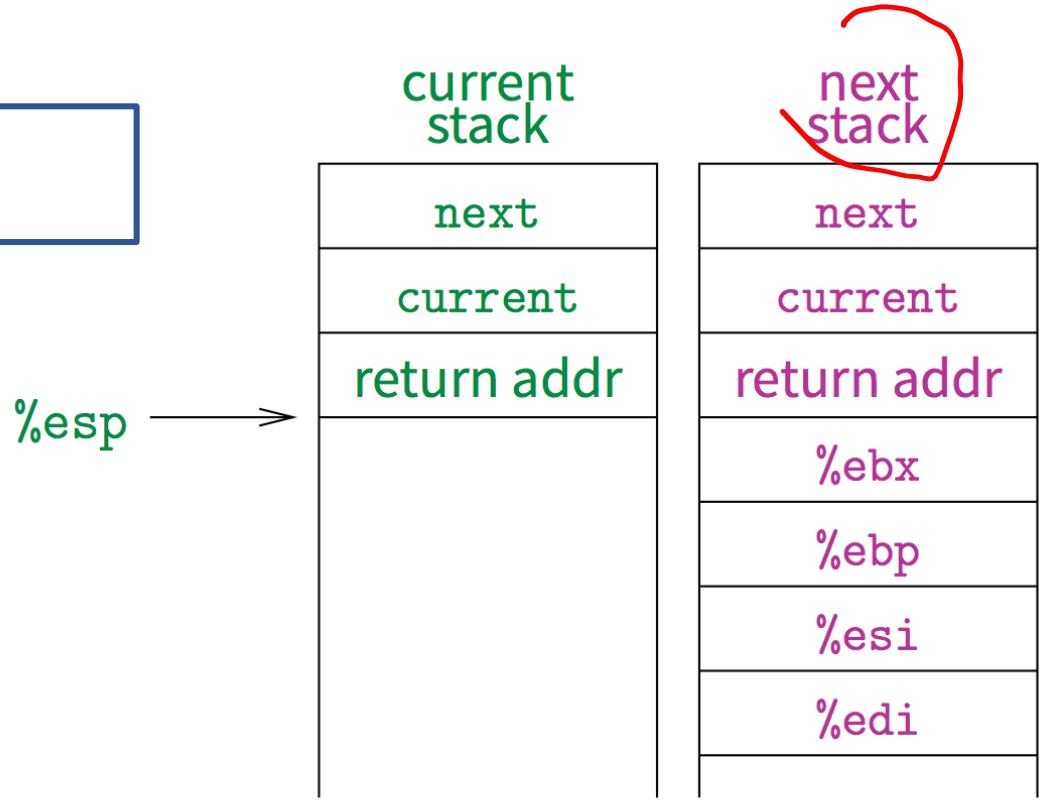


This is actual code from Pintos `switch.S` (slightly reformatted)

- See Thread Switching in documentation

i386 switch_threads

```
pushl %ebx; pushl %ebp
pushl %esi; pushl %edi
```

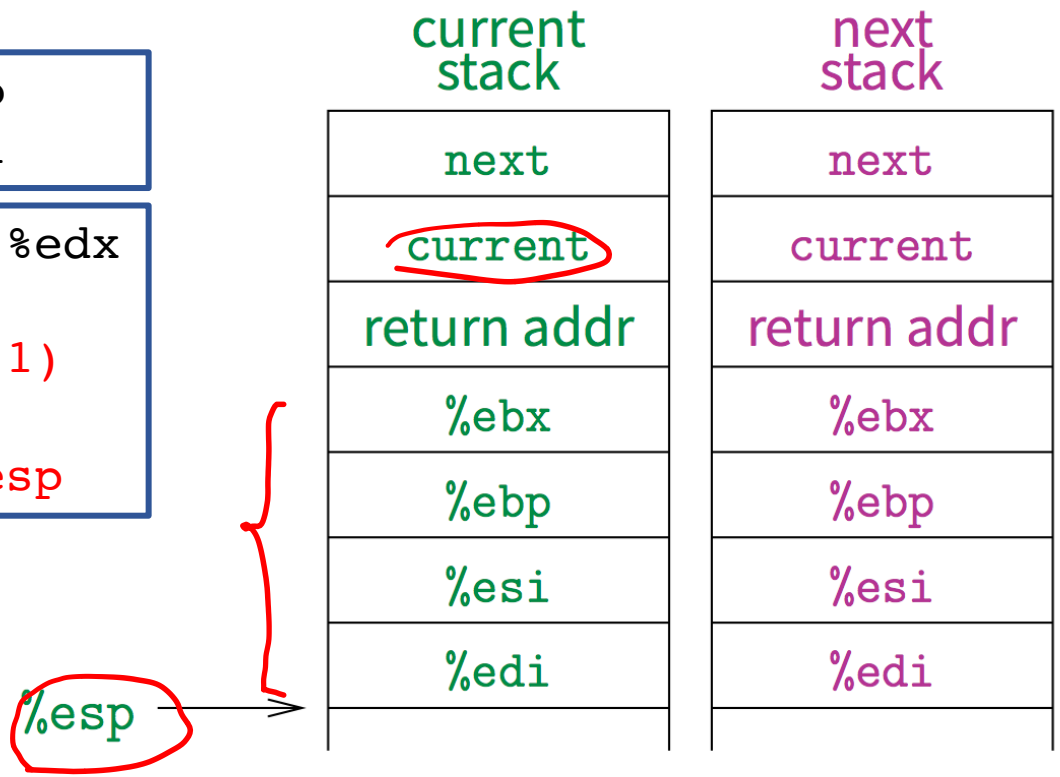


i386 switch_threads

```
pushl %ebx; pushl %ebp
pushl %esi; pushl %edi
```

```
mov thread_stack_ofs, %edx
movl 20(%esp), %eax
movl %esp, (%eax,%edx,1)
movl 24(%esp), %ecx
movl (%ecx,%edx,1), %esp
```

```
# cur->stack = %esp
# %esp = next->stack
```



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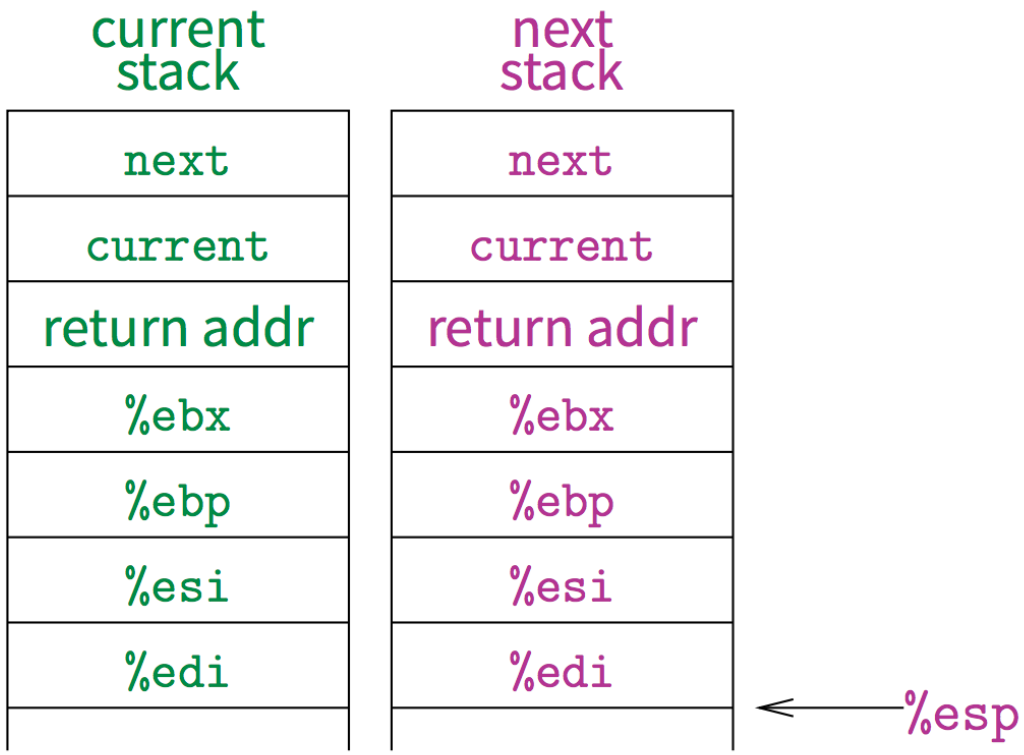
movl 24(%esp), %ecx
movl (%ecx,%edx,1), %esp
```

```
popl %edi; popl %esi
popl %ebp; popl %ebx
```



i386 switch_threads

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```
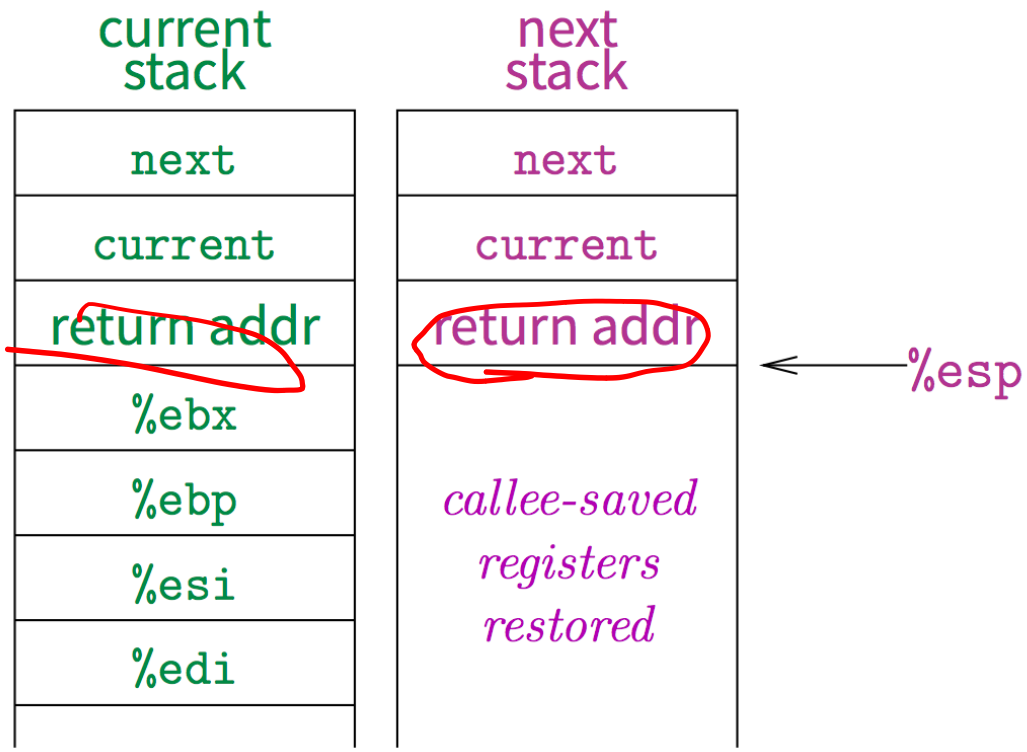

```
popl %edi; popl %esi
popl %ebp; popl %ebx
```

```
ret
```



Threads Summary

The operating system as a large multithreaded program

- Each process executes as a thread within the OS

Multithreading is also very useful for applications

- Efficient multithreading requires fast primitives
- Processes are too heavyweight

Solution is to separate threads from processes

- Kernel-level threads much better, but still significant overhead
- User-level threads even better, but not well integrated with OS

Now, how do we get our threads to correctly cooperate with each other?

- Synchronization…

Next Time…

Read Chapters 28, 29