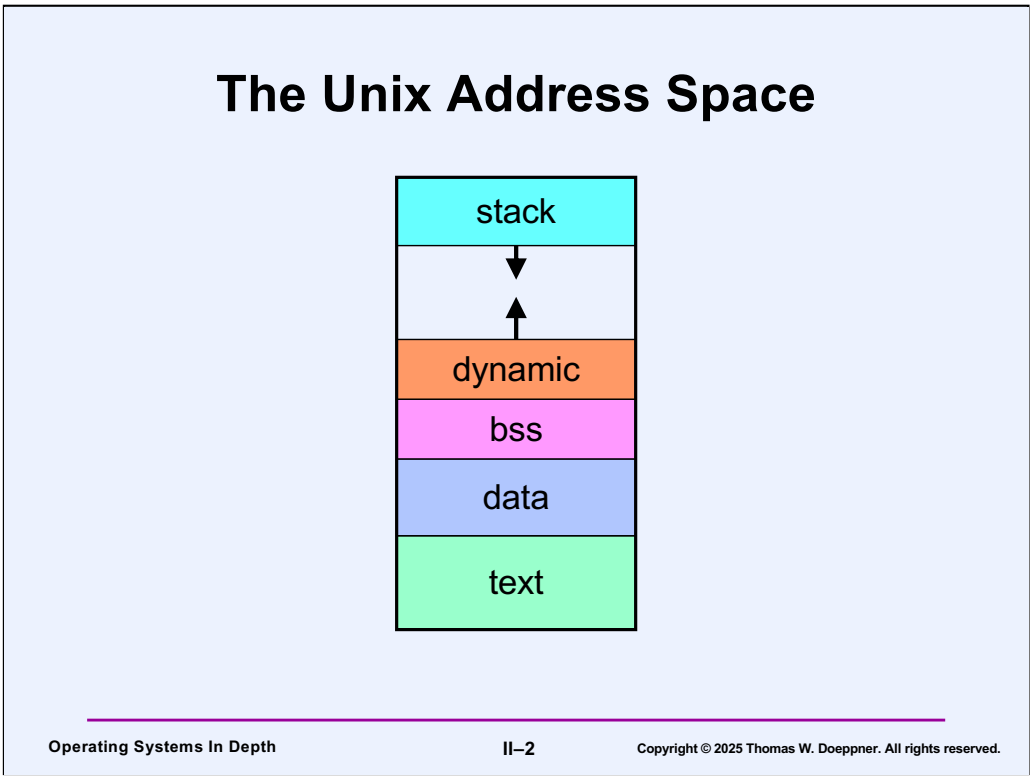
Implementing Threads

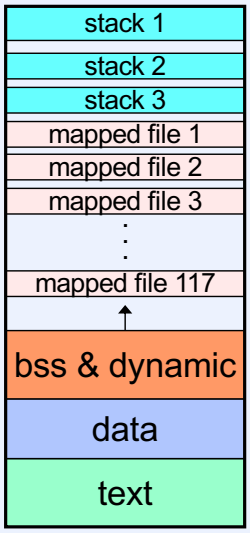


A Unix process's address space appears to be three regions of memory: a read-only **text** region (containing executable code); a read-write region consisting of initialized **data** (simply called data), uninitialized data (**BSS** — a directive from an ancient assembler (for the IBM 704 series of computers), standing for Block Started by Symbol and used to reserve space for uninitialized storage), and a **dynamic area**; and a second read-write region containing the process's user *stack* (a standard Unix process contains only one thread of control).

The first area of read-write storage is often collectively called the data region. Its dynamic portion grows in response to **sbrk** system calls. Most programmers do not use this system call directly, but instead use the **malloc** and **free** library routines, which manage the dynamic area and allocate memory when needed by in turn executing **sbrk** system calls.

The stack region grows implicitly: whenever an attempt is made to reference beyond the current end of stack, the stack is implicitly grown to the new reference. (There are system-wide and per-process limits on the maximum data and stack sizes of processes.)

Adding More Stuff



By the use of the **mmap** system call, one can map files into the address space, as well as anonymous objects (i.e., one can allocate address space that's not associated with a particular file).

Subroutines

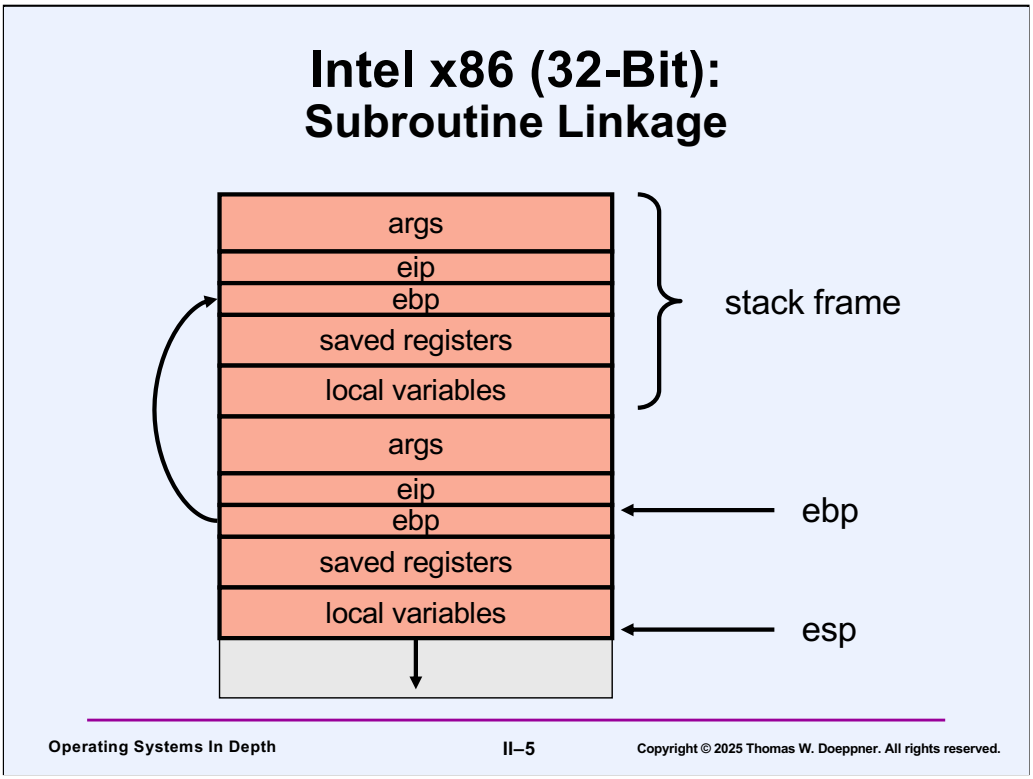
```
int main( ) {
   int i;
   int a;

   ...

   i = sub(a, 1);
   ...
   return(0);
}
```

```
int sub(int x, int y) {
   int i;
   int result = 1;
   for (i=0; i<y; i++)
      result *= x;
   return(result);
}
```


Subroutines are (or should be) a well understood programming concept: one procedure calls another, passing it arguments and possibly expecting a return value. We examine how the linkage between caller and callee is implemented on the Intel x86 architecture.



Subroutine linkage on an Intel x86 is fairly straightforward. (We are discussing the 32-bit version of the architecture.) Associated with each incarnation of a subroutine is a **stack frame** that contains the arguments to the subroutine, the **instruction pointer** (in register **eip**) of the caller (i.e. the address to which control should return when the subroutine completes), a copy of the caller's **frame pointer** (in register ebp), which links the stack frame to the previous frame, space to save any registers modified by the subroutine, and space for *local variables* used by the subroutine. Note that these frames are of variable size—the size of the space reserved for local data depends on the subroutine, as does the size of the space reserved for registers.

The base pointer register (**ebp**) points into the stack frame at a fixed position, just after the saved copy of the caller's instruction pointer (note that lower-addressed memory is towards the bottom of the picture). The value of the frame pointer is not changed by the subroutine, other than setting it on entry to the subroutine and restoring it on exit. The stack pointer (**esp**) always points to the last item on the stack—new allocations (e.g. for arguments to be passed to the next procedure) are performed here.

This picture is idealized: not all portions of the stack frame are always used. For example, registers are not saved if the subroutine doesn't modify them. The base pointer is not saved if it's not used, etc.

The Intel architecture manuals can be found at http://www.intel.com/content/www/us/en/processors/architectures-software-developer-manuals.html.

Intel x86:
Subroutine Code (1)

```
main:
 pushl %ebp
 movl  %esp, %ebp
 pushl %esi
 pushl %edi
 subl  $8, %esp
 …
 pushl $1
 movl  -12(%ebp), %eax
 pushl %eax
 call  sub
 addl  $8, %esp
 movl  %eax, -16(%ebp)
 …
```

set up stack frame

push args

pop args; get result

```
 movl  $0, %eax
 popl  %edi
 popl  %esi
 movl  %ebp, %esp
 popl  %ebp
 ret
```

set return value and restore frame

Intel x86:
Subroutine Code (2)

```
sub:
 pushl %ebp
 movl  %esp, %ebp
 subl  $8, %esp
 movl  $1, -4(%ebp)
 movl  $0, -8(%ebp)
 movl  -4(%ebp), %ecx
 movl  -8(%ebp), %eax
beginloop:
 cmpl  12(%ebp), %eax
 jge endloop
 imull 8(%ebp), %ecx
 addl  $1, %eax
 jmp beginloop
```

result = %ecx

%eax = result

initialize result

initialize i

%ecx holds result

%eax holds i

y:i

result *= x

i++

```
endloop:
 movl  %ecx, -4(%ebp)
 movl  -4(%ebp), %eax
 movl  %ebp, %esp
 popl  %ebp
 ret
```

x86-64

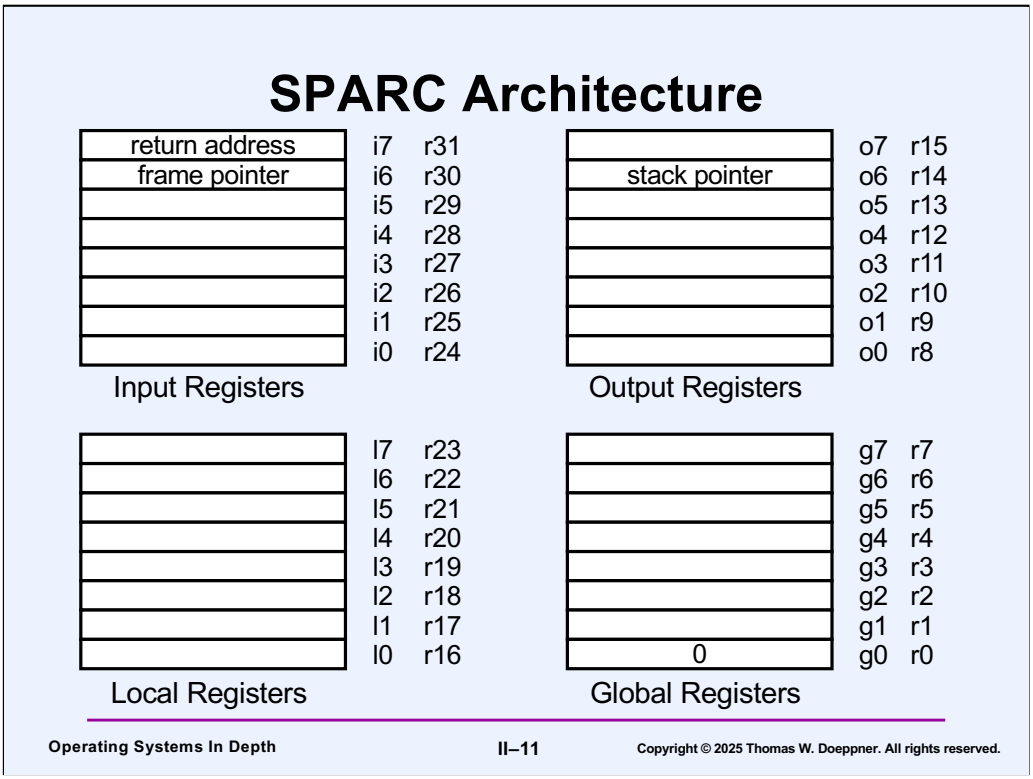
- Twice as many registers
- Arguments may be passed in registers, rather than on stack
- No special-purpose base pointer
  - use stack pointer instead

Intel x86-64:
Subroutine Code (1)

```
main:
 subq $24, %rsp       # reserve space on stack for locals
 …
 movl 12(%rsp), %edi  # set first argument
 movl $1, %esi        # set second argument
 call sub
 addl $24, %rsp
 …
 movl $0, %eax        # set return value
 ret
 …
```

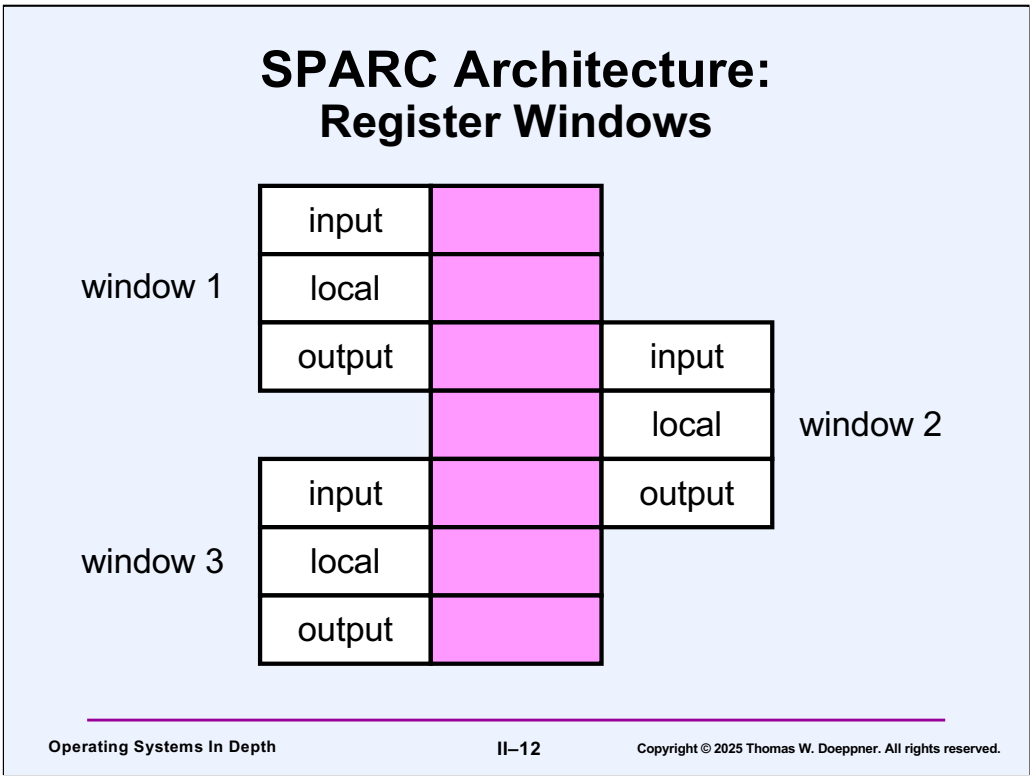
Intel x86-64:
Subroutine Code (2)

```
sub:
 testl %esi, %esi    # leaf function: no stack setup
 jle   skiploop
 movl  $1, %eax
 movl  $0, %edx
loop:
 imull %edi, %eax
 addl  $1, %edx
 cmpl  %esi, %edx
 jne   loop
 ret
skiploop:
 movl  $1, %eax
 ret
```



The SPARC (Scalable Processor ARChitecture) is an example of a RISC (Reduced-Instruction-Set Computer). We won't go into all of the details of its architecture, but we do cover what is relevant from the point of view of subroutine calling conventions. There are nominally 32 registers on the SPARC, arranged as four groups of eight—**input registers**, **local registers**, **output registers**, and **global registers**. Two of the input registers serve the special purposes of a **return address register** and a **frame pointer**, much like the corresponding registers on the x86. One of the output registers is the **stack pointer**. Register 0 (of the global registers) is very special—when read it always reads 0 and when written it acts as a sink.

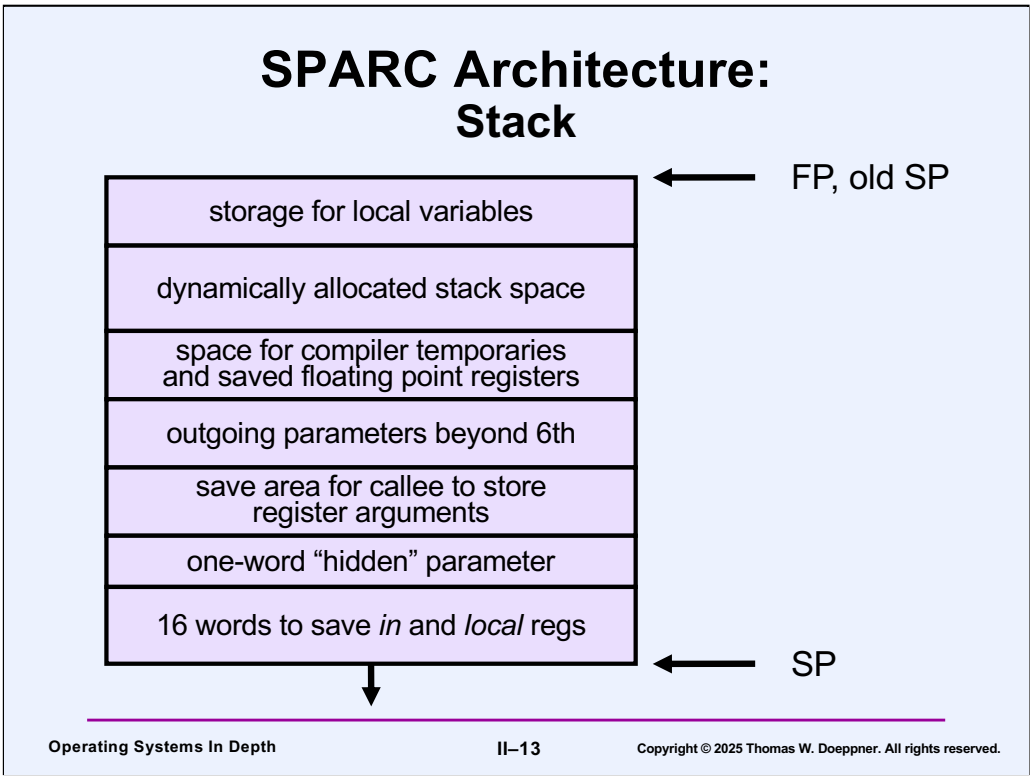
SPARC architecture manuals can be found at http://sparc.org/technical-documents/.



As its subroutine-calling technique the SPARC uses **sliding windows**: when one calls a subroutine, the caller's output registers become the callee's input registers. Thus, the register sets of successive subroutines overlap, as shown in the picture.

Any particular implementation of the SPARC has a fixed number of register sets (of eight registers a piece)—seven in the picture. As long as we do not exceed the number of register sets, subroutine entry and exit is very efficient—the input and local registers are effectively saved (and made unavailable to the callee) on subroutine entry, and arguments (up to six) can be efficiently passed to the callee. The caller just puts outgoing arguments in the output registers and the callee finds them in its input registers. Returning from a subroutine involves first putting the return value in a designated input register (i0). In a single action, control transfers to the location contained in i7, the return address register, and the register windows are shifted so that the caller's registers are in place again.

However, if the nesting of subroutine calls exceeds the available number of register sets, then subroutine entry and exit is not so efficient—the register windows must be copied to an x86-like stack. As implemented on the SPARC, when an attempt is made to nest subroutines deeper than can be handled by the register windows, a trap occurs and the operating system is called upon to copy the registers to the program's stack and reset the windows. Similarly, when a subroutine return encounters the end of the register windows, a trap again occurs and the operating system loads a new set of registers from the values stored on the program's stack.



The form of the SPARC stack is shown in the picture. Space is always allocated for the stack on entry to a subroutine. The space for saving the **in** and **local** registers is not used unless necessary because of a window overflow. The “hidden” parameter supports programs that return something larger than 32 bits—this field within the stack points to the parameter (which is located in separately allocated storage off the stack).

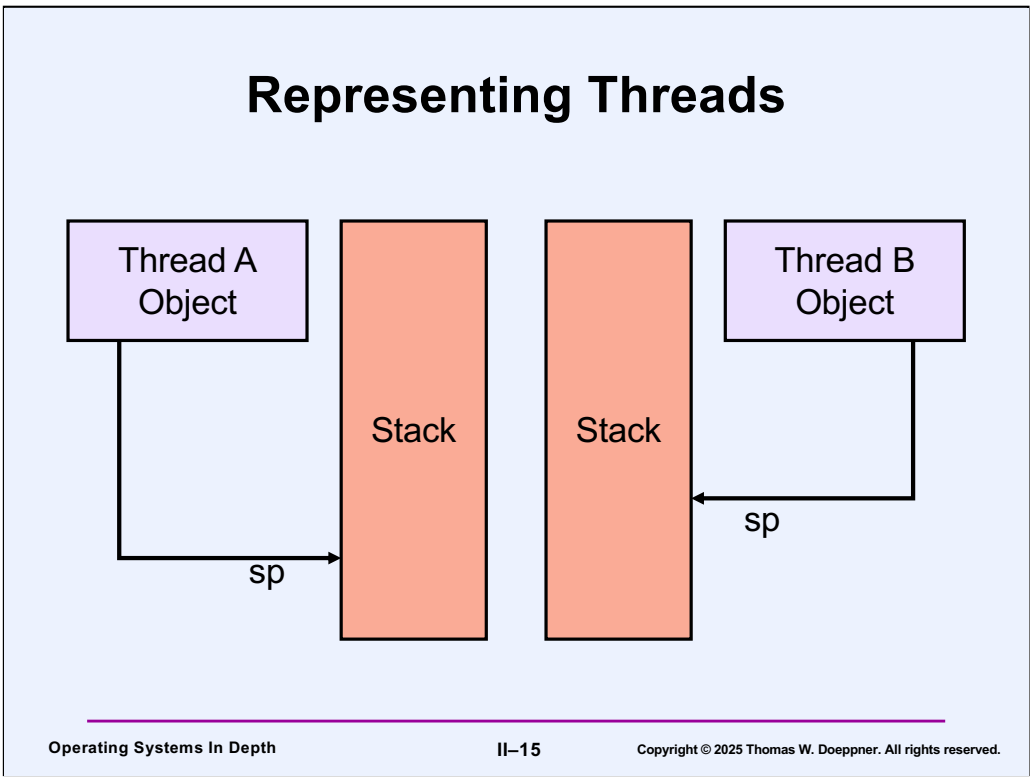
SPARC Architecture:
Subroutine Code

```
ld [%fp-8], %o0
    ! put local var (a)
    ! into out register
mov 1, %o1
    ! deal with 2nd
    ! parameter
call  sub
nop
st    %o0, [%fp-4]
    ! store result into
    ! local var (i)
...
```

```
sub:
    save   %sp, -64, %sp
        ! push a new
        ! stack frame
    add %i0, %i1, %i0
        ! compute sum
    ret
        ! return to caller
    restore
        ! pop frame off
        ! stack (in delay slot)
```

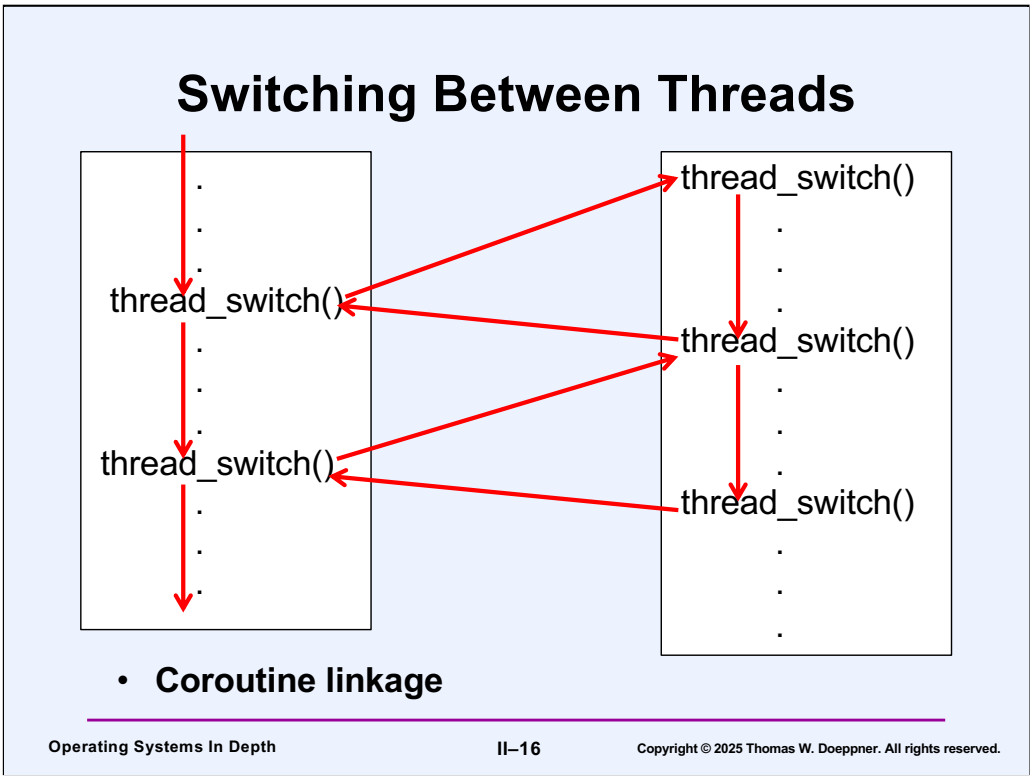

Here we see the assembler code produced by a compiler for the SPARC. The first step, in preparation for a subroutine call, is to put the outgoing parameters into the output registers. The first parameter is a local variable and is found in the stack frame. The second parameter is a constant. The call instruction merely saves the program counter in **o7** and then transfers control to the indicated address. In the subroutine, the **save** instruction creates a new stack frame and advances the register windows. It creates the new stack frame by taking the old value of the stack pointer (in the caller's **o6**), subtracting from it the amount of space that is needed (64 bytes in this example), and storing the result into the callee's stack pointer (**o6** of the callee). At the same time, it also advances the register windows, so that the caller's output registers become the callee's input registers. If there is a window overflow, then the operating system takes over.

Inside the subroutine, the return value is computed and stored into the callee's *i0*. The **restore** instruction pops the stack and backs down the register windows. Thus what the callee left in *i0* is found by the caller in **o0**.



We now consider what happens with multiple threads of control. Each thread must have its own *context*, represented by a control block (the *thread object*) and a stack. Together these represent what needs to be known about a thread within a particular address space. What must be stored in the thread object?

We clearly need the stack pointer, otherwise when we switch between threads we won't be able to switch stacks. If the frame pointer is also essential (as in x86), we'll need that as well. We'll also need the instruction pointer – we need to know where the thread is to be executing. We'll also need copies of all other registers whose values need to be saved for the thread ("callee save registers", using the term introduced in CSCI 330). In the next few slides we'll look at how we switch between threads and then we'll get back to what else must be in the thread object.



The slide show the flow of control of two threads running on a single processor. They explicitly yield the process to the other by calling **thread_switch**. Assume the left thread runs first. It calls **thread_switch**, yielding control to the right thread. At some point later, the right thread calls **thread_switch**, yielding control back to the left thread, which resumes after its original call to **thread_switch**. Thus from the point of view of the left thread, calling **thread_switch** was much like a procedure (or function) call to the right thread: it called **thread_switch**, passing control to the right thread, at some point later control returned to the statement following the call. But, sometime later, the left thread again calls **thread_switch**. Control returns to the right thread, to the location following its original call to **thread_switch**. From the right thread's point of view, calling **thread_switch** behaves like a procedure call to left thread. Thus each thread behaves as if it is calling the other – this sort of back and forth between threads, where each explicitly yields control to the other, is known as **coroutine linkage**: rather than a procedure calling a subroutine, we have co-equal **coroutines** calling each other.

Switching Between Threads

```
1 void thread_switch(thread_t *next_thread) {
2    getcontext(&CurrentThread->ctx);
3    CurrentThread = next_thread;
4    setcontext(&CurrentThread->ctx);
5    return;
6 }
```


This code is suggestive of how we might switch from one thread to another. The thread being switched out of calls thread_switch, passing it the address of the target thread's control block. We save whatever registers are necessary to represent the state of the current thread (including its stack pointer and instruction pointer) in its control block by calling **getcontext**, and we restore the registers of the thread being switched to by calling **setcontext**. **CurrentThread** is a global variable that we make sure always points to the control block of the currently running thread.

Unfortunately, this code isn't correct. Consider what happens if thread 1 switches to thread 2, and then thread 2 switches back to thread 1. Thread 1's state, including its instruction pointer (%rip on the x86-64) is saved at line 2. When it is restored by thread 2, the value of %rip will be restored, but it's as it was when it was saved. Thus thread 1 resumes at line 2, and rather than return, it immediately switches (again) to thread 2).

Switching Between Threads, Take 2

```
1  void thread_switch(thread_t *next_thread) {
2     volatile int first = 1;
3     getcontext(&CurrentThread->ctx);
4     if (first) {
5         first = 0;
6         CurrentThread = next_thread;
7         setcontext(&CurrentThread->ctx);
8     }
9     return;
10 }
```


In this version, we use a local variable to keep track of where we are (it's declared to be volatile so that its value is stored on the stack, not in a register – thus when we switch to a new stack (and thread) by calling **setcontext**, we get that thread's value of first). The first time the thread returns from **getcontext**, **first** is 1, so it switches to the other thread. But when the original thread is resumed, **first** is 0, so rather than switching to the other thread, it simply returns.

Note that we assume that the next thread's context has previously been set up.

Quiz 1

```
1  void thread_switch(thread_t *next_thread) {
2     volatile int first = 1;
3     getcontext(&CurrentThread->ctx);
4     if (first) {
5         first = 0;
6         CurrentThread = next_thread;
7         setcontext(&CurrentThread->ctx);
8     }
9     return;
10 }
```

Does this implementation of thread_switch work?

a) yes: in all cases

b) yes, except for a few edge cases

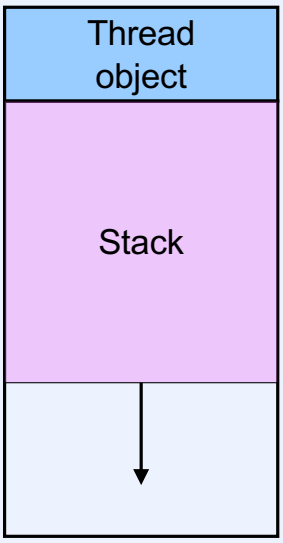
c) no

A Simple Threads Implementation

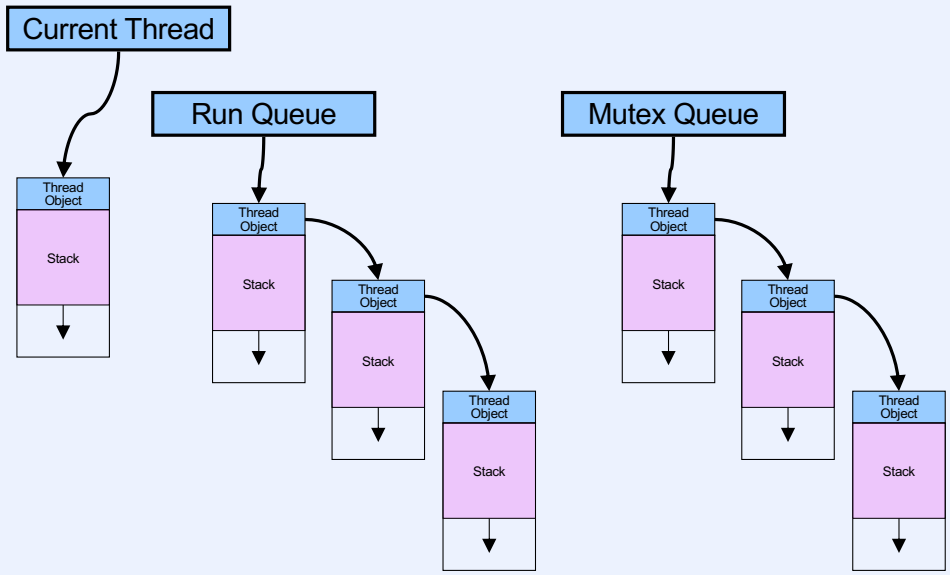
- Basis for user-level threads package
- Straight-threads implementation
  - no interrupts
  - everything in thread contexts
  - one processor

We now begin to describe a real implementation of threads, which is the basis for the uthreads programming assignment. What's assumed for the moment is that there's no time slicing: each thread runs until it voluntarily switches to another thread. We'll relax this assumption for the uthreads assignment, in which you will implement time slicing.

Basic Representation



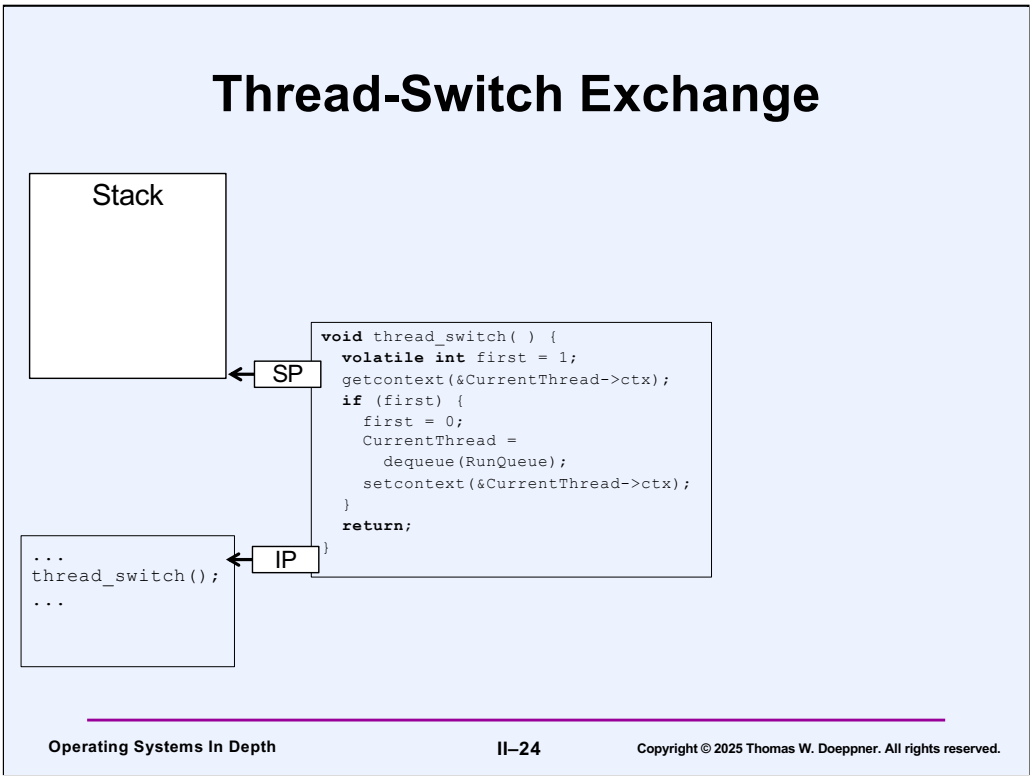
A Collection of Threads



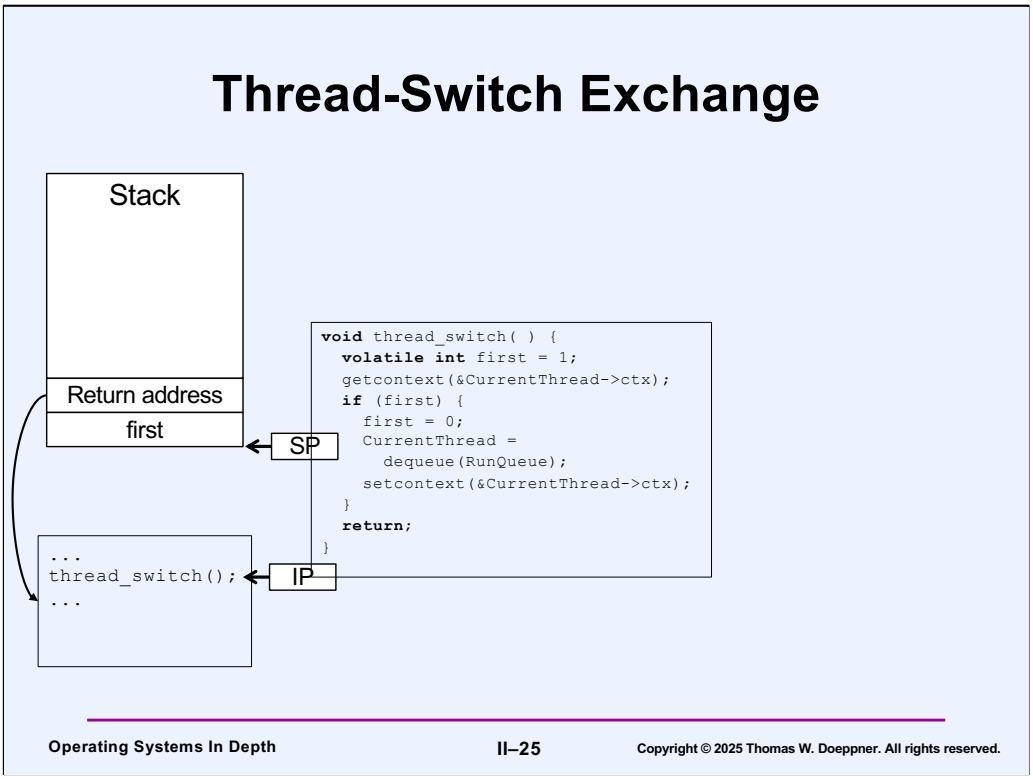
Thread Switch (using Run Queue)

```
void thread_switch( ) {
   volatile int first = 1;
   getcontext(&CurrentThread->ctx);
   if (first) {
      first = 0;
      CurrentThread = dequeue(RunQueue);
      setcontext(&CurrentThread->ctx);
   }
   return;
}
```

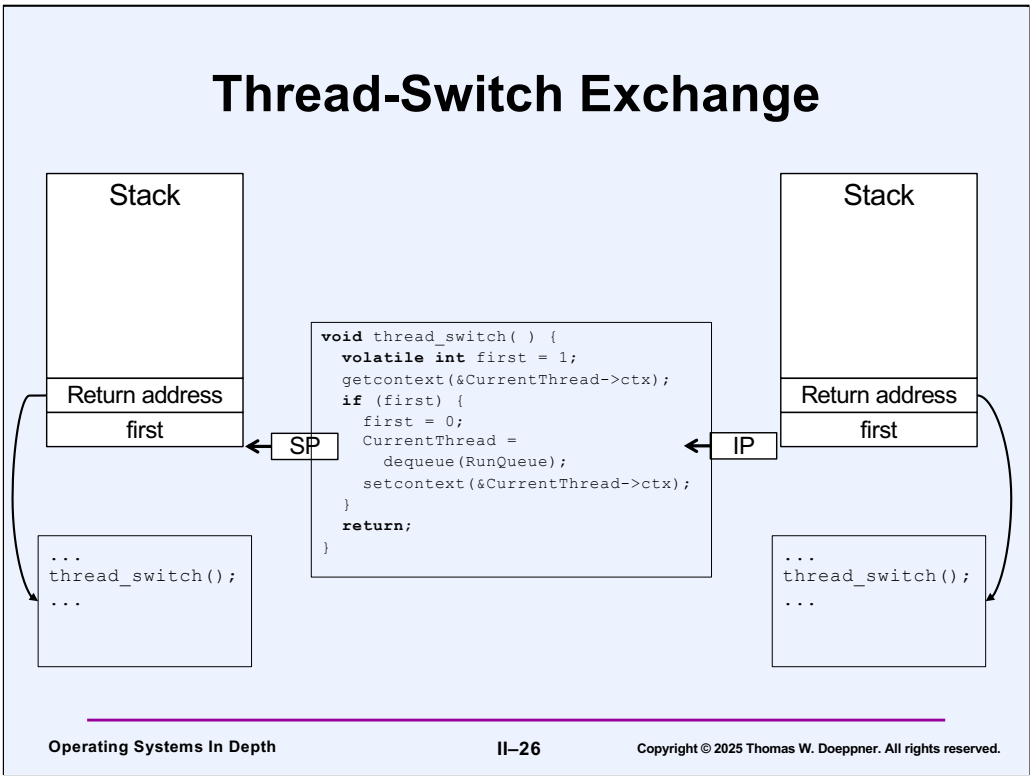

In this version of **thread_switch**, rather than having the target thread passed as an argument, we use the first thread in the run queue.



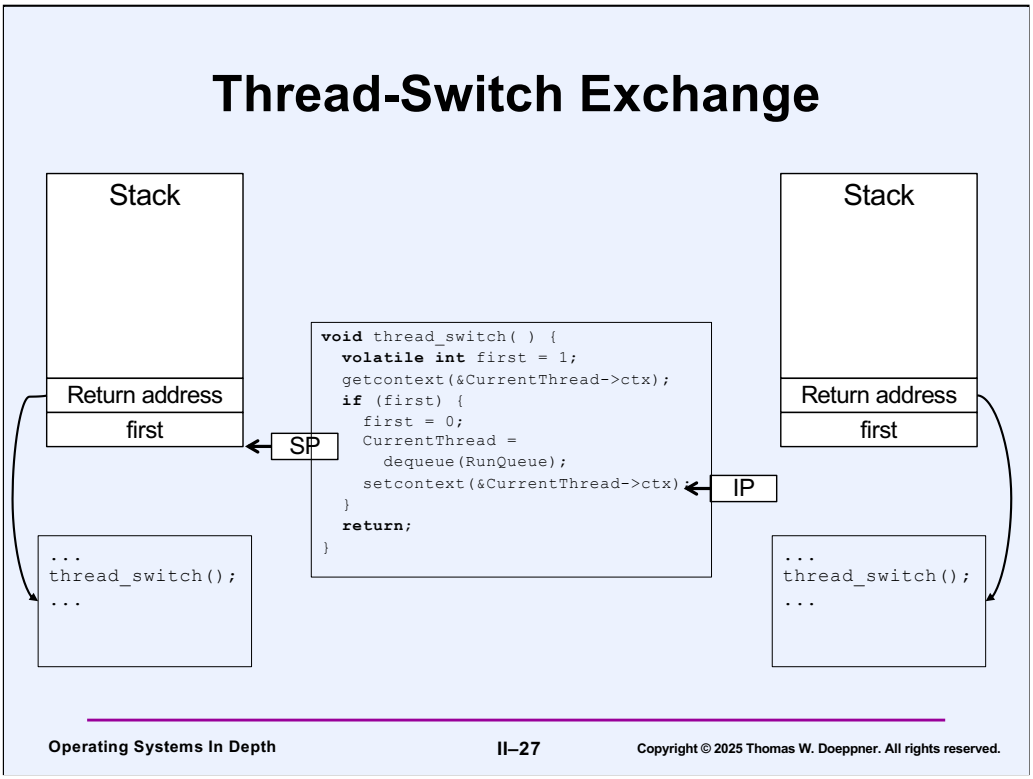
Our thread is about to call **thread_switch**.



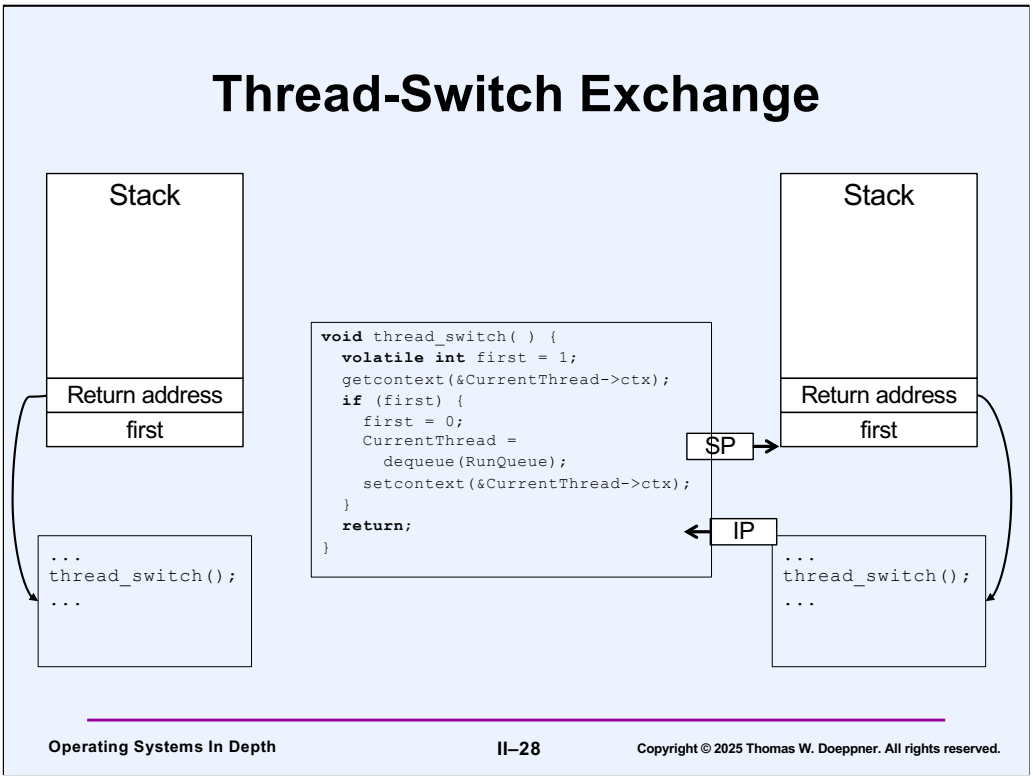
It now enters **thread_switch**. Its return address and the local variable **first** are pushed onto its stack.



Now we identify the thread we are to switch to. Its stack is shown on the right.

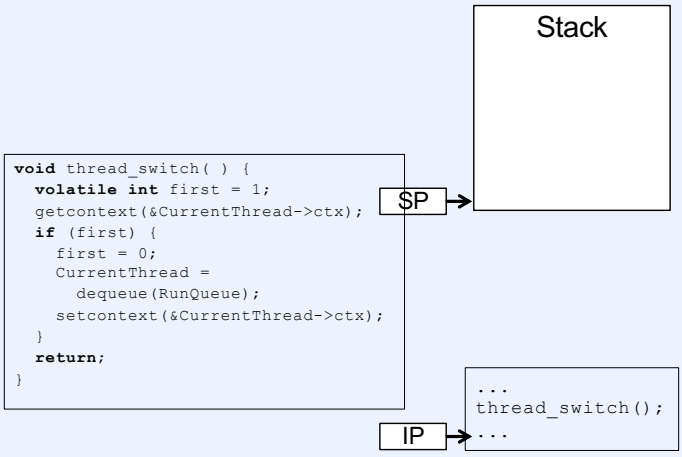


Our original thread now calls **setcontext**.



Setcontext causes the stack-pointer register to point to the other thread's stack. That thread had saved its context in a previous call to **thread_switch**. Thus it resumes execution by returning from **getcontext**. Since **first** is zero, it returns from **thread_switch**.

Thread-Switch Exchange



The other thread continues its execution after returning from **thread_switch**.

Mutexes

```
mutex_t mut;

mutex_lock(&mut);
x = x+1;
mutex_unlock(&mut);
```

Implementing Mutexes

```
void mutex_lock(mutex_t *m) {
  if (m->locked) {
    enqueue(m->wait_queue, CurrentThread);
    thread_switch();
  }
  m->locked = 1;
}

void mutex_unlock(mutex_t *m) {
  m->locked = 0;
  if (!queue_empty(m->wait_queue))
    enqueue(RunQueue, dequeue(m->wait_queue));
}
```


Note that there may be issues if, when **thread_switch** is called, there are no other runnable threads. Let's ignore these issues for now.

Let’s allow for time slicing: if thread **A** is the **running** thread and thread **B** is a **ready-to-run** thread, **A** might spontaneously yield to **B**, causing **B** to be the **running** thread and **A** to be a **ready-to-run** thread.

Quiz 2

```
void mutex_lock(mutex_t *m) {
  if (m->locked) {
    enqueue(m->wait_queue, CurrentThread);
    thread_switch();
  }
  m->locked = 1;
}

void mutex_unlock(mutex_t *m) {
  m->locked = 0;
  if (!queue_empty(m->wait_queue))
    enqueue(RunQueue, dequeue(m->wait_queue));
}
```

a) It works.
b) It works as long as there are no more than two threads.
c) There are situations in which it doesn't work for any number of threads greater than 1.

Note that there may be issues if, when thread_switch is called, there are no other runnable threads. Let's ignore these issues for now.

Implementing Mutexes, Take 2

```
void mutex_lock(mutex_t *m) {
  if (m->locked) {
    enqueue(m->queue, CurrentThread);
    thread_switch();
  } else
    m->locked = 1;
}

void mutex_unlock(mutex_t *m) {
  if (queue_empty(m->queue))
    m->locked = 0;
  else
    enqueue(runqueue, dequeue(m->queue));
}
```

Thread Termination

- Termination
  - thread becomes zombie
  - if joinable
    - notify waiter, if present
  - if detached
    - disappear
      - thread can't do this by itself!

The problem here is that a terminating thread can't free its own stack, since it would still be using that stack on return from **free**.

The Reaper Thread

```
while(1) {
  wait_for_terminated_zombie()
  delete(zombie);
}
```

Thread Yield

Thread Yield Details

```
void thread_yield() {
  if (!queue_empty(runqueue)) {
    enqueue(runqueue, CurrentThread);
    thread_switch();
  }
}
```

Time Slicing

- **Periodically**
  - **current thread forced to do a thread yield**

```
void ClockInterrupt(int sig) {
  thread_yield();
}
```

- **Implement ClockInterrupt with VTALRM signal**

Note that the use of time slicing complicates our implementation of mutexes and other synchronization constructs. We discuss this in our next lecture.