Operating Systems
CMPSCI 377
Spring 2020

Introduction to Concurrency

Clicker Question

What will data be at the end of these two threads?
(assume data=0 and is on the heap or a global)

(A) 0

(B) 1

(C) -1

(D) Any of the above

(E) None of the above

THREAD 1	THREAD 2
a = data;	b = data;
a++;	b--;
data = a;	data = b;

Answer on Next Slide

Last Time

- Scheduling with I/O
- Multi-Level Feedback Queue (MLFQ)

Today's Class

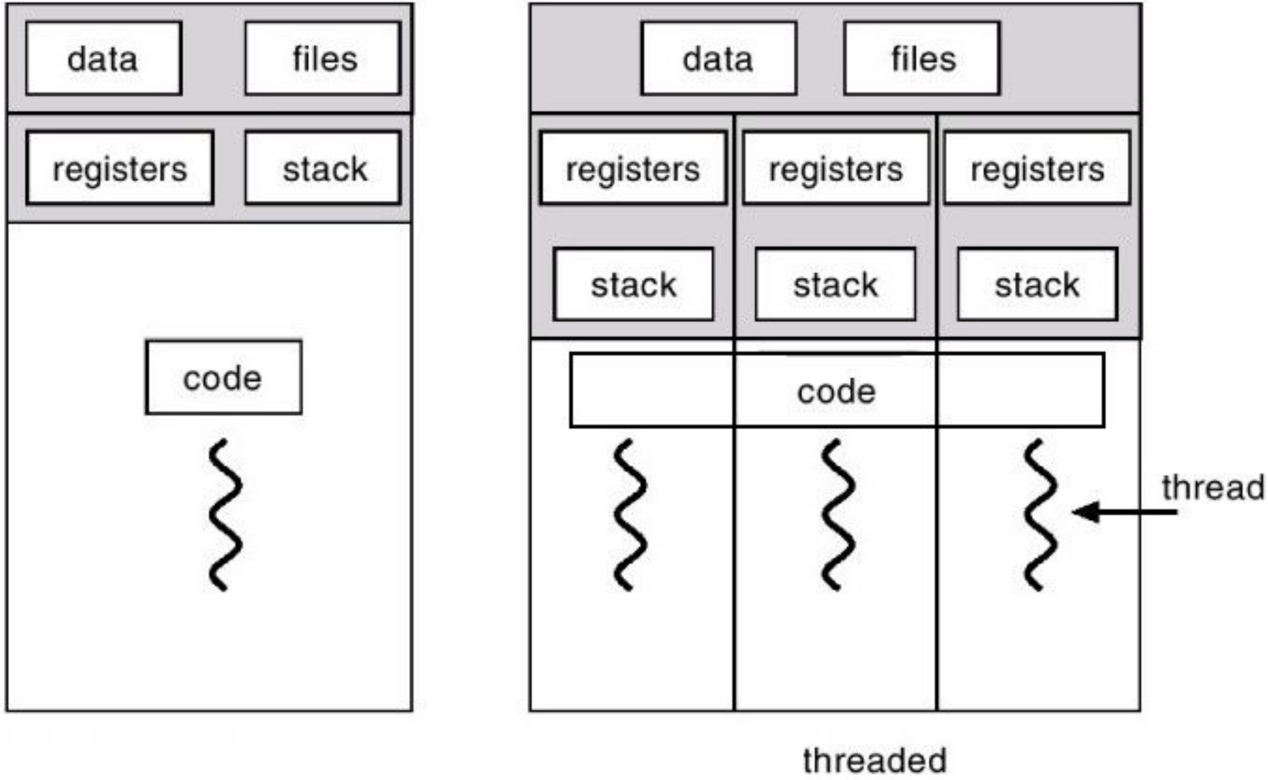
- Concurrency: An Introduction
  - Why use threads?
  - Thread Examples
  - Shared Data
  - Uncontrolled Scheduling
  - Atomicity
  - Waiting for others

Virtualization: Processes

Reality: Single CPU

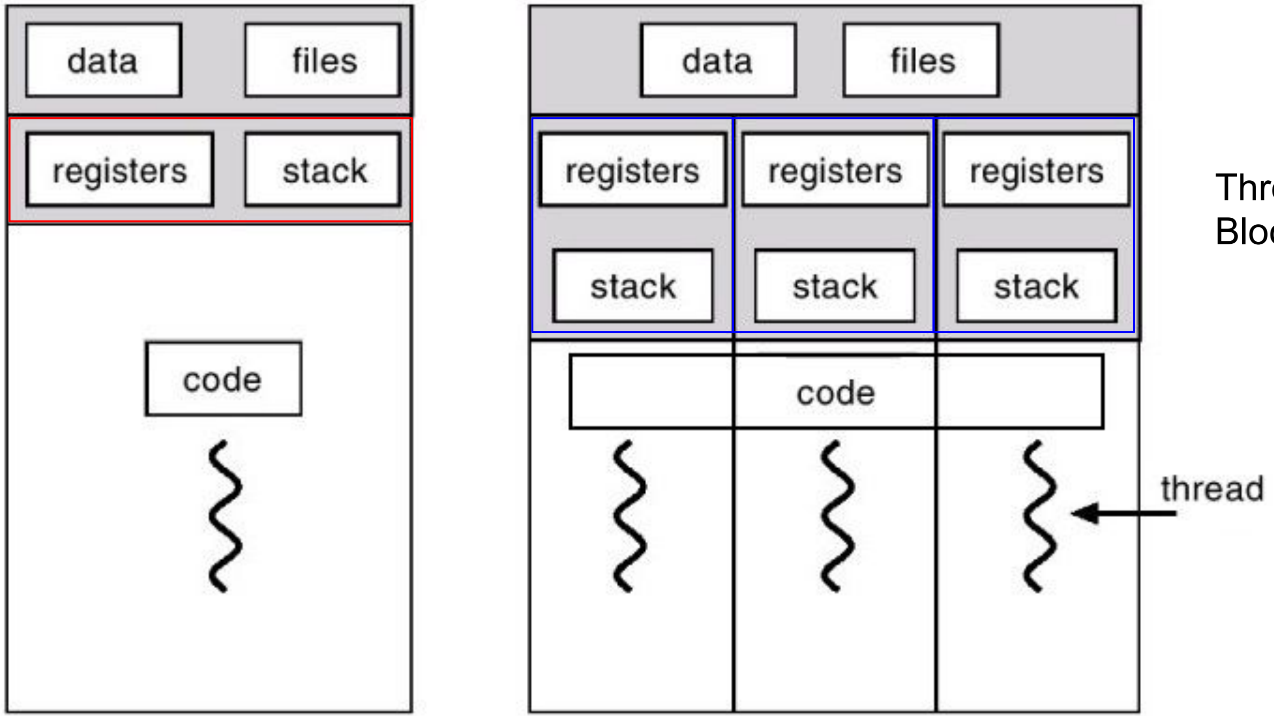
Virtualization: Multiple Processes

Another Abstraction: Threads



Another Abstraction: Threads

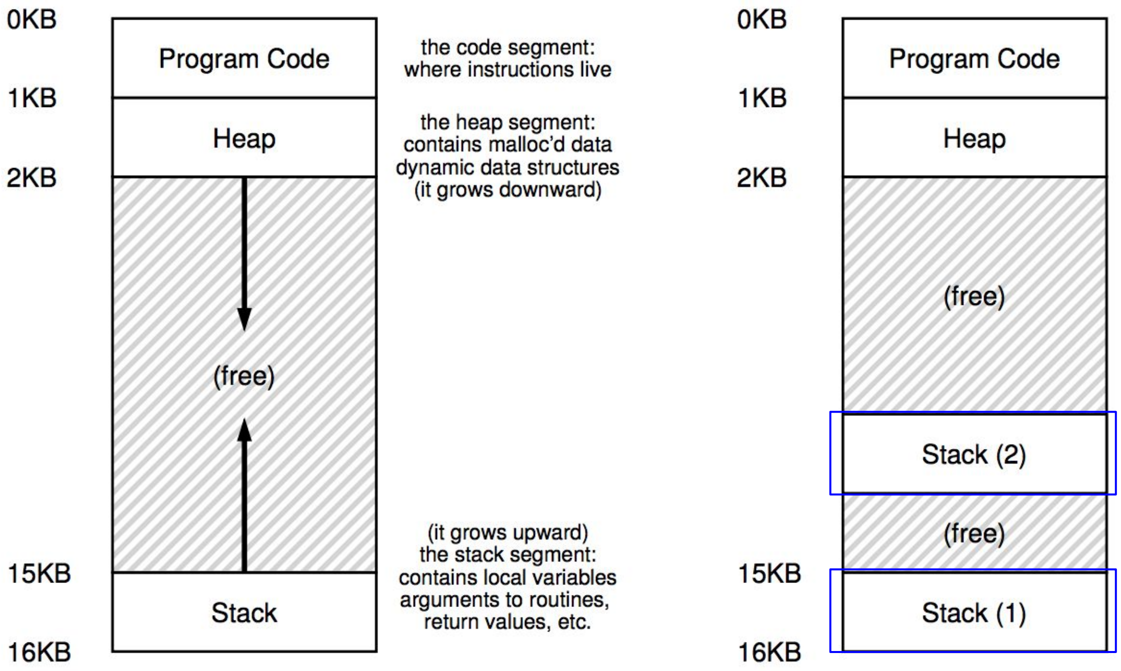
Process Control Block (PCB)



threaded

Thread Control Block (TCB)

Single-Threaded and Multi-Threaded Address Space



Thread Local Storage

Figure 26.1: **Single-Threaded And Multi-Threaded Address Spaces**

Why Use Threads?

The first one is simple: **parallelism**

Imagine you are writing a program that performs operations on very large arrays, for example, adding two large arrays together, or incrementing the value of each element in the array by some amount.

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Why Use Threads?

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Imagine you are writing a program that performs operations on very large arrays, for example, adding two large arrays together, or incrementing the value of each element in the array by some amount.

If you are running on just a single processor, the task is straightforward: just perform each operation and be done.

However, if you are executing the program on a system with multiple processors, you have the potential of speeding up this process considerably by using the processors to each perform a portion of the work.

Why Use Threads?

The second reason is more subtle:

to avoid blocking program progress due to slow I/O

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Why Use Threads?

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Imagine that you are writing a program that performs different types of I/O: either waiting to send or receive a message, for an explicit disk I/O to complete, or even (implicitly) for a trap/fault to finish.

Instead of waiting, your program may wish to do something else, including utilizing the CPU to perform computation, or even issuing further I/O requests. Using threads is a natural way to avoid getting stuck.

Why Use Threads?

The second reason is more subtle:

to avoid blocking program progress due to slow I/O

while one thread in your program waits (i.e., is blocked waiting for I/O), the CPU scheduler can switch to other threads, which are ready to run and do something useful.

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while one thread in your program waits (i.e., is blocked waiting for I/O), the CPU scheduler can switch to other threads, which are ready to run and do something useful.

Threading enables overlap of I/O with other activities within a single program, much like multiprogramming did for processes across programs.

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Threading enables overlap of I/O with other activities within a single program, much like multiprogramming did for processes across programs.

Examples: many modern server-based applications (web servers, database management systems, and the like) make use of threads in their implementations.

Why Not Use Processes?

Of course, in either of the cases mentioned above, you could use multiple processes instead of threads.

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Of course, in either of the cases mentioned above, you could use multiple processes instead of threads.

However, threads **share an address space** and thus make it easy to share data.

Thus, threads are a natural choice when constructing these types of programs.

Processes are a more sound choice for logically separate tasks where little sharing of data structures in memory is needed.

Thread Example

```c
#include <stdio.h>
#include <assert.h>
#include <pthread.h>

void *mythread(void *arg) {
    printf("%s\n", (char *) arg);
    return NULL;
}

int
main(int argc, char *argv[]) {
    pthread_t p1, p2;
    int rc;
    printf("main: begin\n");
    rc = pthread_create(&p1, NULL, mythread, "A"); assert(rc == 0);
    rc = pthread_create(&p2, NULL, mythread, "B"); assert(rc == 0);
    // join waits for the threads to finish
    rc = pthread_join(p1, NULL); assert(rc == 0);
    rc = pthread_join(p2, NULL); assert(rc == 0);
    printf("main: end\n");
    return 0;
}
```

Clicker Question

Which prints first A or B?

(A) A

(B) B

(C) neither

(D) don’t know

```
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Answer on Next Slide

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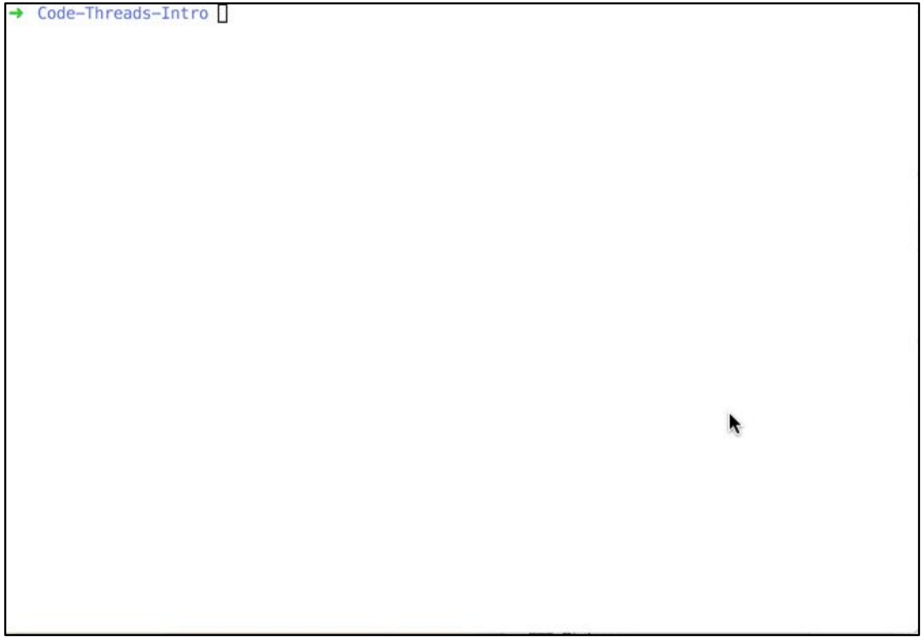
Thread Example

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}
```

Thread Trace (1)

main	Thread 1	Thread2
starts running		
prints "main: begin"		
creates Thread 1		
creates Thread 2		
waits for T1		
	runs	
	prints "A"	
	returns	
waits for T2		
		runs
		prints "B"
		returns
prints "main: end"		

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		runs
		prints "B"
		returns
prints "main: end"		

Thread Trace (2)

main	Thread 1	Thread2
starts running		
prints "main: begin"		
creates Thread 1		
	runs	
	prints "A"	
	returns	
creates Thread 2		
		runs
		prints "B"
		returns
waits for T1		
returns immediately; T1 is done		
waits for T2		
returns immediately; T2 is done		
prints "main: end"		

Thread Trace (2)

main	Thread 1	Thread2
starts running		
prints "main: begin"		
creates Thread 1		
	runs	
	prints "A"	
	returns	
creates Thread 2		
		runs
		prints "B"
		returns
waits for T1		
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waits for T2		
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	returns	
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		returns
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waits for T1		
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prints "main: end"		

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	prints "A"	
	returns	
creates Thread 2		
		runs
		prints "B"
		returns
waits for T1		
returns immediately; T1 is done		
waits for T2		
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		runs
		prints "B"
		returns
waits for T1		
returns immediately; T1 is done		
waits for T2		
returns immediately; T2 is done		
$\boxed{\text{prints "main: end"}}$		

Thread Trace (3)

main	Thread 1	Thread2
starts running		
prints "main: begin"		
creates Thread 1		
creates Thread 2		
		runs
		prints "B"
		returns
waits for T1		
	runs	
	prints "A"	
	returns	
waits for T2		
returns immediately; T2 is done		
prints "main: end"		

Thread Trace (3)

main	Thread 1	Thread2
starts running		
prints "main: begin"		
creates Thread 1		
creates Thread 2		
		runs
		prints "B"
		returns
waits for T1		
	runs	
	prints "A"	
	returns	
waits for T2		
returns immediately; T2 is done		
prints "main: end"		

Thread Trace (3)

main	Thread 1	Thread2
starts running		
prints "main: begin"		
creates Thread 1		
creates Thread 2		
		runs
		prints "B"
		returns
waits for T1		
	runs	
	prints "A"	
	returns	
waits for T2		
returns immediately; T2 is done		
prints "main: end"		

Thread Trace (3)

main	Thread 1	Thread2
starts running		
prints "main: begin"		
creates Thread 1		
creates Thread 2		
		runs
		prints "B"
		returns
waits for T1		
	runs	
	prints "A"	
	returns	
waits for T2		
returns immediately; T2 is done		
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Thread Trace (3)

main	Thread 1	Thread2
starts running		
prints "main: begin"		
creates Thread 1		
creates Thread 2		
		runs
		prints "B"
		returns
waits for T1		
	runs	
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	returns	
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Thread Trace (3)

main	Thread 1	Thread2
starts running		
prints "main: begin"		
creates Thread 1		
creates Thread 2		
		runs
		prints "B"
		returns
waits for T1		
	runs	
	prints "A"	
	returns	
waits for T2		
returns immediately; T2 is done		
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Thread Trace (3)

main	**Thread 1**	**Thread2**
starts running		
prints "main: begin"		
creates Thread 1		
creates Thread 2		
		runs
		prints "B"
		returns
waits for T1		
	runs	
	prints "A"	
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Thread Trace (3)

main	Thread 1	Thread2
starts running		
prints "main: begin"		
creates Thread 1		
creates Thread 2		
		runs
		prints "B"
		returns
waits for T1		
	runs	
	prints "A"	
	returns	
waits for T2		
returns immediately; T2 is done		
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Thread Trace (3)

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prints "main: begin"		
creates Thread 1		
creates Thread 2		
		runs
		prints "B"
		returns
waits for T1		
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returns immediately; T2 is done		
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Threads are useful, but there are problems.

```
static volatile int counter = 0;

void *
mythread(void *arg)
{
    printf("%s: begin\n", (char *) arg);
    int i;
    for (i = 0; i < 1e7; i++) {
        counter = counter + 1;
    }
    printf("%s: done\n", (char *) arg);
    return NULL;
}
```

```
int
main(int argc, char *argv[])
{
    pthread_t p1, p2;
    printf("main: begin (counter = %d)\n", counter);
    Pthread_create(&p1, NULL, mythread, "A");
    Pthread_create(&p2, NULL, mythread, "B");

    // join waits for the threads to finish
    Pthread_join(p1, NULL);
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    printf("main: done with both (counter = %d)\n", counter);
    return 0;
}
```

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    return 0;
}
```

```
prompt> gcc -o main main.c -Wall -pthread
prompt> ./main
main: begin (counter = 0)
A: begin
B: begin
A: done
B: done
main: done with both (counter = 20000000)
```

Threads are useful, but there are problems.

```c
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void *
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{
    printf("%s: begin\n", (char *) arg);
    int i;
    for (i = 0; i < 1e7; i++) {
        counter = counter + 1;
    }
    printf("%s: done\n", (char *) arg);
    return NULL;
}
```

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    printf("main: done with both (counter = %d)\n", counter);
    return 0;
}
```

```
prompt> ./main
main: begin (counter = 0)
A: begin
B: begin
A: done
B: done
main: done with both (counter = 19345221)
```

Threads are useful, but there are problems.

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static volatile int counter = 0;

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    int i;
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    return 0;
}
```

```
prompt> ./main
main: begin (counter = 0)
A: begin
B: begin
A: done
B: done
main: done with both (counter = 19221041)
```

Threads are useful, but there are problems

```
static volatile int counter = 0;

void *
mythread(void *arg)
{
    printf("%s: be
    int i;
    for (i = 0; i
        counter =
    }
    printf("%s: do
    return NULL;
}
```

```
int
main(int argc, char
{
    pthread_t p1, p
    printf("main: be
    Pthread_create(
    Pthread_create(

    // join waits for the threads to finish
    Pthread_join(p1, NULL);
    Pthread_join(p2, NULL);
    printf("main: done with both (counter = %d)\n", counter);
    return 0;
}
```

= 0)

(counter = 19221041)

Aren't computers supposed to produce deterministic results, as you have been taught?!

Not only is each run wrong, but also yields a different result!

A big question remains:
why does this happen?

The Heart of the Problem: Uncontrolled Scheduling

To understand why this happens, we must understand the code sequence that the compiler generates for the update to counter. In this case, we wish to simply add a number (1) to counter.

The Heart of the Problem: Uncontrolled Scheduling

To understand why this happens, we must understand the code sequence that the compiler generates for the update to counter. In this case, we wish to simply add a number (1) to counter.

Thus, the code sequence for doing so might look something like this (in x86):

```
mov 0x8049a1c, %eax
add $0x1, %eax
mov %eax, 0x8049a1c
```

The Heart of the Problem: Uncontrolled Scheduling

To understand why this happens, we must understand the code sequence that the compiler generates for the update to counter. In this case, we wish to simply add a number (1) to counter.

Thus, the code sequence for doing so might look something like this (in x86):

```
mov 0x8049a1c, %eax
add $0x1, %eax
mov %eax, 0x8049a1c
```

counter

The Heart of the Problem: Uncontrolled Scheduling

OS	Thread 1	Thread 2	PC	%eax	counter
			(after instruction)		
	before critical section		100	0	50
	mov 0x8049a1c, %eax		105	**50**	50
	add $0x1, %eax		108	**51**	50
interrupt					
save T1's state					
restore T2's state			100	0	50
		mov 0x8049a1c, %eax	105	**50**	50
		add $0x1, %eax	108	**51**	50
		mov %eax, 0x8049a1c	113	51	**51**
interrupt					
save T2's state					
restore T1's state			108	51	51
	mov %eax, 0x8049a1c		113	51	**51**

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RACE CONDITION!

The Wish for Atomicity

The problem is that we must execute 3 instructions to perform the increment:

```
mov 0x8049a1c, %eax
add $0x1, %eax
mov %eax, 0x8049a1c
```

The Wish for Atomicity

The problem is that we must execute 3 instructions to perform the increment:

```
mov 0x8049a1c, %eax
add $0x1, %eax
mov %eax, 0x8049a1c
```

What if we could do this with only a single atomic instruction:

```
memory-add 0x8049a1c, $0x1
```

The Wish for Atomicity

Thus, what we will instead do is ask the hardware for a few useful instructions upon which we can build a general set of what we call synchronization primitives.

By using these hardware synchronization primitives, in combination with some help from the operating system, we will be able to build multi-threaded code that accesses critical sections in a synchronized and controlled manner.

THE CRUX:
HOW TO PROVIDE SUPPORT FOR SYNCHRONIZATION

What support do we need from the hardware in order to build useful synchronization primitives? What support do we need from the OS? How can we build these primitives correctly and efficiently? How can programs use them to get the desired results?

One more problem: waiting for another

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accessing shared variables and the need to support atomicity for critical sections.

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One thread must wait for another to complete some action before it continues.

This interaction arises, for example, when a process performs a disk I/O and is put to sleep; when the I/O completes, the process needs to be roused from its slumber so it can continue.

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We will be looking at how synchronization primitives and conditional variables help tame **uncontrolled scheduling**.

Why study this in an OS class?

Before wrapping up, one question that you might have is:

why are we studying this in OS class?

“History” is the one-word answer!

The OS was the **first concurrent program**, and many techniques were created for use within the OS. Later, with multi-threaded processes, application programmers also had to consider such things.

Next Time

Ch 28: Locks

Make sure you also read Ch 27: Interlude: Thread API

This chapter will help you become more acquainted with the thread and locking API in a typical Unix-like system.