Synchronization Basics and Semaphores

CS 4410
Operating Systems
Spring 2017
Cornell University

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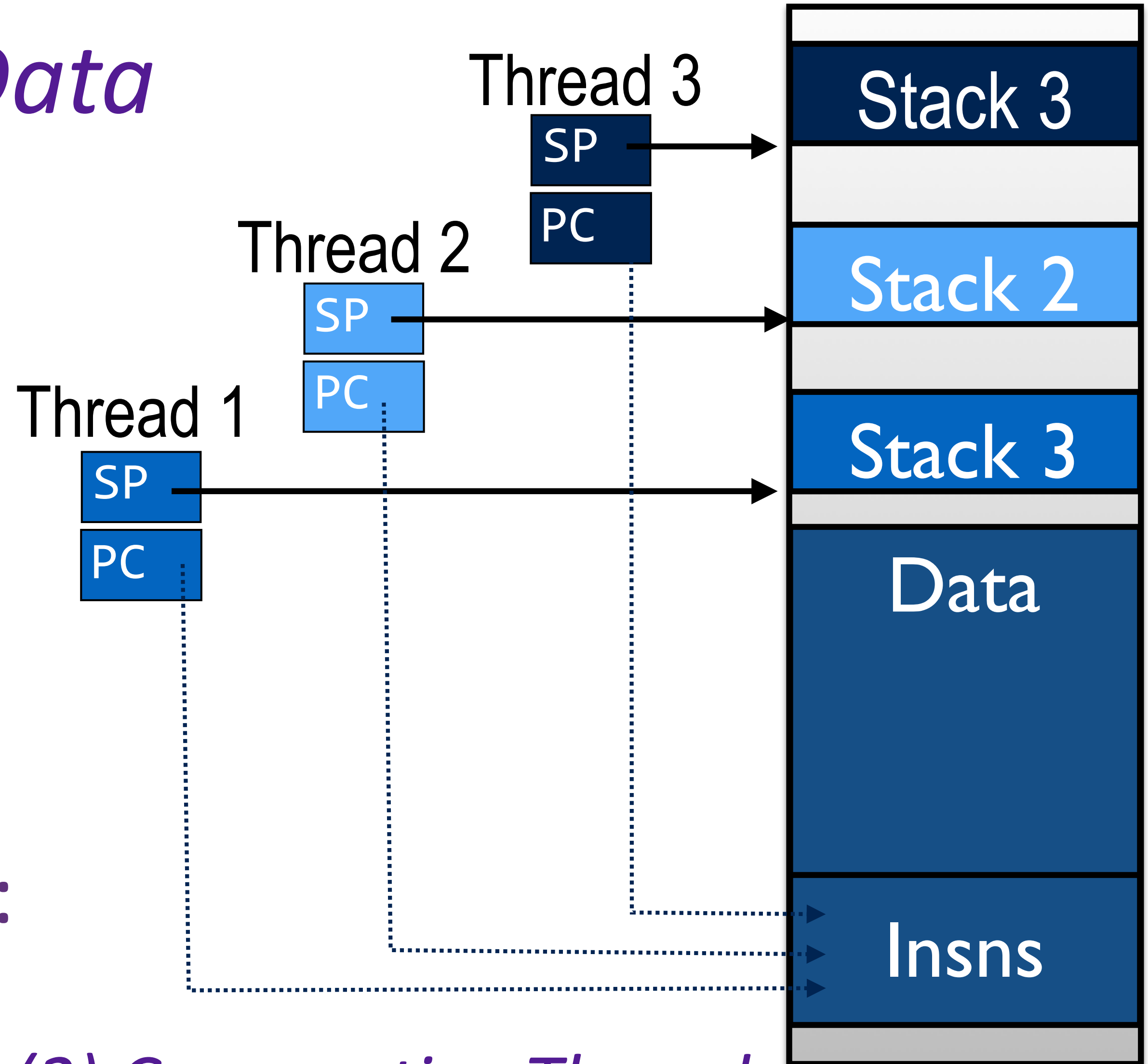
See: Ch 5&6 in OSPP textbook

The slides are the product of many rounds of teaching CS 4410 by Professors Sirer, Bracy, Agarwal, George, and Van Renesse.

Threads and their Data

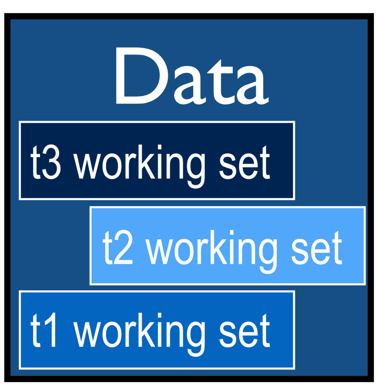
Threads have:

- Private stack
- Private registers
- Shared globals
- What about data?



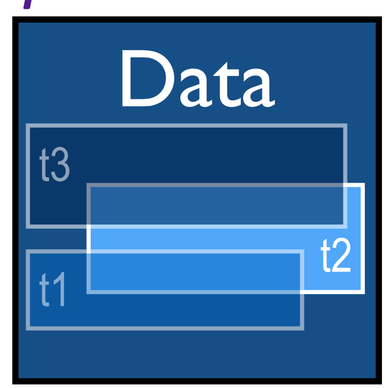
2 possibilities:

(1) Independent Threads



(private by agreement)

(2) Cooperative Threads



2 Threads, 1 Shared Variable

Code like this:

T1
```
...
amount -= 10,000;
...
```

T2
```
...
amount *= 0.5;
...
```

Might execute like this:

T1
```
. . .
r1 = load amount
r1 = r1 – 10,000
store r1 to amount
. . .
```

T2
```
. . .
r2 = load amount

. . .

r2 = 0.5 * r2
store r2 to amount
. . .
```

Race Conditions

When the behavior of a program depends on the interleaving of operations of different threads.

(Once thread starts, it needs to “race” to finish.)

Number of possible interleavings is huge

- Some interleavings are good
- Some interleavings are bad:
  - Bad interleavings may be rare!
  - ***Works 100 times ≠ correct***
  - *Case Study: Therac-25*

<u>ALL</u> possible interleavings should be safe!

Problems with Sequential Reasoning

1. Program execution depends on the possible interleavings of threads' access to shared state.

2. Program execution can be nondeterministic.

3. Compilers and processor hardware can reorder instructions.

CONCURRENT APPLICATIONS

. . .

SYNCHRONIZATION VARIABLES

Locks Semaphores Condition Variables

ATOMIC INSTRUCTIONS

Interrupt Disable Atomic R/W Instructions

HARDWARE

Multiple Processors Hardware Interrupts

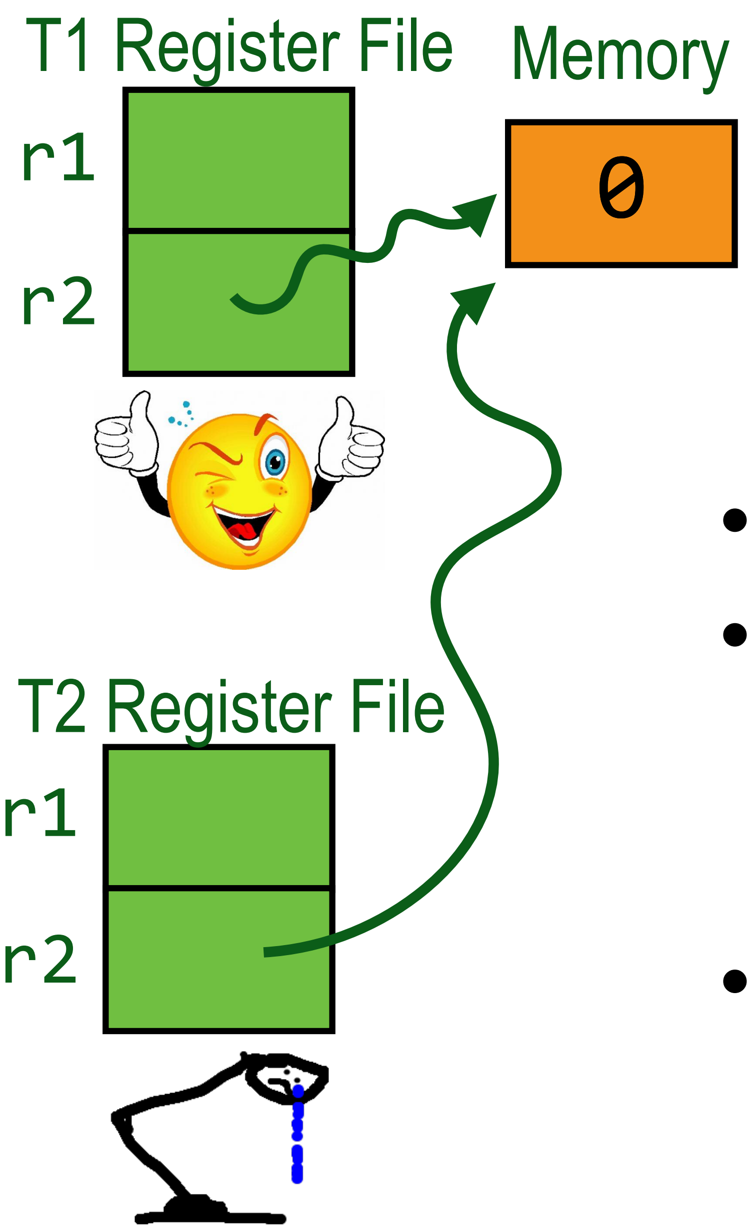
Race Condition Revisited

T1 | T2

```
                                 disable_interrupts();
                                 r2 = load amount
                                 r2 = 0.5 * r2
                                 store r2 to amount
                                 enable_interrupts();
disable_interrupts();
r1 = load amount
r1 = r1 – 10,000
store r1 to amount
enable_interrupts();
```

That was easy…. class dismissed?

Test and Set



MIPS version:

```
tas r1, 0(r2):
   r1 ← 0(r2)    # test
   0(r2) ← 1     # set
```

0-free
1-taken

- atomic hardware primitive
- typically a multi-cycle bus operation that atomically reads and updates a memory location
- supports mutual exclusion

Test and Set to provide Mutual Exclusion

```
ATOMIC int TestAndSet(int *var)
{
  int oldVal = *var;
  *var = 1;
  return oldVal;
}
```

C semantics of Test-And-Set

```
acquire(int *lock) {
   while(test_and_set(lock))
     /* do nothing */;
}
```

```
release(int *lock) {
  *lock = 0;
}
```

Race Condition Revisited

Now with Locks!

Is this a good solution?

T1

```
acquire();
 while(test_and_set(lock))
 ~~while(test_and_set(lock))~~
 ~~while(test_and_set(lock))~~
     yield()

 while(test_and_set(lock))
r1 = load amount
r1 = r1 – 10,000
store r1 to amount
release();
```

T2

```
acquire();
r2 = load amount

r2 = 0.5 * r2
store r2 to amount
release();
```

Thou shalt not busy-wait!

CONCURRENT APPLICATIONS

...

SYNCHRONIZATION VARIABLES

Locks   Semaphores   Condition Variables

ATOMIC INSTRUCTIONS

Interrupt Disable   Atomic R/W Instructions

HARDWARE

Multiple Processors   Hardware Interrupts

Semaphores

[Dijkstra 1962]

Dijkstra introduced in the THE Operating System

- Stateful:
  - a semaphore has a non negative VALUE associated with it
  - value is incremented and decremented atomically

- Interface
  - Two operations: P() and V()
  - No operation to read the value!

Semaphore Operations: P and V

P(S):

- wait until value is positive
- when so, atomically decrement VALUE by 1

```
P(S) {
    while(S <= 0)
        ;
    S -= 1;
}
```

V(S):

- increment VALUE by 1
- resume a thread waiting on P (if any)

```
V(S) {
    S += 1;
}
```

Dutch 4410: P = Probeer ('Try') and V = Verhoog ('Increment', 'Increase by one')

Binary Semaphore

Semaphore value is either 0 or 1

- Used for **mutual exclusion**

  (semaphore as a more efficient lock)

- Initially 1 in that case

```
Semaphore S
S.init(1)
```

T1

```
P(S)
CriticalSection()
V(S)
```

T2

```
P(S)
CriticalSection()
V(S)
```

Counting Semaphores

Sema count can be any integer

- Used for signaling or counting resources
- Typically:
  - one thread performs P() to await event
  - another thread performs V() to alert waiting thread that event has occurred

```
Semaphore packetarrived
packetarrived.init(0)
```

T1

```
PacketProcessor():
x = get_packet_from_card()
enqueue(packetq, x);
V(packetarrived);
```

T2

```
NetworkingThread():
P(packetarrived);
x = dequeue(packetq);
print_contents(x);
```

Possible Semaphore implementation

P1 Context: *no preemption (threads run until they yield)*

```
P(S) {
    while(S <= 0)
        ;
    S -= 1;
}
```

```
P(Sema *s) {
   if count big enough
     decrement count
   else {
     make note of thread
     stop thread
   }
}
```

```
V(S) {
    S += 1;
}
```

```
V(Sema *s) {
   if no one waiting on s
     increment count
   else
     wake an interested thread

   }
}
```

Producer-Consumer Problem

2+ threads communicate:

some threads **produce** data that others **consume**

Bounded buffer: size **N**

Producer process writes data to buffer

- Writes to **in** and moves rightwards
- Don't write more than **N**!

Consumer process reads data from buffer

- Reads from **out** and moves rightwards
- Don't consume if there is no data!

Example: "pipe" (|) in Unix `> cat file | sort | uniq | more`

Solution #1: No Protection

```
Shared:
int buf[N];
int in, out;
```

```
// add item to buffer
void produce(int item) {
  buf[in] = item;
  in = (in+1)%N;
}
```

```
// remove item
int consume() {
  int item = buf[out];
  out = (out+1)%N;
  return item;
}
```

Problems:

1. Unprotected shared state (multiple producers/consumers)
2. Inventory:
   - Consumer could consume when nothing is there!
   - Producer could overwrite not-yet-consumed data!

Solution #2: Add Mutex Semaphores

```
Shared:
int buf[N];
int in, out;
Semaphore mutex_prod(1), mutex_cons(1);
```

```
// add item to buffer
void produce(int item)
{
  P(mutex_prod);
  buf[in] = item;
  in = (in+1)%N;
  V(mutex_prod);

}
```

now atomic

```
// remove item
int consume()
{
  P(mutex_cons);
  int item = buf[out];
  out = (out+1)%N;
  V(mutex_cons);
  return item;
}
```

Solution #3: Add Communication Semaphores

```
Shared:
int buf[N];
int in, out;
Semaphore mutex_prod(1), mutex_cons(1);
Semaphore enoughRoom(N), dataThere(0);
```

```
void produce(int item)
{
  P(enoughRoom); //space?
  P(mutex_prod);
  buf[in] = item;
  in = (in+1)%N;
  V(mutex_prod);
  V(dataThere); //item!
}
```

```
int consume()
{
  P(dataThere); //need item
  P(mutex_cons);
  int item = buf[out];
  out = (out+1)%N;
  V(mutex_cons);
  V(enoughRoom); // space!
  return item;
}
```

DONE FOR TODAY!

Classic Semaphore Mistakes

```
P(S)
CS
P(S)   ⬅typo
```

I

I stuck on 2nd P(). Subsequent processes freeze up on 1st P().

```
V(S)   ⬅typo
CS
V(S)
```

J

Undermines mutex:

- J doesn't get permission via P()
- "extra" V()s allow other processes into the CS inappropriately

```
P(S)
CS   ⬅omission
```

K

Next call to P() will freeze up. Confusing because the *other* process could be correct but hangs when you use a debugger to look at its state!

```
P(S)
if(x) return;
CS
V(S)
```

L

Conditional code can change code flow in the CS. Caused by code updates (bug fixes, etc.) by someone other than original author of code.

Semaphores Considered Harmful

"During system conception it transpired that we used the semaphores in two completely different ways. The difference is so marked that, looking back, one wonders whether it was really fair to present the two ways as uses of the very same primitives. On the one hand, we have the semaphores used for mutual exclusion, on the other hand, the private semaphores."

— Dijkstra "The structure of the 'THE'-Multiprogramming System" Communications of the ACM v. 11 n. 5 May 1968.

Semaphores NOT to the rescue!

Semaphores are “low-level” primitives. Small errors:

- Easily bring system to grinding halt
- Very difficult to debug

Two usage models:

- **Mutual exclusion:** “real” abstraction is a critical section
- **Communication:** threads use semaphores to communicate (e.g., bounded buffer example)

Simplification: Provide concurrency support in compiler

➙Enter Monitors