CE 440 Introduction to Operating System

Lecture 6: Synchronization
Fall 2025

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Slides courtesy of Manuel Egele, Ryan Huang and Baris Kasikci

Administrivia

Fill out project group form

- https://docs.google.com/forms/d/e/1FAIpQLScqr0QdmoruMu_w7-FizeQ9OYaijg9-d9Y58zOV28wivnYp5A/viewform?usp=dialog

Lab 1 released

- Lab 1 overview session this Friday
- Read the requirement now
- Start with exercise 2.1

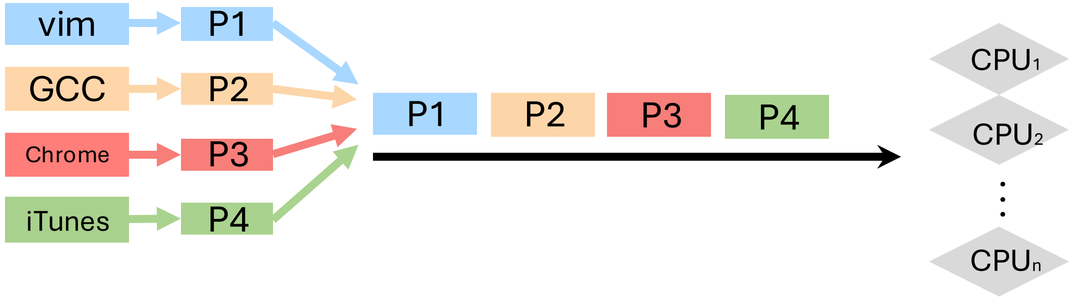
GitHub classroom invitation link

- Used for the following lab assignments

Recap: Scheduling

The scheduling problem:

- Have K jobs ready to run
- Have $N \geq 1$ CPUs



Many potential goals of scheduling algorithms

- Utilization, throughput, wait time, response time, etc.

Various algorithms to meet these goals

- FCFS/FIFO, SJF, RR, Priority

Recap: Single and Multithreaded Processes

Process/Thread Separation

- The thread defines a sequential execution
- The process defines the address space and general process attributes

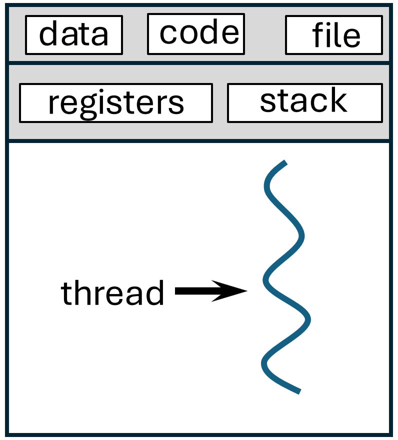
A thread is bound to a single process

- Processes, however, can have multiple threads

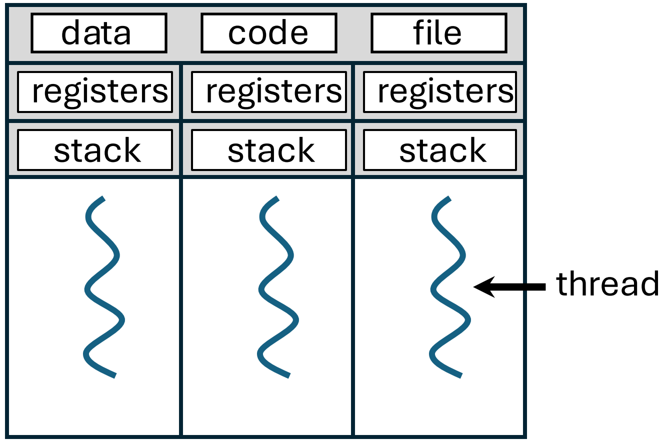
Threads become the unit of scheduling

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

- Synchronization…

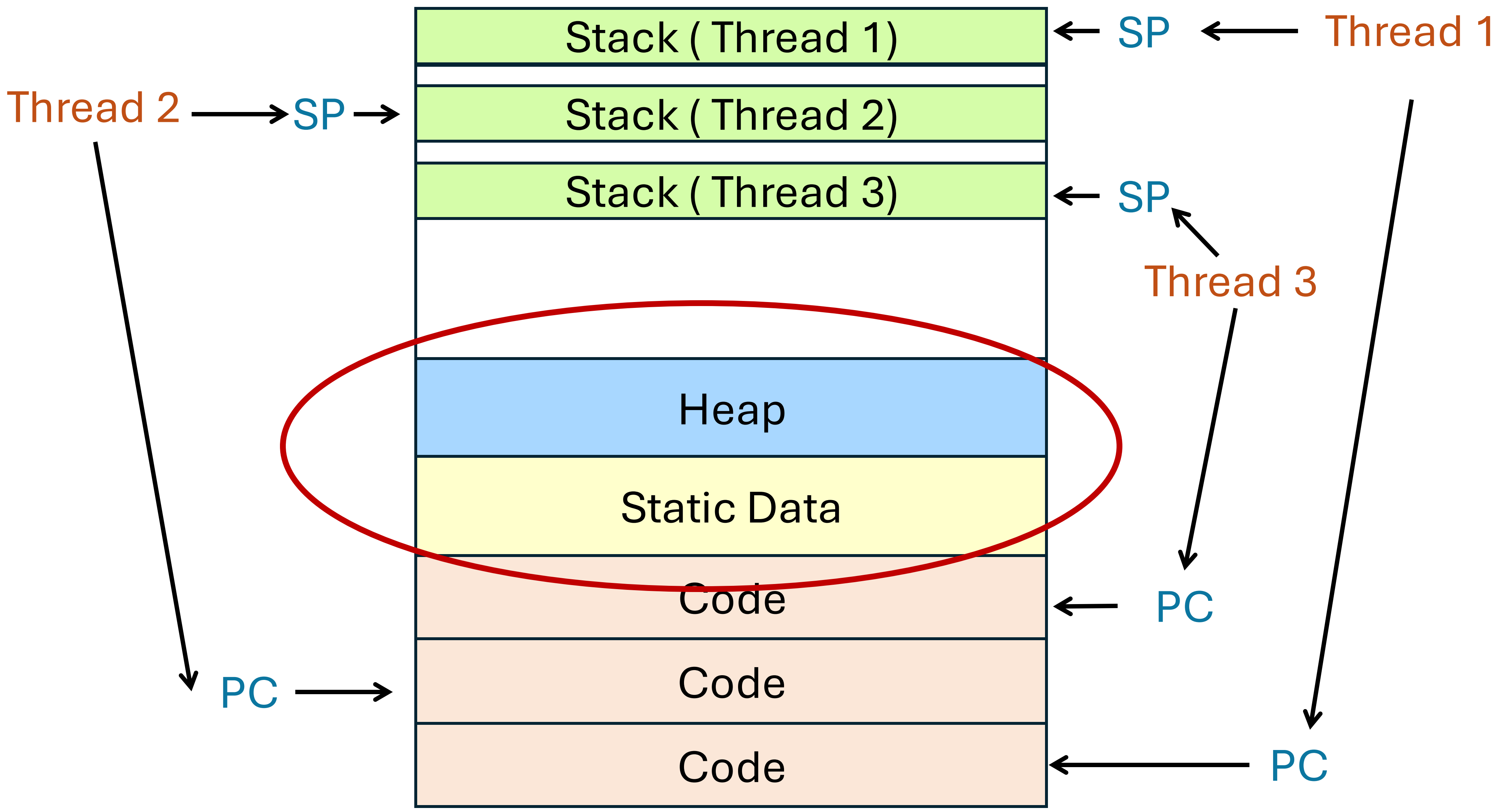


Single-threaded process



Multithreaded process

What Resources Are Shared?



What Resources Are Shared?

Local variables are not shared (private)

- Refer to data on the stack
- Each thread has its own stack
- Never pass/share/store a pointer to a local variable on the stack for thread T1 to another thread T2

Global variables and static objects are shared

- Stored in the static data segment, accessible by any thread

Dynamic objects and other heap objects are shared

- Allocated from heap with malloc/free or new/delete

Correctness with Concurrent Threads

Threads cooperate in multithreaded programs

- To share resources, access shared data structures
- To coordinate their execution

For correctness, we need to control this cooperation

- Thread schedule is non-deterministic (i.e., behavior changes when re-run program)
  - Scheduling is not under program control
  - Threads interleave executions arbitrarily and at different rates
- Multi-word operations are not atomic
- Compiler/hardware instruction reordering

Motivated Example: Too Much Milk

People need to coordinate:

- Alice and Bob are roommate and they share milk
- Here is a story: they both thought they were buying one carton of milk, but they ended up with two!

Time	Alice	Bob
3:00	Look in Fridge. Out of milk.	
3:05	Leave for store.	
3:10	Arrive at store.	Look in fridge. Out of milk.
3:15	Buy milk.	Leave for store.
3:20	Arrive home, put milk away.	Arrive at store.
3:25		Buy milk.
3:30		Arrive home, put milk away. Oh no!

Too Much Milk… Operation?

x is a global variable initialized to 0

```
// Thread 1

void foo() {
    x++;
}
```

```
// Thread 2

void bar() {
    x--;
}
```

After thread 1 and thread 2 finishes, what is the value of x?

- could be 0, 1, -1
- Why?
  - x++ and x-- are not atomic operations
  - Load x from memory
  - Modify value (add or subtract)
  - Store back to memory

One More Exercise

int p = 0, ready = 0;

```
// Thread 1

p = 1000;
ready = 1;
```

```
// Thread 2

while (!ready);
use(p)
```

What value of p is passed to use

- Could be 0, 1000
- Why?

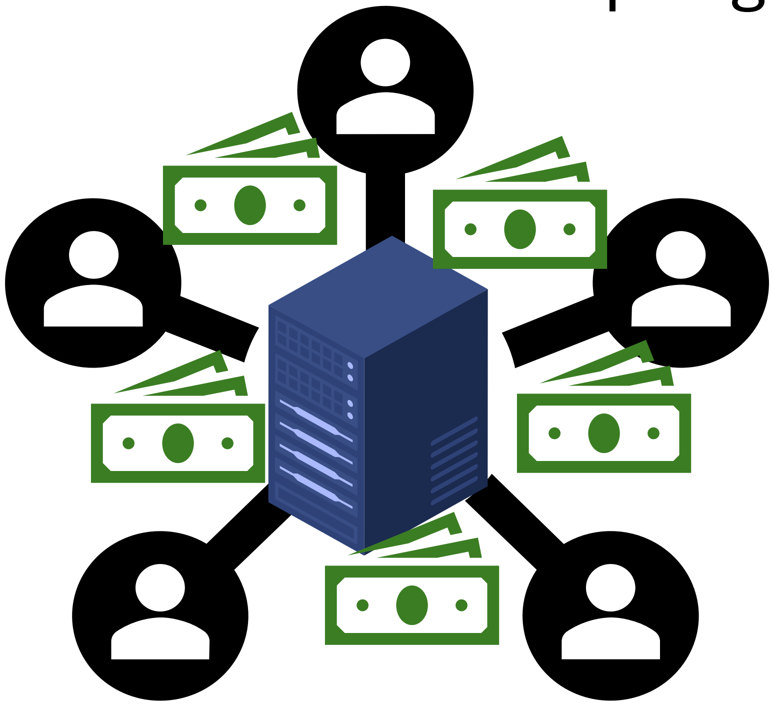
Concurrency Is Important and Hard

Therac-25: Radiation Therapy Machine with Unintended Overdose

- Concurrency errors caused the death of a number of patients

ATM Bank:

- Service a set of requests with out corrupting database



Problem with Shared Resources

We focus on controlling access to shared resources

Basic problem

- If two concurrent threads (processes) are accessing a shared variable, and that variable is read/modified/written by those threads, then access to the variable must be controlled to avoid erroneous behavior.

Over the next couple of lectures, we will look at

- Mechanisms to control access to shared resources
    - Locks, mutexes, semaphores, monitors, condition variables, etc.
- Patterns for coordinating accesses to shared resources
    - Bounded buffer, producer-consumer, etc.

Problem with Shared Resources

Problem: concurrent threads accessed a shared resource without any synchronization

- Know as a race condition

Race Condition Example: Bank Account

Implement a function to handle withdrawals from a bank account:

```
withdraw (account, amount) {
    balance = get_balance(account);
    balance = balance – amount;
    put_balance(account, balance);
    return balance;
}
```

Suppose that you have a family account with a balance of $10,000

Then you and you parent go to separate ATM machines and simultaneously withdraw $1000 from the account

Race Condition Example Continued

The bank server will create separate threads for each person to do the withdrawals

These threads run on the same bank server:

```
withdraw (account, amount) {
    balance = get_balance(account);
    balance = balance – amount;
    put_balance(account, balance);
    return balance;
}
```

```
withdraw (account, amount) {
    balance = get_balance(account);
    balance = balance – amount;
    put_balance(account, balance);
    return balance;
}
```

Let’s examine the schedules of these two threads together

Interleaved Schedules

The execution of the two threads can be interleaved

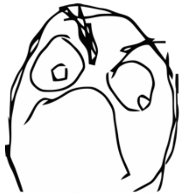
```
balance = get_balance(account);
balance = balance – amount;
```

```
balance = get_balance(account);
balance = balance – amount;
put_balance(account, balance);
```

```
put_balance(account, balance);
```

Context switch

After withdrawing $2000 from $10,000, balance of the account is…

- **$ 9,000** 
- **The banker would be very unhappy about it** 

How Interleaved Can It Get?

How many possible interleaving?

- Only instructions are atomic
- A context switch can occur at any time
- OS can delay a thread for any time as long as it's not delayed forever

```
balance = get_balance(account);
balance = get_balance(account);
balance = balance – amount;
balance = balance – amount;
put_balance(account, balance);
put_balance(account, balance);
```

Shared Resources

Problem: concurrent threads accessed a shared resource without any synchronization

- Know as a race condition

Although our example was updating a shared bank account, it is apply to any shared data structure

- Buffers, queues, lists, hash tables, etc.

We need mechanisms to control access to these shared resources in the face of concurrency

- So we can reason about how the program will operate

What do We Need for Controlling Concurrency

Mutual Exclusion

- When one thread access shared resource, other thread can not access it

Code that uses mutual exclusion to synchronize its execution is called a critical section

- Only one thread at a time can execute in the critical section
- All other threads are forced to wait on entry
- When a thread leaves a critical section, another can enter
- Example: sharing your bathroom with housemates

What requirements would you place on a critical section?

Critical Section Requirements

1. **Mutual exclusion (mutex)**
   - If one thread is in the critical section, then no other is

2. **Progress**
   - If some thread T is not in the critical section, then T cannot prevent some other thread S from entering the critical section
   - A thread in the critical section will eventually leave it

3. **Bounded waiting (no starvation)**
   - If some thread T is waiting on the critical section, then T will eventually enter the critical section

Critical Section Requirements

4. Performance

- The overhead of entering and exiting the critical section is small with respect to the work being done within it

In summary:

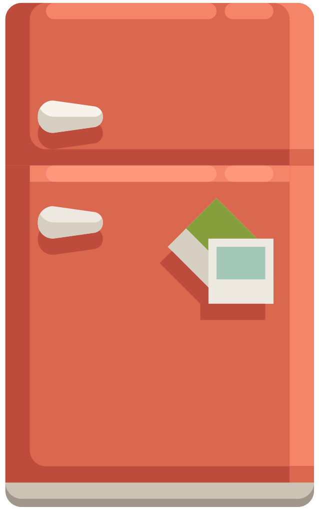
- **Safety property**: nothing bad happens
  - Mutex
- **Liveness property**: something good happens
  - Progress, Bounded Waiting
- **Performance requirement**
  - Performance

Note: correctness of concurrent is guarantee by design

Too Much Milk: Solution #1

How about leave a note?

```
if (milk == 0) {               // if no milk
    if (note == 0) {           // if no note
        note = 1;              // leave note
        milk++;                // buy milk
        note = 0;              // remove note
    }
}
```



Does it solve the problem?

Too Much Milk: Solution #1

Problem with leave a note

Alice

```
if (milk == 0) {




    if (note == 0) {
        note = 1;
        milk++;
        note = 0;
    }
}
```

Bob

```
if (milk == 0) {
    if (note == 0) {
        note = 1;
        milk++;
        note = 0;
    }
}
```

Too Much Milk: Solution #2

How about leave two notes

Alice

```
noteA = 1;
if (noteB == 0) {
    if (milk == 0) {
        milk++;
    }
}
noteA = 0;
```

Bob

```
noteB = 1;
if (noteA == 0) {
    if (milk == 0) {
        milk++;
    }
}
noteB = 0;
```

Is this safe?

- Yes
- What if Alice executes noteA = 1. At the same time, Bob executes noteB = 1?
  - I'm not getting milk, You're getting milk
  - Starvation

Too Much Milk: Solution #3

Monitoring note:

Alice

```
noteA = 1;
while (noteB == 1);
if (noteB == 0) {
    if (milk == 0) {
        milk++;
    }
}
noteA = 0;
```

Bob

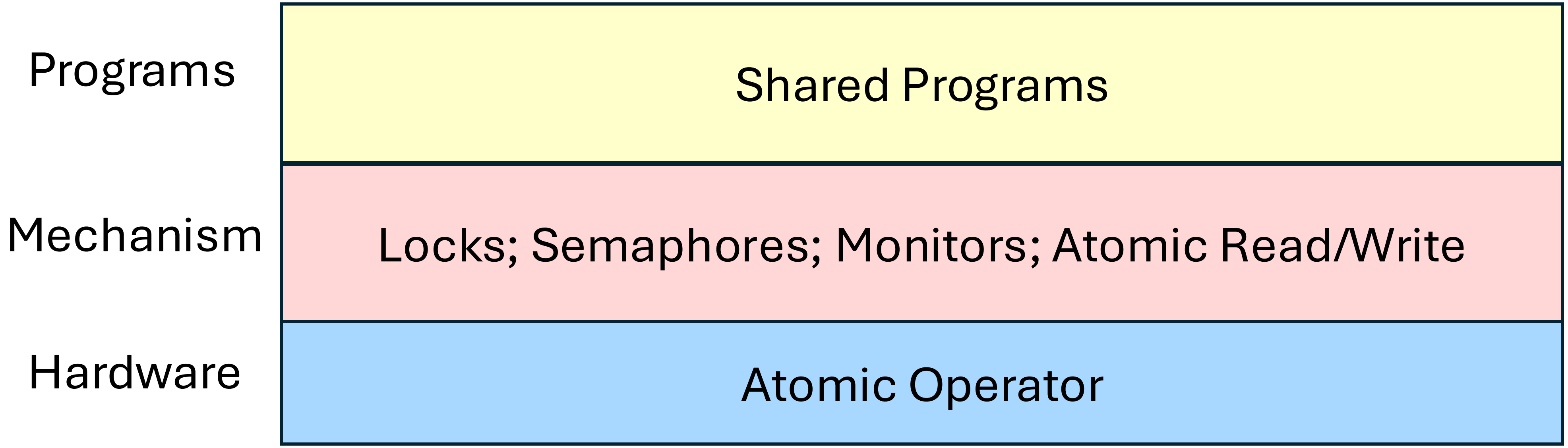
```
noteB = 1;
if (noteA == 0) {
    if (milk == 0) {
        milk++;
    }
}
noteB = 0;
```

Is this safe?

- Yes

Do it ensure liveness?

Where Are We Going with Synchronization?



Coordination happens across all layers

Atomic Operations

Atomic Operation: an operation that always runs to completion or not at all

- annot be stopped in the middle
- cannot be modified by someone else in the middle
- fundamental building block for synchronization

On most machines, memory references and assignments are atomic

Many instructions are not atomic

- Double-precision floating point store often not atomic

Mechanisms For Building Critical Sections

Atomic read/write

- Can it be done?

Locks

- Primitive, minimal semantics, used to build others

Semaphores

- Basic, easy to get the hang of, but hard to program with

Monitors

- High-level, requires language support, operations implicit

Mutex with Atomic R/W: Try #1

```
int turn = 1;
```

T_1

```
while (true) {
    while (turn != 1);
    critical section
    turn = 2;
    outside of critical section
}
```

T_2

```
while (true) {
    while (turn != 2);
    critical section
    turn = 1;
    outside of critical section
}
```

This is called alternation

Does it satisfy the safety requirement?

- Yes

Does it satisfy the liveness requirement?

- No, T1 can go into infinite loop outside of the critical section preventing T2 from entering

Mutex with Atomic R/W: Peterson's Algorithm

```
int turn = 1;
bool try1 = false, try2 = false;
```

T_1

```
while (true) {
   try1 = true;
   turn = 2;
   while (try2 && turn != 1);
   critical section
   try1 = false;
   outside of critical section
}
```

T_2

```
while (true) {
   try2 = true;
   turn = 1;
   while (try1 && turn != 2);
   critical section
   try2 = false;
   outside of critical section
}
```

Does it satisfy the liveness requirement?

Does it satisfy the safety requirement?

Proof Sketch of Peterson's Algorithm

```
int turn = 1;
bool try1 = false, try2 = false;
```

T_1

```
while (true) {
{¬ try1 ∧ (turn == 1 ∨ turn == 2) }
1    try1 = true;
{ try1 ∧ (turn == 1 ∨ turn == 2) }
2    turn = 2;
{ try1 ∧ (turn == 1 ∨ turn == 2) }
3    while (try2 && turn != 1);
{ try1 ∧ (turn == 1 ∨ ¬ try2 ∨
(try2 ∧ (line at 6 or at 7))) }
     critical section
4    try1 = false;
{¬ try1 ∧ (turn == 1 ∨ turn == 2) }
    outside of critical section
}
```

T_2

```
while (true) {
{¬ try2 ∧ (turn == 1 ∨ turn == 2) }
5   try2 = true;
{ try2 ∧ (turn == 1 ∨ turn == 2) }
6    turn = 1;
{ try2 ∧ (turn == 1 ∨ turn == 2) }
7   while (try1 && turn != 2);
{ try2 ∧ (turn == 2 ∨ ¬ try1 ∨
(try1 ∧ (line at 2 or at 3))) }
    critical section
8   try2 = false;
 {¬ try2 ∧ (turn == 1 ∨ turn == 2) }
    outside of critical section
}
```

Safety property: (line 4) ∧ (line 8) ⇒ (turn == 1 ∧ turn == 2)

Locks

A lock is an object in memory providing two operations

- acquire(): wait until lock is free, then take it to enter a C.S
- release(): release lock to leave a C.S, waking up anyone waiting for it

Threads pair calls to acquire and release

- Between acquire/release, the thread holds the lock
- acquire does not return until any previous holder releases
- What can happen if the calls are not paired?

Locks can spin (a spinlock) or block (a mutex)

- Can break apart Peterson's to implement a spinlock

Too Much Milk: Solution #4

Solution #4: lock

Alice

```
lock.acquire();
if (milk == 0) {
   milk++;
}
lock.release();
```

Bob

```
lock.acquire();
if (milk == 0) {
   milk++;
}
lock.release();
```

Fix Banking Problem with Lock

```
withdraw (account, amount) {
   acquire(lock)
   balance = get_balance(account);
   balance = balance – amount;
   put_balance(account, balance);
   release(lock);
   return balance;

}
```

Critical Section

```
acquire(lock);
balance = get_balance(account);
balance = balance – amount;
```

```
acquire(lock);
```

```
put_balance(account, balance);
release(lock);
```

```
balance = get_balance(account);
balance = balance – amount;
put_balance(account, balance);
release(lock);
```

- What happens when green tries to acquire the lock?
- Why is the “return” outside the critical section? Is this ok?
- What happens when a third thread calls acquire?

Implementing Locks (1)

How do we implement locks? Here is one attempt:

```
struct lock {
    int held = 0;
}
void acquire (lock) {
    while (lock→held);
    lock→held = 1;
}

void release (lock) {
    lock→held = 0;
}
```

busy-wait (spin-wait) for lock to be released

Called a spinlock because a thread spins waiting for the lock to be released

Implementing Locks (2)

The `while` is not atomic:

- Two independent threads may both notice that a lock has been released and thereby acquire it.

```
struct lock {
    int held = 0;
}
void acquire (lock) {
    while (lock→held);
    lock→held = 1;
}

void release (lock) {
    lock→held = 0;
}
```

A context switch can occur here, causing a race condition

Implementing Locks (3)

The problem is that the implementation of locks has critical sections, too!

How do we stop the recursion?

The implementation of acquire/release must be atomic

- An atomic operation is one which executes as though it could not be interrupted
- Code that executes “all or nothing”

How do we make them atomic?

Need help from hardware

- Atomic instructions (e.g., test-and-set)
- Disable/enable interrupts (prevents context switches)

Atomic Instructions: Test-And-Set

The semantics of test-and-set are:

- Record the old value
- Set the value to indicate available
- Return the old value

```
bool test_and_set(bool *flag) {
    bool old = *flag;
    *flag = True;
    return old;
}
```

Hardware executes it atomically!

When executing test-and-set on "flag"

- What is value of flag afterwards if it was initially False? True?
- What is the return result if flag was initially False? True?

Other similar flavor atomic instructions: xchg, CAS

Using Test-And-Set to Implement Lock

Here is our lock implementation with test-and-set:

```
struct lock {
    int held = 0;
}
void acquire (lock) {
    while (test_and_set(&lock→held));
}

void release (lock) {
    lock→held = 0;
}
```

When will the while return? What is the value of held?

What about multiprocessors?

Implement it with xchg, Compare-And-Swap

Problems with Spinlocks

The problem with spinlocks is that they are wasteful

- If a thread is spinning on a lock, then the thread holding the lock cannot make progress (on a uniprocessor)

How did the lock holder give up the CPU in the first place?

- Lock holder calls yield or sleep
- Involuntary context switch

Only want to use spinlocks as primitives to build higher-level synchronization constructs

Disabling Interrupts

Another implementation of acquire/release is to disable interrupts:

```
struct lock {
    int held = 0;
}
void acquire (lock) {
    disable interrupts;
}

void release (lock) {
    enable interrupts;
}
```

Note that there is no state associated with the lock

Can two threads disable interrupts simultaneously?

On Disabling Interrupts

Disabling interrupts blocks notification of external events that could trigger a context switch (e.g., timer)

- This is what Pintos uses as its primitive

In a "real" system, this is only available to the kernel

- Why?

Disabling interrupts is insufficient on a multiprocessor

- Interrupts are only disabled on a per-core basis
- Back to atomic instructions

Like spinlocks, only want to disable interrupts to implement higher-level synchronization primitives

- Don't want interrupts disabled between acquire and release

Summarize Where We Are

Goal: Use mutual exclusion to protect critical sections of code that access shared resources

Method: Use locks (either spinlocks or disable interrupts)

Problem: Critical sections (CS) can be long

Spinlocks:
- Threads waiting to acquire lock spin in test-and-set loop
- Wastes CPU cycles
- Longer the CS, the longer the spin, greater the chance for lock holder to be interrupted

acquire(lock)
…
Critical section
…
release(lock)

Disabling Interrupts:
- Disabling interrupts for long periods of time can miss or delay important events (e.g., timer, I/O)

Higher-Level Synchronization

Spinlocks and disabling interrupts are useful only for very short and simple critical sections

- Wasteful otherwise
- These primitives are “primitive” – don’t do anything besides mutual exclusion

Need higher-level synchronization primitives that:

- Block waiters
- Leave interrupts enabled within the critical section

All synchronization requires atomicity

So we’ll use our “atomic” locks as primitives to implement them

Implementing Locks (4)

Block waiters, interrupts enabled in critical sections

```
struct lock {
    int held = 0;
    queue Q;
}
void acquire (lock) {
    Disable interrupts;
    while (lock→held) {
        put current thread on lock Q;
        block current thread;
    }
    lock→held = 1;
    Enable interrupts;
}
```

```
void release (lock) {
    Disable interrupts;
    if (Q) remove waiting thread;
    unblock waiting thread;
    lock→held = 0
    Enable interrupts;
}
```

acquire(lock) — Interrupts Disabled

…

Critical section — Interrupts Enabled

…

release(lock) — Interrupts Disabled

Pintos threads/synch.c: sema_down/up

Summary

Why we need synchronizations

Critical sections

Simple algorithms to implement critical sections

Locks

Lock implementations

Next Time…

Read Chapters 30,31

Shared Resources

Threads cooperate in multithreaded programs

- To share resources, access shared data structures
- To coordinate their execution

For correctness, we need to control this cooperation

- Thread schedule is non-deterministic (i.e., behavior changes when re-run program)
  - Scheduling is not under program control
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