Concurrency

CS 5007: Systems

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Review from Last Time

- Threads, Processes
- Viewing threads & processes
- POSIX and threading on UNIX (pthread)
- Using pthreads in C
- Briefly: sharing data in threads

Issues to address

Concurrency: Two things are ***concurrent*** if we cannot tell what will happen first just by looking at the code.

Synchronization: The Simple Case

So far:

Program

instruction 1

instruction 2

instruction 3

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Program

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instruction 3

- Computers execute one instruction after another in sequence
- Synchronization is trivial: we can tell the order of events by looking at the program.
- Instruction 1 comes before Instruction 2 comes before Instruction 3

Synchronization: More Complex

Processor A	Processor B
instruction 1	instruction 1
instruction 2	instruction 2
instruction 3	instruction 3

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  - If there are multiple threads, then the processor can work on one for a while, then switch to another, and so on.

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- ***Case 2:*** A single processor is running multiple threads of execution.
  - If there are multiple threads, then the processor can work on one for a while, then switch to another, and so on.

In both cases: within one processor or thread, we know the order of execution, but between processors (or threads) it is impossible to tell.

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  - What if you had lunch starting at 11:59, and he had lunch starting at 12:01?

Example

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- One day, you start to wonder: who ate lunch first today? You, or Ben? How do you find out?
- Call him and ask!
  - What if you had lunch starting at 11:59, and he had lunch starting at 12:01?
- Unless you know that both of you have accurate clocks, you can't be sure who ate first.

New Goal: Guarantee that you eat before Ben

One approach is to tell Ben not to eat lunch until you call. Then, call him after you each lunch.

Your instructions:

```
Eat breakfast
Work
Eat lunch
Call Ben
```

Ben's Instructions:

```
Eat breakfast
Wait for a call
Eat lunch
```

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You and Ben ate lunch ***sequentially***: we know the order of events

You and Ben ate breakfast ***concurrently***, because we don't know the order.

Determinism vs Nondeterminism

What gets printed?

Thread A

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print "hello"
```

Thread B

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print "goodbye"
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Non-deterministic: It's not possible to tell what will happen when a program executes simply by looking at it.

(I can't demonstrate this...)

Deterministic: We know exactly how a program will behave when executed.

```c
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>
#include <unistd.h>

int my_count = 5;

void *thread1(void *vargp)
{
Iprintf("thread1: %d\n", my_count);
Ireturn NULL;
}

void *thread2(void *vargp){
Iprintf("thread2: %d\n", my_count++);
Ireturn NULL;
}

int main()
{
    pthread_t tid;
    pthread_t tid2;
    printf("Before Thread\n");

    pthread_create(&tid, NULL, thread1, NULL);
    pthread_create(&tid2, NULL, thread2, NULL);

    pthread_join(tid, NULL);
    pthread_join(tid2, NULL);

    printf("After Thread\n");
    exit(0);
}
```

Listing 1: Sharing data via a variable

Sharing Variables via threads

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1. One thread reads a variable that another thread has written to
2. Two (or more) threads write to a single variable
3. Two (or more) threads read *and* write a single variable (update)
4. Two (or more) threads reading the same variable rarely causes problems

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- If the threads are ***unsynchronized***, we can't tell whether the reader will see the original value or the written value
- One constraint we can enforce is: Reader should not read until after the writer writes.
  - This is like lunch with Ben: He's not going to eat until I tell him I ate.
- That is, synchronization by *policy* or *convention*

Case 2: Concurrent Writes

We care about 2 things here:
What gets printed?
What's the final value of x?

Thread A

```
x = 5
print x
```

Thread B

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- Is there a path that yields output 7 and final value 5?

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- yield output 7 and final value 7? $a1 < b1 < a2$
- yield output 5 and final value 7? $a1 < a2 < b1$
- Is there a path that yields output 7 and final value 5? Nope.

Case 3: Concurrent Updates

Update: Read the value of a variable, compute a new value based on the old value, and write the new value to the variable.

Thread A

```
x = x + 1
```

Thread B

```
x = x + 1
```

What could go wrong?

Concurrent Updates

What if we re-write the code such:

Thread A

```
temp = x
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```

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- Would the same thing happen if we had written `x++`?

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- Both threads *read* the same value, so they both *write* the same value...
- Would the same thing happen if we had written `x++`?
- Maybe... depends on the computer.
- ***atomic***: An operation that cannot be interrupted.

Mutex

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To write concurrent programs and ensure they are correct, we:

- Assume all updates and all writes are **not** atomic
- Use synchronization to control concurrent access to shared resources.
- "Mutual Exclusion"
- Guarantees that only one thread accesses a shared section of code at a time

Mutex Example

Semaphore and Mutex

How do we add a mutex to this?

Thread A

```
count = count + 1;
```

Thread B

```
count = count + 1;
```

Semaphore and Mutex

How do we add a mutex to this (semantically)?

Thread A

```
count = count + 1;
```

Thread B

```
count = count + 1;
```

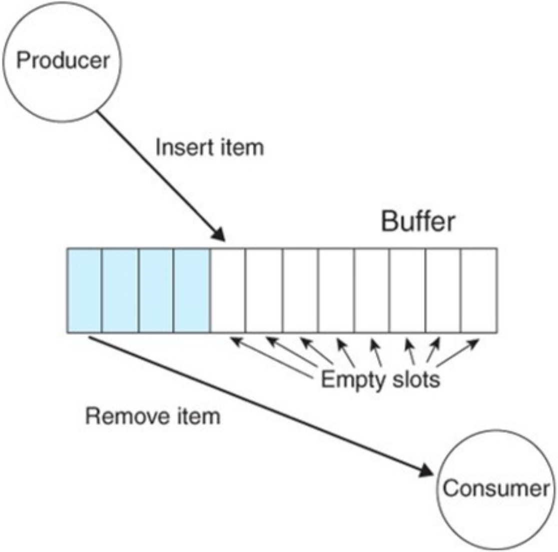
Mutexes in C

```c
int pthread_mutex_init(pthread_mutex_t *restrict mutex, const pthread_mutexattr_t *restrict
    attr);
int pthread_mutex_lock(pthread_mutex_t *mutex);
int pthread_mutex_unlock(pthread_mutex_t *mutex);
int pthread_mutex_destroy(pthread_mutex_t *mutex);
```

Mutexes in C

```c
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>
#include <unistd.h>


int my_count = 5;

pthread_mutex_t lock;

void *thread1(void *vargp){
    pthread_mutex_lock(&lock);
    printf("thread1: %d\n", my_count);
    pthread_mutex_unlock(&lock);
    return NULL;
}

void *thread2(void *vargp){
    pthread_mutex_lock(&lock);
    printf("thread2: %d\n", my_count++);
    pthread_mutex_unlock(&lock);
    return NULL;
}

int main(){
    // Initialize mutex
    if (pthread_mutex_init(&lock, NULL) != 0)
    {
        printf("\n mutex init failed\n");
        return 1;
    }

    pthread_t tid;
    pthread_t tid2;
    printf("Before Thread\n");
    pthread_create(&tid, NULL, thread1, NULL);
    pthread_create(&tid2, NULL, thread2, NULL);
```

Producer-Consumer Problem



Dining Philosophers[1]

A philosopher sits at each spot.
Each philosopher follows the given process:

- Think until the left fork is available; when it is, pick it up
- Think until the right fork is available; when it is, pick it up
- When both forks are held, eat for a fixed amount of time
- Put the right fork down
- Put the left fork down
- Repeat from the beginning

[1] https://en.wikipedia.org/wiki/Dining_philosophers_problem

Dining Philosophers[2]

- Each philosopher is a thread, doing some work
- The plate of food is the data on which the philosopher is acting
- The forks are the resources the philosopher needs to do the work

[2] https://en.wikipedia.org/wiki/Dining_philosophers_problem

Semaphore

- A ***semaphore*** is a data structure that is useful for solving a variety of synchronization problems

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  1. When you create the semaphore:
     - You can initialize its value to any integer.
     - After that the only operations you are allowed to perform are increment (increase by one) and decrement (decrease by one).
     - You cannot read the current value of the semaphore.

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     - You cannot read the current value of the semaphore.
  2. When a thread decrements the semaphore:
     - If the result is negative, the thread blocks itself and cannot continue until another thread increments the semaphore.

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  2. When a thread decrements the semaphore:
     - If the result is negative, the thread blocks itself and cannot continue until another thread increments the semaphore.
  3. When a thread increments the semaphore:
     - If there are other threads waiting, one of the waiting threads gets unblocked

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Semaphore: Implementation

Semaphor operations

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- `increment()` `signal()` `V()`
- `decrement()` `wait()` `P()`
- `destroySemaphor()`

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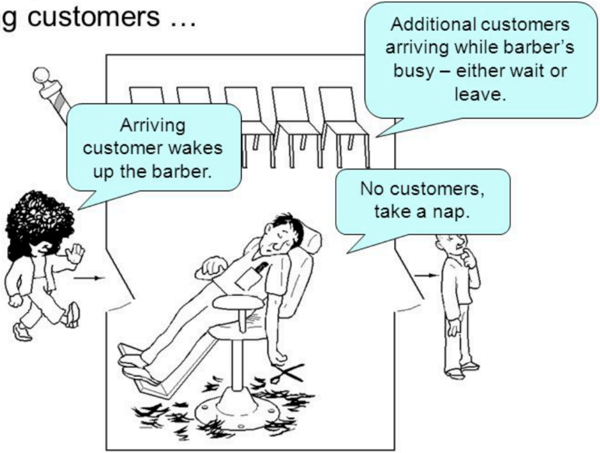
- Solutions using semaphores are often clean and organized, making it easy to demonstrate their correctness.
- Semaphores can be implemented efficiently on many systems, so solutions that use semaphores are portable and usually efficient.

Using Semaphores for mutual exclusion

In order for a thread to access a shared variable, it has to "get" the mutex; when it is done, it "releases" the mutex. Only one thread can hold the mutex at a time.

Sleeping Barber

One barber, one barber chair and *n* chairs for waiting customers …



Sleeping Barber

We have a barber that works when there are customers, and sleeps when there are none.

- We have a hypothetical barber shop with one barber.
- The barber has one barber's chair in a cutting room and a waiting room containing a number of chairs in it.
- When the barber finishes cutting a customer's hair, he dismisses the customer and goes to the waiting room to see if there are others waiting.
- If there are, he brings one of them back to the chairs and cut their hair.
- If there are none, he returns to the chair and sleeps in it.
- Each customer, when they arrive, looks to see what the barber is doing.
- If the barber is sleeping, the customer wakes him up and sits in the cutting room chair.
- If the barber is cutting hair, the customer stays in the waiting room.
- If there is a free chair in the waiting room, the customer sits in it and waits their turn.

Sleeping Barber[4]

- The barber is the thread that does work.

[4] https://en.wikipedia.org/wiki/Dining_philosophers_problem

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Sleeping Barber[4]

- The barber is the thread that does work.
- The customer is the data on which the philosopher is acting
- The waiting room is the thing that controls whether there is more data to process

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- The barber is now waiting for a customer, but the customer is waiting for the barber.
- In another example, two customers may arrive at the same time when there happens to be a single seat in the waiting room. They observe that the barber is cutting hair, go to the waiting room, and both attempt to occupy the single chair.

Barber; a psuedocode solution

```
# The first two are mutexes (only 0 or 1 possible)
Semaphore barberReady = 0
Semaphore accessWRSeats = 1     # if 1, the number of seats in the waiting room can be incremented or decremented
Semaphore custReady = 0         # the number of customers currently in the waiting room, ready to be served
int numberOfFreeWRSeats = N     # total number of seats in the waiting room

def Barber():
  while true:                   # Run in an infinite loop.
    wait(custReady)             # Try to acquire a customer - if none is available, go to sleep.
    wait(accessWRSeats)         # Awake - try to get access to modify # of available seats, otherwise sleep.
    numberOfFreeWRSeats += 1    # One waiting room chair becomes free.
    signal(barberReady)         # I am ready to cut.
    signal(accessWRSeats)       # Don't need the lock on the chairs anymore.
    # (Cut hair here.)

def Customer():
    wait(accessWRSeats)         # Try to get access to the waiting room chairs.
    if numberOfFreeWRSeats > 0: # If there are any free seats:
      numberOfFreeWRSeats -= 1  #   sit down in a chair
      signal(custReady)         #   notify the barber, who's waiting until there is a customer
      signal(accessWRSeats)     #   don't need to lock the chairs anymore
      wait(barberReady)         #   wait until the barber is ready
      # (Have hair cut here.)
    else:                       # otherwise, there are no free seats; tough luck --
      signal(accessWRSeats)     #   but don't forget to release the lock on the seats!
      # (Leave without a haircut.)
```

Definitions/Vocab

- ***deadlock***
- ***semaphore***
- ***mutex***
- ***concurrency***