Concurrency and Synchronization (How to Avoid the Dangers of Threading)

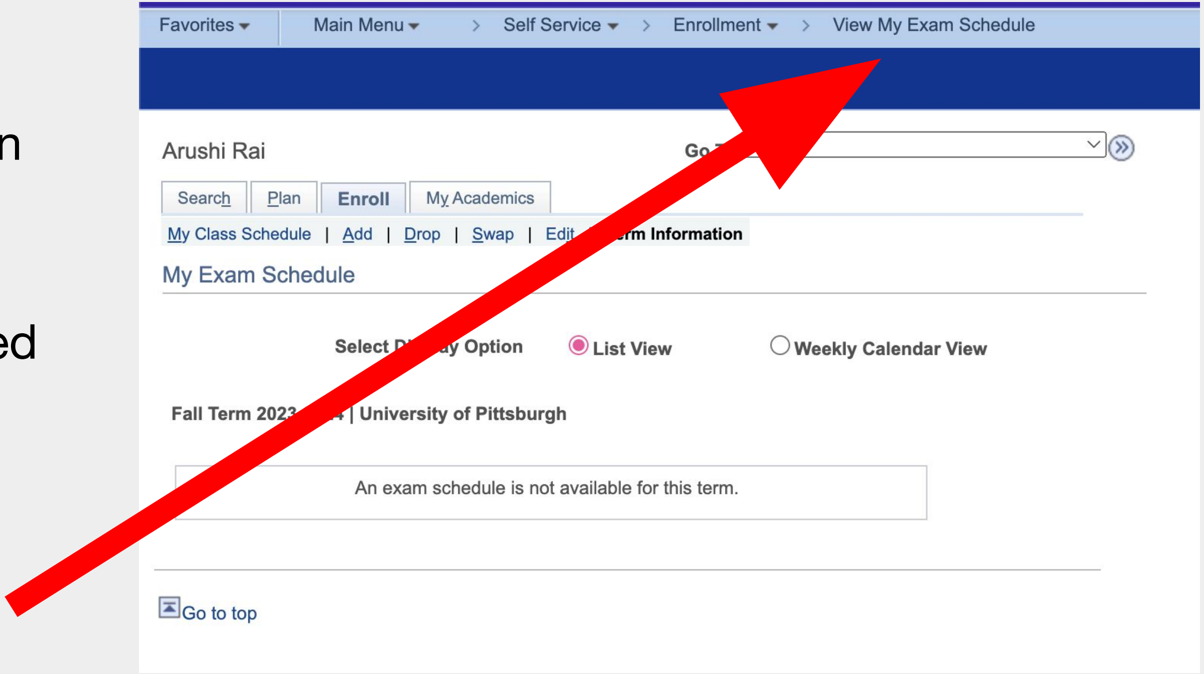
CS 0449: Introduction to System Software

CS0449 TEACHING ASSISTANTS

University of Pittsburgh | School of Computing and Information

This almost the time for final exams…

- Final Exam Schedule on PeopleSoft
    - During finals week
    - Report to scheduled location



Arushi Rai

My Exam Schedule

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Fall Term 2023 | University of Pittsburgh

An exam schedule is not available for this term.

Course News

- Project 4 - Due: 17:59 Friday, 1st December, 2023
- Lab 7?
    - Virtual Memory & Scheduling
- Project 5
    - Threads & Concurrency

Threads

Achieving Concurrency without `fork()`s

____ provides an API for creating and managing threads

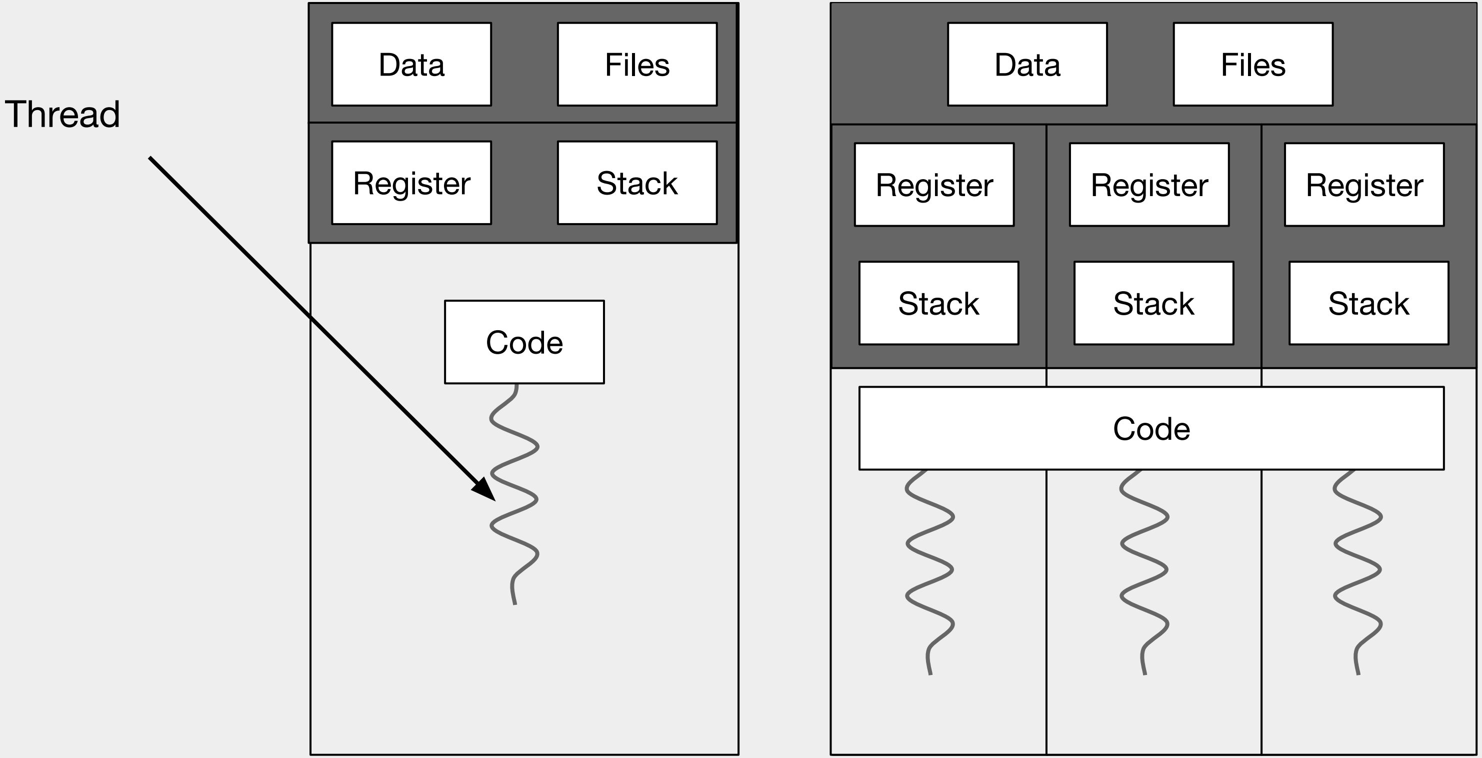
System calls

Threading library

Multicore processor

None of the above

Processes and Threads



Single-threaded process

Multi-threaded process

Threads can share data!

Posix Threads (`pthread`) — *POSIX.1c*

- POSIX: Portable Operating System Interface
  - Standard to unify the program and system calls that many different operating systems provide
  - Provides us a ‘standard library’ to help create and manage threads
  - `#include <pthread.h>`

  -
    ```
    int pthread_create(pthread_t threadID,
                       FLAGS, void *(*function)(void *),
                       void *restrict arg);
    ```
  - `int pthread_join(pthread_t thread, void **retval);`
- Other libraries exist
  - Win32 Threads for Windows
  - C11 Threads - not popular, not fully portable Thanks Microsoft
    - C++11 Threads - popular and widely used

pthread_create()

```c
#include <stdio.h>
#include <pthread.h>
void *do_stuff(void *p) //function to be executed by the thread
{
    printf("Hello from thread %d\n", *(int *)p);
}

int main()
{
    pthread_t thread; //variable to store thread ID
    int id, arg1, arg2; //variables for thread IDs and arguments
    arg1 = 1; //set the argument for the 1st thread
    //create the 1st thread
    id = pthread_create(&thread, NULL, do_stuff, (void *)&arg1);
    arg2 = 2; //set the argument for the 2ed thread
    do_stuff((void *)&arg2); //call the function directly for the 2ed thread
    return 0;
}
```

Output

```
Hello from thread 2
```

pthread_create()

```
#include <stdio.h>
#include <pthread.h>
void *do_stuff(void *p)
{
    printf("Hello from thread %d\n", *(int *)p);
}

int main()
{
    pthread_t thread;
    int id, arg1, arg2;
    arg1 = 1;
    id = pthread_create(&thread, NULL, do_stuff, (void *)&arg1);
    arg2 = 2;
    do_stuff((void *)&arg2);
    return 0;
}
```

When the process exits, all threads are canceled. Here, the process exited before the second thread got to print its message

pthread_yield()

```
#include <stdio.h>
#include <pthread.h>
void *do_stuff(void *p)
{
    printf("Hello from thread %d\n", *(int *)p);
}

int main()
{
    pthread_t thread;
    int id, arg1, arg2;
    arg1 = 1;
    id = pthread_create(&thread, NULL, do_stuff, (void *)&arg1);
    pthread_yield();
    arg2 = 2;
    do_stuff((void *)&arg2);
    return 0;
}
```

Output

-
  ```
  Hello from thread 1
  Hello from thread 2
  ```
- `pthread_yield()` relinquishes the CPU
  - Allowing another thread to assume the CPU
  - Technically **deprecated**, but still portable and widely used!

    ⇒ You shouldn't use it in your own code, but you may encounter it in the wild!

pthread_join()

```
#include <stdio.h>
#include <pthread.h>
void *do_stuff(void *p)
{
    printf("Hello from thread %d\n", *(int *)p);
}

int main()
{
    pthread_t thread;
    int id, arg1, arg2;
    arg1 = 1;
    id = pthread_create(&thread, NULL, do_stuff, (void *)&arg1);
    pthread_join(thread, NULL);
    arg2 = 2;
    do_stuff((void *)&arg2);
    return 0;
}
```

Output

-
  ```
  Hello from thread 1
  Hello from thread 2
  ```
- `pthread_join(thread, NULL)` waits until `thread` terminates

Linking the `pthread` library

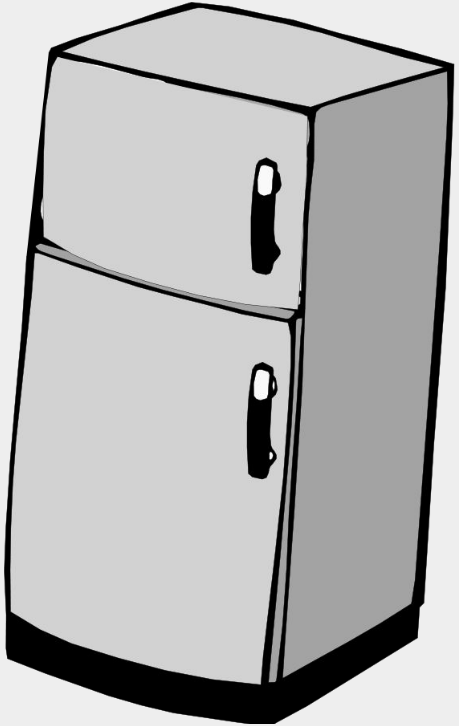
- At compile time, need to link the POSIX thread library to your code
- Using `-pthread` option to `gcc`
- `gcc -o thread_program source.c -pthread`
  - Writing a Makefile might be useful here…

Synchronization

The Dangers of Threading

Race Condition: A Refrigerator Analogy

- Alice and Bob are roommates living in a dorm
    - They share one refrigerator in the kitchen
- Alice wakes up at 9:30 AM
    - She checks the refrigerator for milk and sees that there is none
    - She goes out to the store to get milk
- While Alice is at the store, Bob wakes up
    - He checks the refrigerator for milk and sees that there is none
    - He goes out to the store to get milk
- At 1 PM, Alice returns from the store
    - And places the milk in the fridge
- At 1:30 PM, Bob returns from the store
    - And tries to place the milk in the fridge
    - But there's already another milk in the fridge!

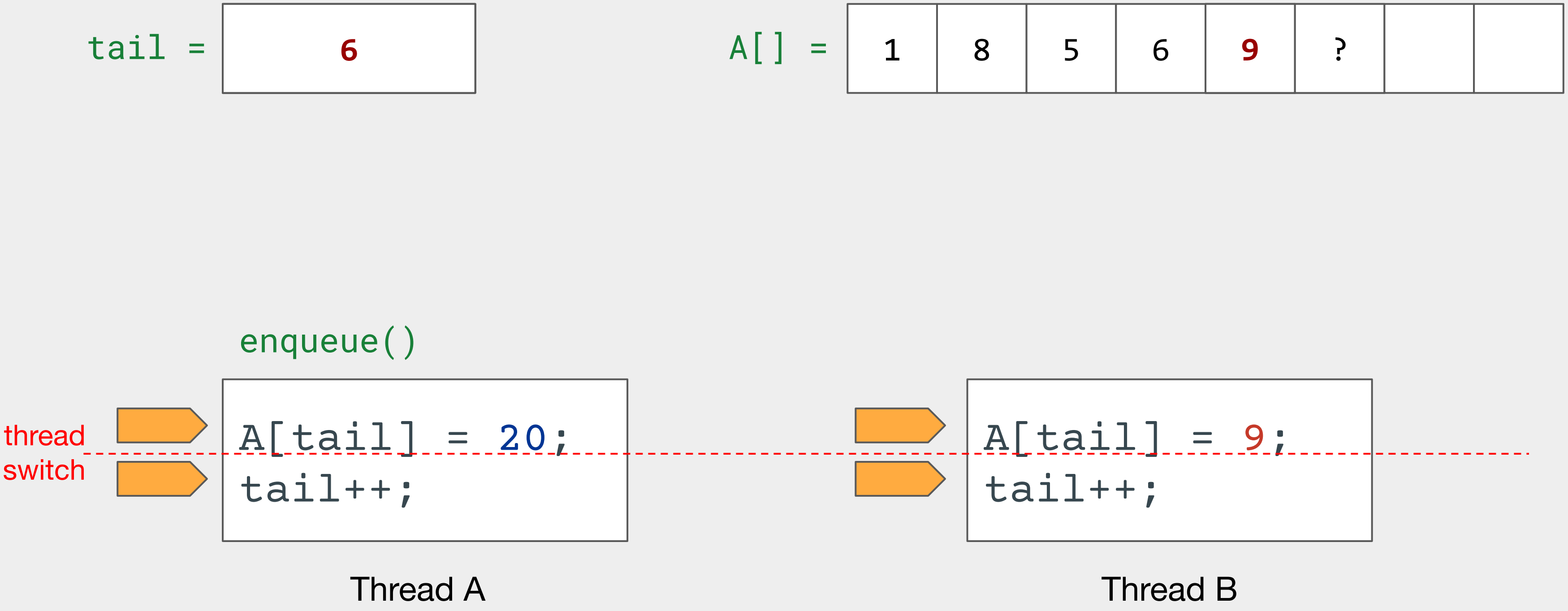


Synchronization

- What went wrong?
- Bob and Alice did not **communicate!**

- Some shared resource (refrigerator)
- Time delay between checking the condition (looking inside the refrigerator)
- And taking an action (placing milk inside refrigerator)

Race Conditions Animated



tail = 6

A[] =							
1	8	5	6	9	?		

enqueue()

```
A[tail] = 20;
tail++;
```

Thread A

```
A[tail] = 9;
tail++;
```

Thread B

thread switch

Synchronization

- What went wrong?
- The threads did not **communicate!**
  - Same problem may occur with processes!

- Some shared resource (array)
- Time delay between checking some condition (loading the `tail`)
- And the action (updating the `tail`)
  - Preempted during this delay!

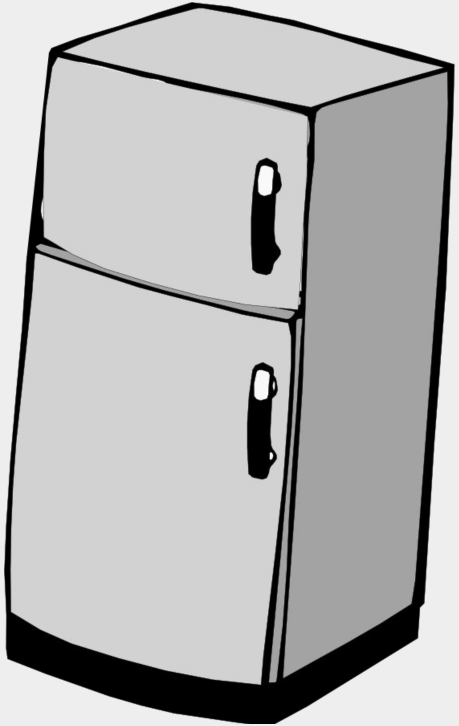
- Scheduling can be random and preemption can happen at any time
- Need some way to *synchronize* the threads
  - Need help from the operating system

Fixing Race Conditions: A Refrigerator Analogy

- Alice and Bob are roommates living in a dorm
    - They share one refrigerator in the kitchen
- Alice wakes up at 9:30 AM
    - She checks the refrigerator for milk and sees that there is none
    - **Alice locks the fridge**
    - She goes out to the store to get milk
- While Alice is at the store, Bob wakes up
    - He attempts to check the refrigerator for milk, but the refrigerator is **locked**
    - He waits until Alice comes back and unlocks the fridge
- At 1 PM, Alice returns from the store
    - Places the milk in the fridge
    - **And unlocks the refrigerator for Bob**
- Now, Bob can check the refrigerator
    - And enjoy his milk!

atomic

atomic



Mutex

- MUTual EXclusion
- A mutex is a lock that only one thread can acquire
- All other threads attempting to access the resource protected by a *locked* mutex will be blocked
- `#include <pthread.h>`
- `int pthread_mutex_init(pthread_mutex_t, NULL)`
    - Creates a new unlocked mutex
- `int pthread_mutex_lock(pthread_mutex_t*)`
    - Waits until it can lock the mutex
- `int pthread_mutex_unlock(pthread_mutex_t*)`
    - Unlocks the mutex

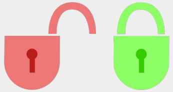
Fixing Race Conditions Animated

`tail =` 6

`A[] =`

1	8	5	6	20	9		

`mutex =`



`enqueue()`

thread switch

```
lock(&mutex);
A[tail] = 20;
tail++;
unlock(&mutex);
```

Thread A

```
lock(&mutex);
A[tail] = 9;
tail++;
unlock(&mutex);
```

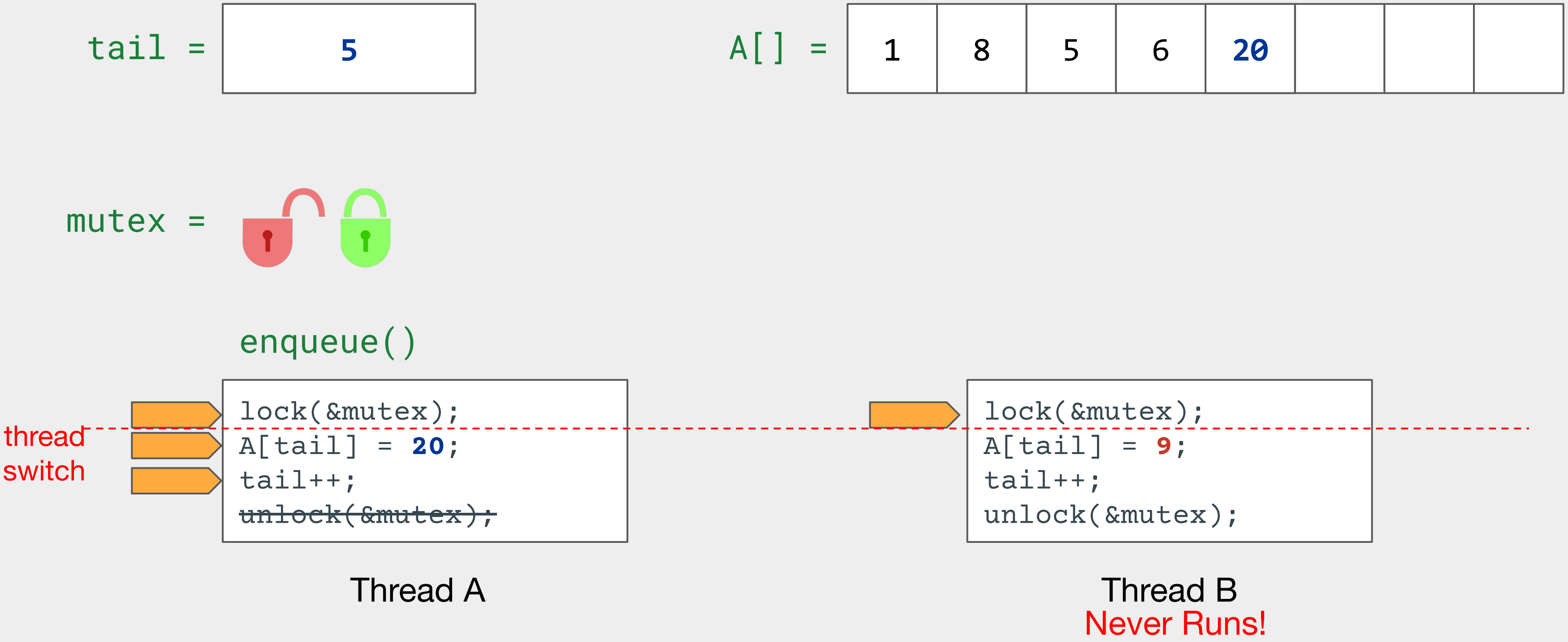
Thread B

Mutex at the Gas Station Bathroom

- A popular real-life example of a mutex involves toilets.
- When a person enters a toilet partition, they lock the door from the inside.

- The **toilet** is like a **shared object** that can be accessed by multiple threads.
- The **lock** on the door is like a **mutex**, and the line of people outside represents threads.
- The lock on the door is the toilet's mutex: it ensures that only one person can get inside.

Deadlocked



`tail =` 5

`A[] =`

1	8	5	6	20			

`mutex =` 🔓 🔒

`enqueue()`

```
lock(&mutex);
A[tail] = 20;
tail++;
```
~~`unlock(&mutex);`~~

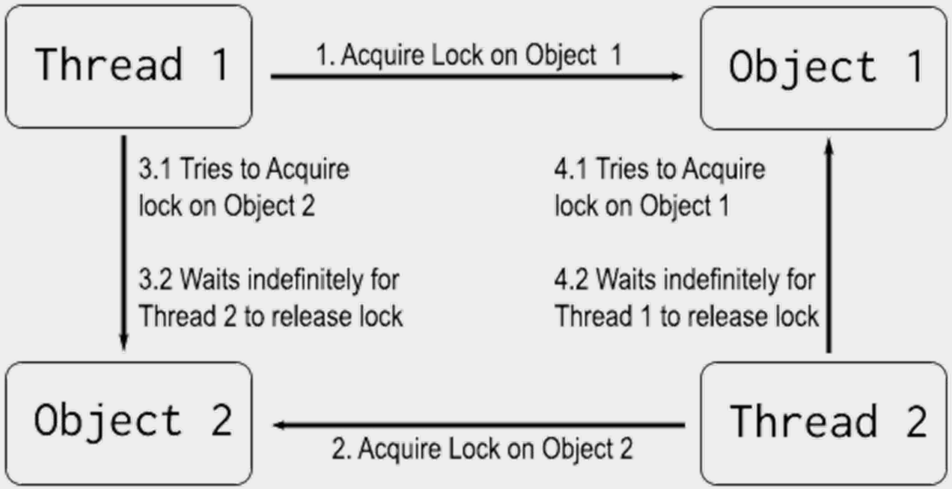
Thread A

```
lock(&mutex);
A[tail] = 9;
tail++;
unlock(&mutex);
```

Thread B
Never Runs!

Be careful with synchronization primitives

- "A set of processes are **deadlocked** if each process in the set is waiting for an event only another process in the set can cause"



Thread 1

1. Acquire Lock on Object 1

Object 1

3.1 Tries to Acquire lock on Object 2

3.2 Waits indefinitely for Thread 2 to release lock

4.1 Tries to Acquire lock on Object 1

4.2 Waits indefinitely for Thread 1 to release lock

Object 2

2. Acquire Lock on Object 2

Thread 2

Semaphore at the Gas Station Bathroom

- Now suppose that there are two bathroom stalls instead of one.
- Since bathroom entry is no longer exclusive, this is not a mutex scenario.

- Instead, the keys are called **semaphores**.
- A semaphore enables two or more (two in this example) threads (people) to use a shared resource (gas station bathroom) simultaneously.

1. If two keys (semaphores) are available, the value of the semaphore is 2.
2. If one key is available, the value of the semaphore is 1.
3. If no keys are available, that means that two tasks (people) are currently working (in the bathroom). Hence, the value of the semaphore is 0.
    - The next task (person) must wait until a semaphore becomes available (i.e. a task finishes, and the semaphore is incremented by 1).

Semaphores

- A special counter used for synchronization
  - Essentially counties the number of *free resources*
- Down (wait) reduces the counter
  - Denoting that a resource is being used
  - Waits if the counter is 0
- Up (signal) operation increases the counter
  - Denoting that a resource is now free
- `#include <semaphore.h>`
- `int sem_init(sem_t*, 0, unsigned int initial_value);`
  - Creates a semaphore with the given initial value. (The second argument means it the semaphore data is in shared memory. If non-zero, it can’t be seen by other threads.)
- `int sem_wait(sem_t*);`
  - Decrements counter unless it is 0 in which case it waits.
- `int sem_post(sem_t*);`
  - Increments counter.

Semaphores & Nomenclature

- There are no “official definitions” for each synchronization primitive
    - Different texts and implementers have slightly different implementations and associated characteristics
- Edsger W. Dijkstra `P()` and `V()`
    - Legendary Computer Scientist (Dijkstra's algorithm,...)
- Andrew Tanenbaum `down()` and `up()`
    - Modern Operating Systems - Influential for Linux
- Abraham Silberschatz `wait()` and `signal()`
    - Operating Systems Concept - The ‘Dinosaur’ Book
- POSIX `sem_wait()` and `sem_post()`

```
while (s == 0) wait;    s++;
s--;
```

Condition Variables

A condition under which a thread executes or is blocked

Condition Variables

- **Condition Variables** are used to wait for a particular condition to become true
- `wait(condition, lock)`: release lock, put thread to sleep until condition is signaled; when thread wakes up again, re-acquire lock before returning.
- `signal(condition, lock)`: if any threads are waiting on condition, wake up one of them. Caller must hold lock, which must be the same as the lock used in the wait call.
- `broadcast(condition, lock)`: same as signal, except wake up all waiting threads.

Condition Variables

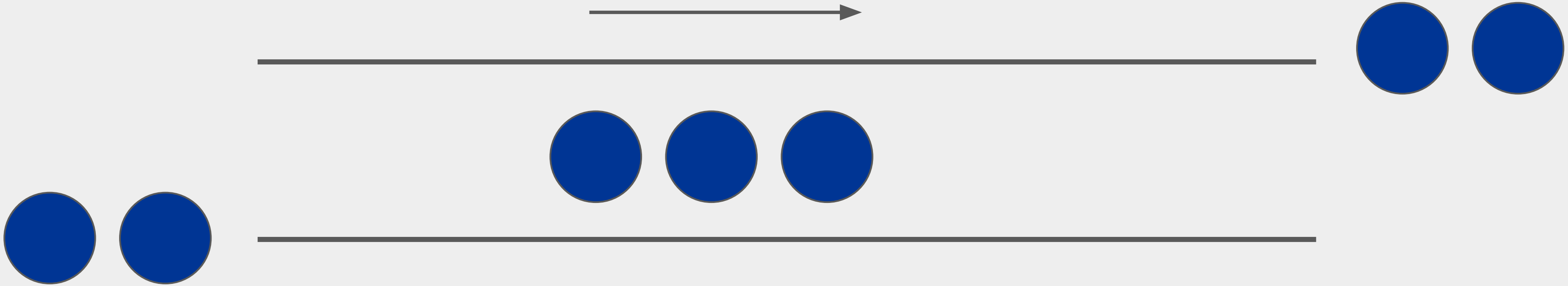
- Essentially a queue of waiting threads
- Thread **B** waits for a signal on `CV` before running
  - `wait(CV, …);`
- Thread **A** sends `signal()` on `CV` when time for **B** to run
  - `signal(CV, …);`

Condition Variables at the DMV

- Consider PennDOT (DMV)
  - Which serves two functions:
    1. Title work
    2. License renewal
- **Critical resource: representative; threads: people in line**
- When a title-works window representative comes to the window after a break, a condition ‘`title_window_ready`’ is satisfied.
- The title representative could look for the next ticket (for title work) and **signal** the customer to come to the window.
- Here we have two condition variables, `title_window_ready` & `license_window_ready`.
- These conditions satisfy if one customer is handled and now the representative is ready to handle next customer.

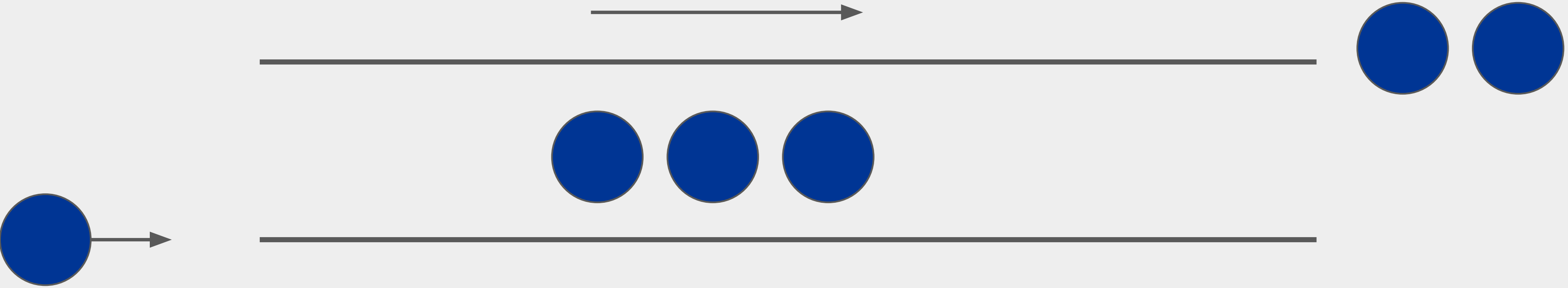
The Bridge Problem

- Consider a narrow bridge that can only allow three vehicles in the same direction to cross at the same time.
- If there are three vehicles on the bridge, any incoming vehicle must wait as shown below.



The Bridge Problem

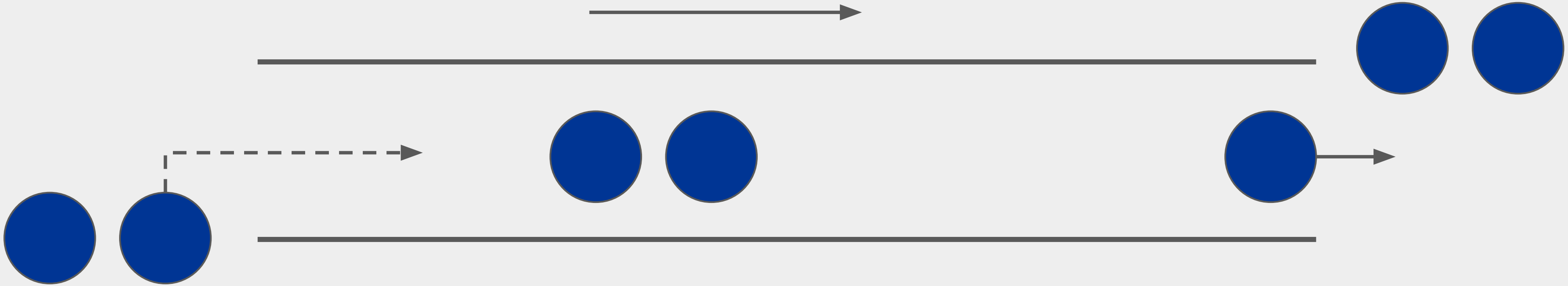
- When new cars get to the bridge, have them wait



```
if(new car from left) wait(left, bridgelock)
```

The Bridge Problem

- When a vehicle exits the bridge, we have two cases to consider.
- Case 1: there are other vehicles on the bridge
    - Shown below
    - In this case, one vehicle in the same direction should be allowed to proceed
- Case 2: the exiting vehicle is the last one on bridge.



```
if(bridge.numCars != 0) signal(left, bridgelock)
```

The Bridge Problem

- Case 2 is more complicated and has two subcases.
- In this case, the exiting vehicle is the last vehicle on the bridge.
- If there are vehicles waiting in the opposite direction, one of them should be allowed to proceed. This is illustrated below:

```
if(bridge.numCars == 0 && rightCars != 0)
    signal(right, bridgelock)
```

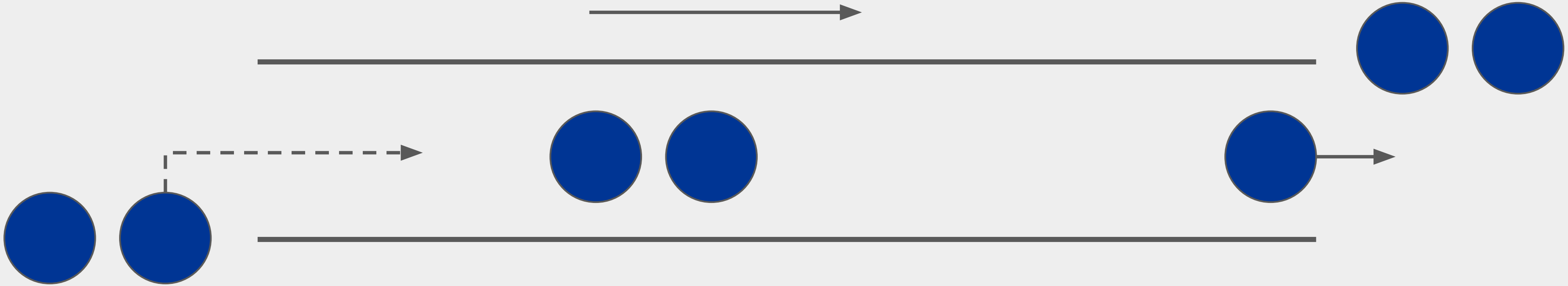
The Bridge Problem

- Or, if there is no vehicle waiting in the opposite direction, then let the waiting vehicle in the same direction to proceed.

```
if(bridge.numCars == 0 && rightCars == 0)
    signal(left, bridgelock)
```

Problem with the Bridge Problem

- Consider Case 1: there are other vehicles on the bridge
    - Shown below
    - In this case, one vehicle in the same direction should be allowed to proceed
- But what if there are **infinite number of vehicles** on the left?
    - Will the vehicles on the right ever get to go?



```
if(bridge.numCars != 0) signal(left, bridgelock)
```

Starvation

- **Starvation** describes a situation where a thread is unable to gain regular access to shared resources and is unable to make progress.
- This happens when shared resources are made unavailable for long periods by "greedy" threads.

Live Lock

- A **Livelock** is when two tasks are actively signaling the other to go and making no progress.
- *Example: Two friends at a dinner table with only one spoon*
  - *A tells B to use the spoon and eat first*
  - *B tells A to use the spoon and eat first*
  - *A tells B to use the spoon and eat first*
  - *…*
  - *No one gets to eat*
- Aside: This is a weird example…
  - Why are you at a dinner table with only one spoon?
  - Why doesn't one of them go and get another spoon?
- Many 'classical IPC problems' are built around weird premises [1550]
  - Dining Philosopher Problems
  - Sleeping Barber Problem

So many more synchronization primitives…

- **Mutex** [449]
- **Semaphore** [449]
- **Condition Variables** [449]
- Signals [449, Tanenbaum]
  - Interrupts can be used to synchronize with appropriate handlers
- Binary Semaphores [1550]
  - Special case of semaphores where the value can either be 0 or 1
- Events [Tanenbaum, Nutt]
  - Similar to condition variables, but without the mutex
- Barriers [1550]
- Monitors [1550]
  - Declares a region of code to be *critical*
- Atomic Machine Instructions (`test-and-set-lock`) [1550]
  - Hardware supported primitive
- Spinlocks, Readers–writer lock, Read-copy-update,... [1550]
- AND Synchronization [Nutt p. 222]

Labs & Projects

cs0449.gitlab.io/sp2023/

Lab

- Virtual Memory
- Scheduling
- Questions on GradeScope
  - You may work in pairs!
    - Select group member on GradeScope

Project

- Part I: Protection
  - The `pi.c` (provided on website) program works when we run it as a single threads
    - But produces …*interesting…* results when multi-threaded
  - Identify the issue and fix it!
    - Hint: Synchronization Primitives
  - Make sure that you do so in a performant manner!
- Part II: Synchronization Primitives
  - Implement your own synchronization primitive so that it works with the provided code
    - Semaphore: `sem.c`
    - You can use and adapt existing synchronization primitives to create your own Semaphores
- Part III: Virtual Memory

Referred Sources

- Dr. Jonathan Misurda's *CS 0449: Introduction to System Software*
  - University of Pittsburgh
- Dr. Henning Schulzrinne's *Operating System Resources*
  - Columbia University
- Dr. C.-K. Shene's *Multithreaded Programming with ThreadMentor*
  - Michigan Technological University
- Allen B. Downey's *The Little Book of Semaphores*
- Andrew S Tanenbaum's *Modern Operating Systems 4th Ed.*
- Gary Nutt's *Sistemas Operativos (Operating Systems 3rd Ed.)*
- Abraham Silberschatz's *Operating System Concepts 8th Edition*