# Semaphores

2024 Fall ECE 344: Operating Systems
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Lecture 23
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## Locks Ensure Mutual Exclusion

Only one thread at a time can be between the `lock` and `unlock` calls

It does not help you ensure ordering between threads

How would we ensure an ordering between two threads?

## Problem: Make One Thread Always Print First

**Thread 1** (`print_first`)
```
printf("This is first\n");
```

**Thread 2** (`print_second`)
```
printf("I'm going second\n");
```

Try executing `./ordered-print` and see what happens

Recall: `printf` is thread safe, which you may need to ensure
- Try executing `./safe-print` which (oddly) prints using multiple system calls
- Practice: ensure `./safe-print` behaves the same as `./ordered-print`

## Semaphores are Used for Signaling

Semaphores have a `value` that's shared between threads (optionally processes)
- Think of `value` as an integer that is always $\geq 0$

It has two fundamental operations `wait` and `post`
- `wait` decrements the value atomically
- `post` increments the value atomically

If `wait` will not return until the value is greater than 0

You can initially set `value` to whatever you want
- That number of `wait` calls may occur without any `post` calls

## Semaphore API is Similar to `pthread` Locks

```c
#include <semaphore.h>

int sem_init(sem_t *sem, int pshared, unsigned int value)
int sem_destroy(sem_t *sem);

int sem_wait(sem_t *sem);
int sem_trywait(sem_t *sem);

int sem_post(sem_t *sem);
```

All functions return 0 on success

The `pshared` argument is a boolean, you can set it to 1 for IPC
For IPC the semaphore needs to be in shared memory

## Problem: Make One Thread Always Print First

See `ordered-print.c` for the full code

Note: `return` statements are removed for space

```c
void* print_first(void* arg) {
  printf("This is first\n");
}

void* print_second(void* arg) {
  printf("I'm going second\n");
}

int main(int argc, char *argv[]) {
  /* Initialize, create, and join threads */
}
```

## This Always Executes `print_first` Then `print_second`

```
static sem_t sem; /* New */

void* print_first(void* arg) {
  printf("This is first\n");
  sem_post(&sem); /* New */
}

void* print_second(void* arg) {
  sem_wait(&sem); /* New */
  printf("I'm going second\n");
}

int main(int argc, char *argv[])
{
  sem_init(&sem, 0, 0); /* New */
  /* Initialize, create, and join threads */
}
```

## No Matter Which Thread Executes First, We Get the Same Order

The `value` is initially 0

Assume `print_second` executes first
  It executes `sem_wait`, which is 0, and doesn't continue

`print_first` doesn't have to wait, it prints first before it increments the `value`

`print_second` can then execute its print statement

What happens if we initialized the `value` to 1?

## We Can Use a Semaphore as a Mutex

How?

## Using a Semaphore as a Mutex, Note the `value`

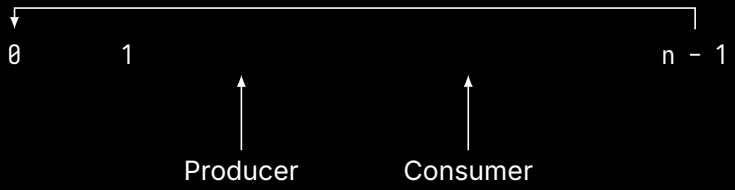
```
static sem_t sem; /* New */
static int counter = 0;

void* run(void* arg) {
    for (int i = 0; i < 100; ++i) {
        sem_wait(&sem); /* New */
        ++counter;
        sem_post(&sem); /* New */
    }
}

int main(int argc, char *argv[]) {
  sem_init(&sem, 0, 1); /* New */
  /* Initialize, create, and join multiple threads */
  printf("counter = %i\n", counter);
}
```

## Can We Come Up with a Solution for a Producer/Consumer Problem?

Assume you have a circular buffer (each slot is either empty or filled):




The producer should write to the buffer (if the buffer is not full)
The consumer should read from the buffer (if the buffer is not empty)

All consumers share an index and all producers share an index
In both cases the index is initially 0 and increases sequentially

## Problem 1: Ensure Producers Never Overwrite Filled Slots

```
static uint32_t buffer_size;

void init_semaphores() {
  sem_init(&empty_slots, 0, /* ? */);
}
void producer() {
  while (/* ... */) {
    /* spend time producing data */
    fill_slot();
  }
}
void consumer() {
  while (/* ... */) {
    empty_slot();
    /* spend time consuming data */
  }
}
```

## Use a Semaphore to Track the Number of Empty Slots

```
void init_semaphores() {
  sem_init(&empty_slots, 0, buffer_size);
}
void producer() {
  while (/* ... */) {
    /* spend time producing data */
    sem_wait(&empty_slots); /* New */
    fill_slot();
  }
}
void consumer() {
  while (/* ... */) {
    empty_slot();
    sem_post(&empty_slots); /* New */
    /* spend time consuming data */
  }
}
```

What is our next problem?

## Problem 2: Ensure Consumers Never Consume Empty Slots

```
void init_semaphores() {
  sem_init(&empty_slots, 0, buffer_size);
  sem_init(&filled_slots, 0, /* ? */);
}
void producer() { while (/* ... */) {
  /* spend time producing data */
  sem_wait(&empty_slots);
  fill_slot();
} }
void consumer() { while (/* ... */) {
  empty_slot();
  sem_post(&empty_slots);
  /* spend time consuming data */
} }
```

## Two Semaphores Ensure Proper Order for Producers and Consumers

```
void init_semaphores() {
  sem_init(&empty_slots, 0, buffer_size);
  sem_init(&filled_slots, 0, 0);
}
void producer() { while (/* ... */) {
  /* spend time producing data */
  sem_wait(&empty_slots);
  fill_slot();
  sem_post(&filled_slots); /* New */
} }
void consumer() { while (/* ... */) {
  sem_wait(&filled_slots); /* New */
  empty_slot();
  sem_post(&empty_slots);
  /* spend time consuming data */
} }
```

## What Happens If We Initialize Both Semaphore Values to 0?

```
void init_semaphores() {
  sem_init(&empty_slots, 0, 0);
  sem_init(&filled_slots, 0, 0);
}
void producer() { while (/* ... */) {
  /* spend time producing data */
  sem_wait(&empty_slots);
  fill_slot();
  sem_post(&filled_slots);
} }
void consumer() { while (/* ... */) {
  sem_wait(&filled_slots);
  empty_slot();
  sem_post(&empty_slots);
  /* spend time consuming data */
} }
```

## We Used Semaphores to Ensure Proper Order

Previously we ensured mutual exclusion, now we can ensure order

- Semaphores contain an initial value you choose
- You can increment the value using post
- You can decrement the value using wait (it blocks if the current value is 0)
- You still need to be prevent data races