Operating Systems

Lecture 7

Semaphore

Semaphore: A definition

An object with an integer value

- We can manipulate with two routines; `sem_wait()` and `sem_post()`.
- Initialization

```
#include <semaphore.h>
sem_t s;
sem_init(&s, 0, 1); // initialize s to the value 1
```

- Declare a semaphore `s` and initialize it to the value 1
- The second argument, 0, indicates that the semaphore is shared between *threads in the same process*.

Semaphore: Interact with semaphore

`sem_wait()`

```c
int sem_wait(sem_t *s) {
      // decrement the value of semaphore s by one
      // wait if value of semaphore s is negative
}
```

- If the value of the semaphore was *one* or *higher* when called `sem_wait()`, **return right away**.
- When negative, the value of the semaphore is equal to the number of waiting threads.
- It will cause the caller to suspend execution and wait for a subsequent post.

Semaphore: Interact with semaphore

`sem_post()`

```c
int sem_post(sem_t *s) {
      // increment the value of semaphore s by one
      // if there are one or more threads waiting, wake one
}
```

Simply **increments** the value of the semaphore.

If there is a thread waiting to be woken, **wakes** one of them up.

time	T_1	T_2	T_3	T_4	Semaphore S
t_0					0
t_1	sem_wait(s);				-1
t_2		sem_wait(s);			-2
t_3			sem_wait(s);		-3
t_4				sem_post(s)	-2

Binary Semaphores (Locks)

What should **x** be?

The initial value should be **1**.

```
sem_t m;
sem_init(&m, 0, X); // initialize semaphore to X; what should X be?

sem_wait(&m);
//critical section here
sem_post(&m);
```

Value of Semaphore	Thread 0	Thread 1
1		
1	call sema_wait()	
0	sem_wait() returns	
0	(crit sect)	
0	call sem_post()	
1	sem_post() returns	

Thread Trace: Two Threads Using A Semaphore

Value	Thread 0	State	Thread 1	State
1		Running		Ready
1	call sem_wait()	Running		Ready
0	sem_wait() returns	Running		Ready
0	(crit set: begin)	Running		Ready
0	*Interrupt; Switch → T1*	Ready		Running
0		Ready	call sem_wait()	Running
-1		Ready	decrement sem	Running
-1		Ready	(sem < 0)→sleep	sleeping
-1		Running	*Switch → T0*	sleeping
-1	(crit sect: end)	Running		sleeping
-1	call sem_post()	Running		sleeping
0	increment sem	Running		sleeping
0	wake(T1)	Running		Ready
0	sem_post() returns	Running		Ready
0	*Interrupt; Switch → T1*	Ready		Running
0		Ready	sem_wait() retruns	Running
0		Ready	(crit sect)	Running
0		Ready	call sem_post()	Running
1		Ready	sem_post() returns	Running

Semaphores As Condition Variables

```
sem_t s;

void *
child(void *arg) {
    printf("child\n");
    sem_post(&s); // signal here: child is done
    return NULL;
}

int
main(int argc, char *argv[]) {
    sem_init(&s, 0, X); // what should X be?
    printf("parent: begin\n");
    pthread_t c;
    pthread_create(c, NULL, child, NULL);
    sem_wait(&s); // wait here for child
    printf("parent: end\n");
    return 0;
}
```

A Parent Waiting For Its Child

```
parent: begin
child
parent: end
```

The execution result

What should **x** be?

The value of semaphore should be set to is **0**.

Thread Trace: Parent Waiting For Child (Case 1)

The parent call `sem_wait()` before the child has called `sem_post()`.

Value	Parent	State	Child	State
0	`Create(Child)`	Running	*`(Child exists; is runnable)`*	Ready
0	`call sem_wait()`	Running		Ready
-1	`decrement sem`	Running		Ready
-1	`(sem < 0)→sleep`	sleeping		Ready
-1	*`Switch→Child`*	sleeping	`child runs`	Running
-1		sleeping	`call sem_post()`	Running
0		sleeping	`increment sem`	Running
0		Ready	`wake(Parent)`	Running
0		Ready	`sem_post() returns`	Running
0		Ready	*`Interrupt; Switch→Parent`*	Ready
0	`sem_wait() retruns`	Running		Ready

Thread Trace: Parent Waiting For Child (Case 2)

The child runs to completion before the parent call `sem_wait()`.

Value	Parent	State	Child	State
0	`Create(Child)`	Running	*(Child exists; is runnable)*	Ready
0	*`Interrupt; switch→Child`*	Ready	`child runs`	Running
0		Ready	`call sem_post()`	Running
1		Ready	`increment sem`	Running
1		Ready	`wake(nobody)`	Running
1		Ready	`sem_post() returns`	Running
1	`parent runs`	Running	*`Interrupt; Switch→Parent`*	Ready
1	`call sem_wait()`	Running		Ready
0	`decrement sem`	Running		Ready
0	`(sem>=0)→awake`	Running		Ready
0	`sem_wait() returns`	Running		Ready

The Producer/Consumer (Bounded-Buffer) Problem

Producer: `put()` interface

Wait for a buffer to become *empty* in order to put data into it.

Consumer: `get()` interface

Wait for a buffer to become *filled* before using it.

```
int buffer[MAX];
int fill = 0;
int use = 0;

void put(int value) {
     buffer[fill] = value;      // line f1
     fill = (fill + 1) % MAX;   // line f2
}

int get() {
     int tmp = buffer[use];     // line g1
     use = (use + 1) % MAX;     // line g2
     return tmp;
}
```

```c
sem_t empty;
sem_t full;

void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
            sem_wait(&empty);           // line P1
            put(i);                     // line P2
            sem_post(&full);            // line P3
    }
}

void *consumer(void *arg) {
    int i, tmp = 0;
    while (tmp != -1) {
            sem_wait(&full);            // line C1
            tmp = get();                // line C2
            sem_post(&empty);           // line C3
            printf("%d\n", tmp);
    }
}
…
```

First Attempt: Adding the Full and Empty Conditions

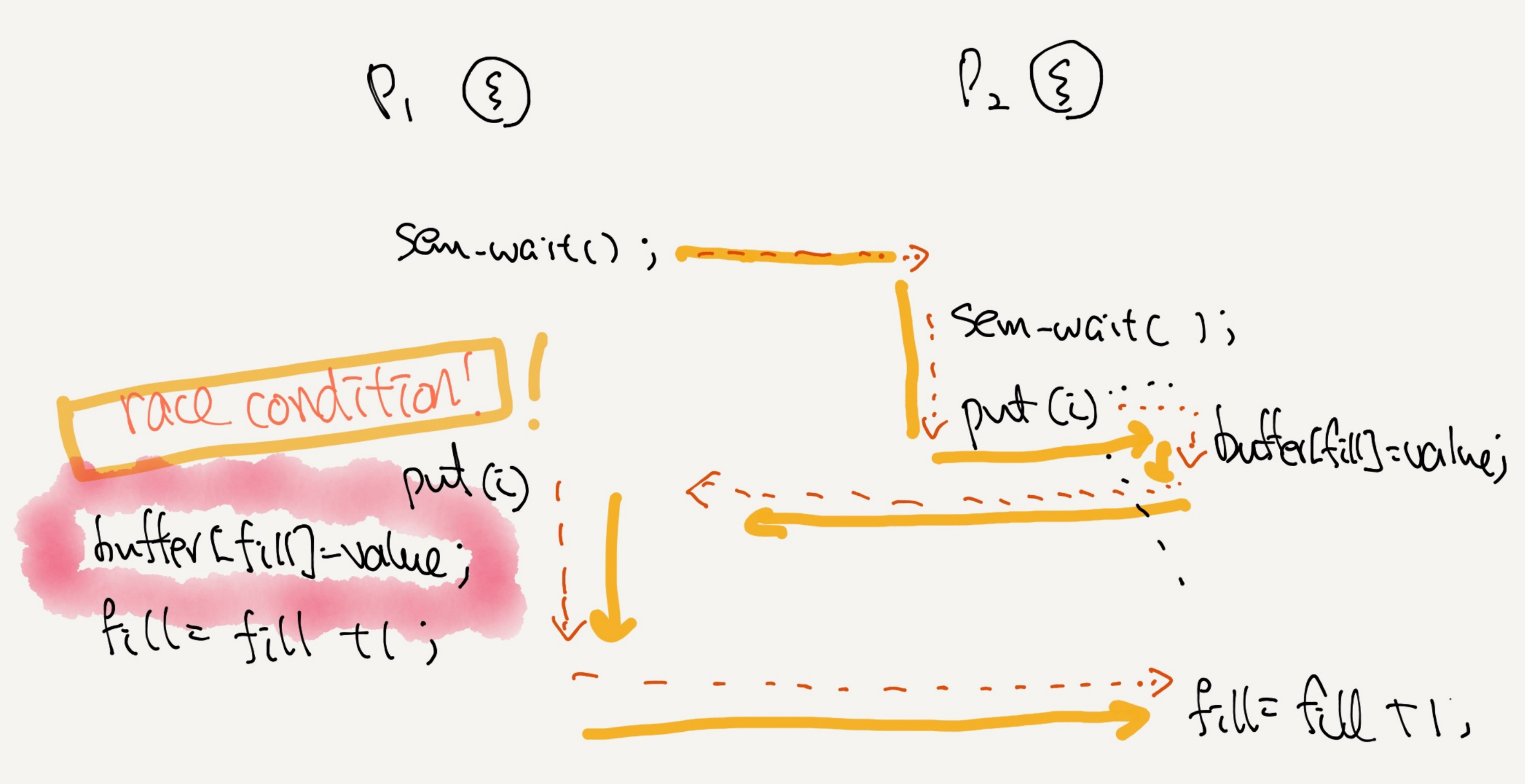
The Producer/Consumer (Bounded-Buffer) Problem

```
int main(int argc, char *argv[]) {
    // …
    sem_init(&empty, 0, MAX);      // MAX buffers are empty to begin with…
    sem_init(&full, 0, 0);         // … and 0 are full
    // …
}
```

First Attempt: Adding the Full and Empty Conditions (Cont.)

- Imagine that `MAX` is greater than 1 .
  - If there are multiple producers, race condition can happen at line *f1* in put().
  - It means that the old data there is overwritten.

- We've forgotten here is **mutual exclusion**.
  - The filling of a buffer and incrementing of the index into the buffer is a critical section.


P1 {
P2 {
sem-wait();
sem-wait( );
race condition!
put(i)
put(i)
buffer[fill]=value;
buffer[fill]=value;
fill= fill +1;
fill= fill +1;

A Solution: Adding Mutual Exclusion

```
sem_t empty;
sem_t full;
sem_t mutex;

void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
            sem_wait(&mutex);         // line p0 (NEW LINE)
            sem_wait(&empty);         // line p1
            put(i);                   // line p2
            sem_post(&full);          // line p3
            sem_post(&mutex);         // line p4 (NEW LINE)
    }
}

```

Adding Mutual Exclusion (Incorrectly)

A Solution: Adding Mutual Exclusion

```
void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        sem_wait(&mutex);      // line c0 (NEW LINE)
        sem_wait(&full);       // line c1
        int tmp = get();       // line c2
        sem_post(&empty);      // line c3
        sem_post(&mutex);      // line c4 (NEW LINE)
        printf("%d\n", tmp);
    }
}
```

Deadlock!

Adding Mutual Exclusion (Incorrectly)

Deadlock

Imagine two thread: one producer and one consumer.

- The consumer **acquire** the `mutex` (line c0).
- The consumer **calls** `sem_wait()` on the full semaphore (line c1).
- The consumer is **blocked** and **yield** the CPU.
  - The consumer <u>still holds the mutex</u>!
- The producer **calls** `sem_wait()` on the binary `mutex` semaphore (line p0).
- The producer is now **stuck** waiting too. a classic deadlock.

A Working Solution

```
sem_t empty;
sem_t full;
sem_t mutex;

void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
            sem_wait(&empty);          // line p1
            sem_wait(&mutex);          // line p1.5 (MOVED MUTEX HERE…)
            put(i);                    // line p2
            sem_post(&mutex);          // line p2.5 (… AND HERE)
            sem_post(&full);           // line p3
    }
 }

```

Adding Mutual Exclusion (Correctly)

A Working Solution

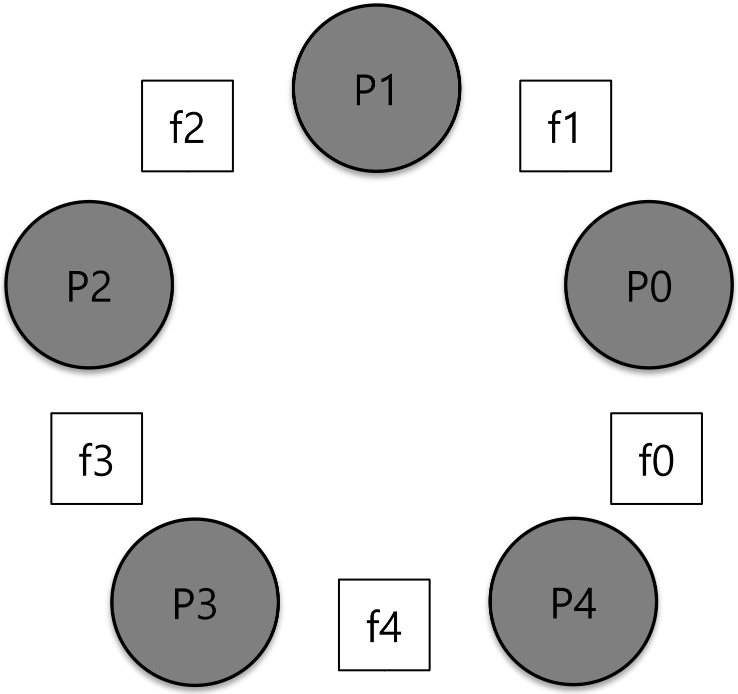
```
void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
            sem_wait(&full);            // line c1
            sem_wait(&mutex);           // line c1.5 (MOVED MUTEX HERE…)
            int tmp = get();            // line c2
            sem_post(&mutex);           // line c2.5 (… AND HERE)
            sem_post(&empty);           // line c3
            printf("%d\n", tmp);
    }
}

int main(int argc, char *argv[]) {
    // …
    sem_init(&empty, 0, MAX); // MAX buffers are empty to begin with …
    sem_init(&full, 0, 0);    // ... and 0 are full
    sem_init(&mutex, 0, 1);   // mutex=1 because it is a lock
    // …
}
            …
```

Adding Mutual Exclusion (Correctly)

The Dining Philosophers

Assume there are five “**philosophers**” sitting around a table.

- Between each pair of philosophers is a single fork (five total).
- The philosophers each have times where they **think**, and don’t need any forks, and times where they **eat**.
- In order to *eat*, a philosopher needs two forks, both the one on their *left* and the one on their *right*.
- **The contention for these forks.**



The Dining Philosophers

Key challenge

There is **no deadlock**.

No philosopher **starves** and never gets to eat.

Concurrency is high.

```
while (1) {
        think();
        getforks();
        eat();
        putforks();
}
```

Basic loop of each philosopher

```
// helper functions
int left(int p) { return p; }

int right(int p) {
        return (p + 1) % 5;
}
```

Helper functions (Downey's solutions)

Philosopher `p` wishes to refer to the fork on their left → call `left(p)`.

Philosopher `p` wishes to refer to the fork on their right → call `right(p)`.

The Dining Philosophers

We need some **semaphore**, one for each fork: `sem_t forks[5]`.

```
void getforks() {
    sem_wait(forks[left(p)]);
    sem_wait(forks[right(p)]);
}

void putforks() {
    sem_post(forks[left(p)]);
    sem_post(forks[right(p)]);
}
```

The `getforks()` and `putforks()` Routines (Broken Solution)

- Deadlock occur!
  - If each philosopher happens to **grab the fork on their left** before any philosopher can grab the fork on their right.
  - Each will be stuck *holding one fork* and waiting for another, *forever*.

A Solution: Breaking The Dependency

Change how forks are acquired.

Let's assume that philosopher 4 acquire the forks in a *different order*.

```
void getforks() {
    if (p == 4) {
        sem_wait(forks[right(p)]);
        sem_wait(forks[left(p)]);
    } else {
        sem_wait(forks[left(p)]);
        sem_wait(forks[right(p)]);
    }
}
```

There is no situation where each philosopher grabs one fork and is stuck waiting for another. **The cycle of waiting is broken**.

The END