31. Semaphores

Operating System: Three Easy Pieces

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()`

```
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**.
- It will cause the caller to <u>suspend execution</u> waiting for a subsequent post.
- When negative, the value of the semaphore is equal to the number of waiting threads.

Semaphore: Interact with semaphore (Cont.)

- sem_post()

```
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.

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);
```

Thread Trace: Single Thread Using A Semaphore

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 (1 CPU)

Value	Thread 0	State	Thread 1	State
1		Running		Ready
1	`call sem_wait()`	Running		Ready
0	`sem_wait() retruns`	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() retruns`	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;
}
```

The Producer/Consumer (Bounded-Buffer) Problem

```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 *P1*.
  - 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.

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)
    }
}

(Cont.)
```

Adding Mutual Exclusion (Incorrectly)

A Solution: Adding Mutual Exclusion

```
(Cont.)
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);
     }
}
```

Adding Mutual Exclusion (Incorrectly)

A Solution: Adding Mutual Exclusion (Cont.)

- 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 still holds the mutex!
  - The producer **calls** `sem_wait()` on the binary `mutex` semaphore (line p0).
  - The producer is now **stuck** waiting too. a classic deadlock.

Finally, 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
    }
}

(Cont.)
```

Adding Mutual Exclusion (Correctly)

Finally, A Working Solution

```
(Cont.)
 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)

Reader-Writer Locks

- Imagine a number of concurrent list operations, including **inserts** and simple **lookups**.
  - **insert:**
    - Change the state of the list
    - A traditional critical section makes sense.
  - **lookup:**
    - Simply *read* the data structure.
    - As long as we can guarantee that no insert is on-going, we can allow many lookups to proceed concurrently.

This special type of lock is known as a reader-write lock.

A Reader-Writer Locks

- Only **a single writer** can acquire the lock.
- Once a reader has acquired a read lock,
  - **More readers** will be allowed to acquire the read lock too.
  - A writer will <u>have to wait</u> until all readers are finished.

```
typedef struct _rwlock_t {
    sem_t lock;      // binary semaphore (basic lock)
    sem_t writelock; // used to allow ONE writer or MANY readers
    int readers;     // count of readers reading in critical section
} rwlock_t;

void rwlock_init(rwlock_t *rw) {
    rw->readers = 0;
    sem_init(&rw->lock, 0, 1);
    sem_init(&rw->writelock, 0, 1);
}

void rwlock_acquire_readlock(rwlock_t *rw) {
    sem_wait(&rw->lock);
    …
```

A Reader-Writer Locks (Cont.)

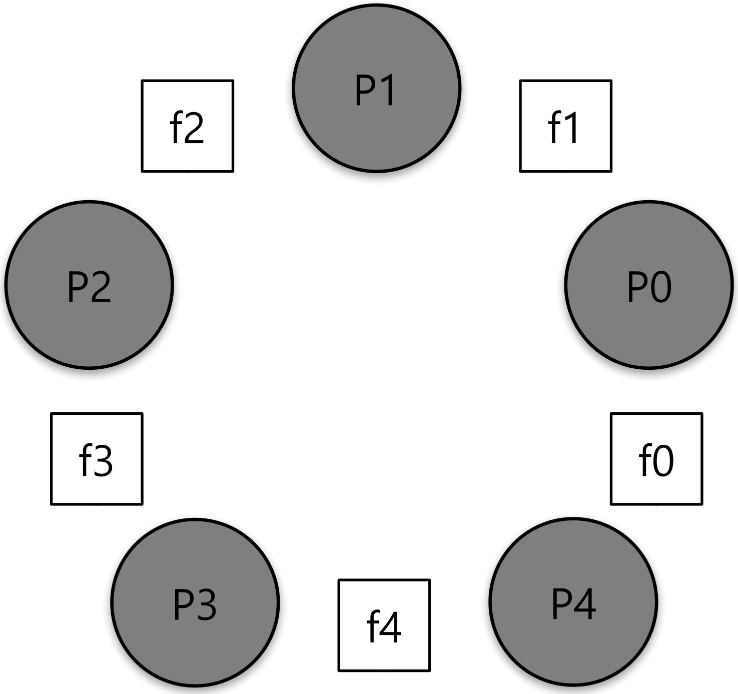
```
    rw->readers++;
    if (rw->readers == 1)
        sem_wait(&rw->writelock); // first reader acquires writelock
    sem_post(&rw->lock);
}

void rwlock_release_readlock(rwlock_t *rw) {
    sem_wait(&rw->lock);
    rw->readers--;
    if (rw->readers == 0)
        sem_post(&rw->writelock); // last reader releases writelock
    sem_post(&rw->lock);
}

void rwlock_acquire_writelock(rwlock_t *rw) {
    sem_wait(&rw->writelock);
}

void rwlock_release_writelock(rwlock_t *rw) {
    sem_post(&rw->writelock);
}
```

A Reader-Writer Locks (Cont.)

- The reader-writer locks have fairness problem.
  - It would be relatively easy for reader to **starve writer**.
  - How to prevent more readers from entering the lock once a writer is waiting?

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 (Cont.)

- 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 for on their left → call `left(p)`.
- Philosopher `p` wishes to refer to the for on their right → call `right(p)`.

The Dining Philosophers (Cont.)

- 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**.

How To Implement Semaphores

- Build our own version of semaphores called Zemaphores

```
typedef struct __Zem_t {
    int value;
    pthread_cond_t cond;
    pthread_mutex_t lock;
} Zem_t;

// only one thread can call this
void Zem_init(Zem_t *s, int value) {
    s->value = value;
    Cond_init(&s->cond);
    Mutex_init(&s->lock);
}

void Zem_wait(Zem_t *s) {
    Mutex_lock(&s->lock);
    while (s->value <= 0)
    Cond_wait(&s->cond, &s->lock);
    s->value--;
    Mutex_unlock(&s->lock);
}
…
```

How To Implement Semaphores (Cont.)

```
void Zem_post(Zem_t *s) {
    Mutex_lock(&s->lock);
    s->value++;
    Cond_signal(&s->cond);
    Mutex_unlock(&s->lock);
}
```

- Zemaphore don't maintain the invariant that *the value of* the semaphore.
  - The value never be lower than zero.
  - This behavior is **easier** to implement and **matches** the current Linux implementation.

- Implement locks and cond var from semaphores is much trickier
  - "Implementing Condition Variables with Semaphores", Andrew Birrell, December 2004 (ha mistakes)

- Disclaimer: Disclaimer: This lecture slide set is used in AOS course at University of Cantabria by V.Puente. Was initially developed for Operating System course in Computer Science Dept. at Hanyang University. This lecture slide set is for OSTEP book written by Remzi and Andrea Arpaci-Dusseau (at University of Wisconsin)