Synchronization II

COMS W4118

References: Operating Systems Concepts (9e), Linux Kernel Development, previous W4118s

Semaphore motivation

- Problem with lock: ensures mutual exclusion, but no execution order
- Producer-consumer problem: need to enforce execution order
  - Producer: create resources
  - Consumer: use resources
  - bounded buffer between them
  - Execution order: producer waits if buffer full, consumer waits if buffer empty
  - E.g., $ cat 1.txt | sort | uniq | wc

Semaphore definition

- A synchronization variable that contains an integer value
  - Can't access this integer value directly
  - Must initialize to some value
    - sem_init (sem_t *s, int pshared, unsigned int value)
  - Has two operations to manipulate this integer
    - sem_wait (or down(), P())
    - sem_post (or up(), V())

```
int sem_wait(sem_t *s) {
    wait until value of semaphore s
          is greater than 0
    decrement the value of
          semaphore s by 1
}
```

```
int sem_post(sem_t *s) {
    increment the value of
          semaphore s by 1
    if there are threads waiting, wake
          up one
}
```

Semaphore uses: mutual exclusion

- Mutual exclusion
  - Semaphore as mutex
  - Binary semaphore: X=1

```
// initialize to X
sem_init(&s, 0, X)

sem_wait(&s);
// critical section
sem_post(&s);
```

- Mutual exclusion with more than one resources
  - Counting semaphore: X>1
  - Initialize to be the number of available resources

Semaphore uses: execution order

- Execution order
  - One thread waits for another
  - What should initial value be?

```
//thread 0

… // 1st half of computation

sem_post(&s);
```

```
// thread 1

sem_wait(&s);

… //2nd half of computation
```

How to implement semaphores?

Pretty much the same as the mutex implementation we saw last time (note the direct transfer of semaphore):

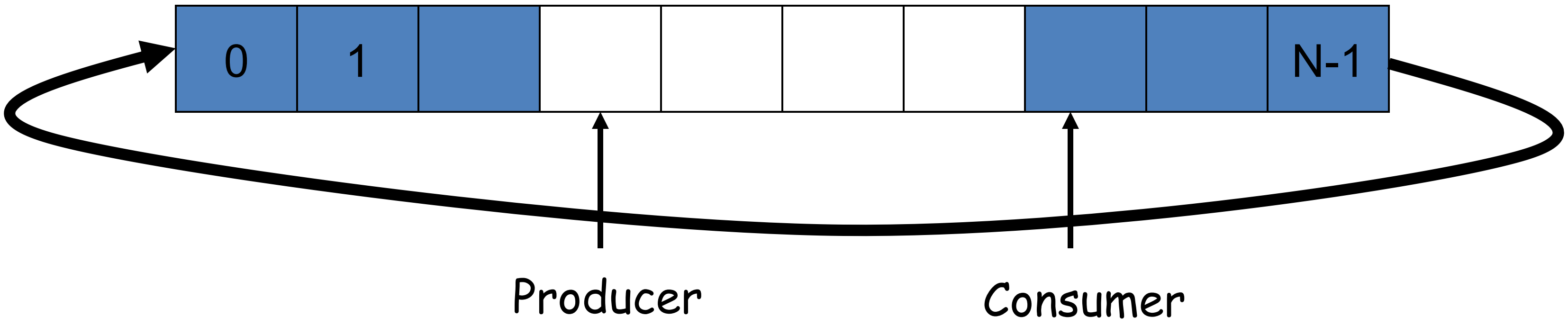
Semaphore { int value = 0; int guard = 0; }

```
P() {
    while (test_and_set(guard))
        ;
    if (value == 0) {
        Add to wait queue;
        Sleep and set guard to 0;
    } else {
        value--;
        guard = 0;
    }
}
```

```
V() {
    while (test_and_set(guard))
        ;
    if (wait queue not empty) {
        Remove from wait queue;
        Add to ready queue;
    } else {
        value++;
    }
    guard = 0;
}
```

Producer-Consumer (Bounded-Buffer) Problem

- Bounded buffer: size N, Access entry 0… N-1, then "wrap around" to 0 again
- Producer process writes data to buffer
- Consumer process reads data from buffer
- Execution order constraints
  - Producer shouldn't try to produce if buffer is full
  - Consumer shouldn't try to consume if buffer is empty



Solving Producer-Consumer problem

- Two semaphores
  - sem_t full; // # of filled slots
  - sem_t empty; // # of empty slots
- What should initial values be?
- Problem: mutual exclusion?

```
sem_init(&full, 0, X);
sem_init(&empty, 0, Y);
```

```
producer() {
    sem_wait(&empty);
    … // fill a slot
    sem_post(&full);
}
```

```
consumer() {
    sem_wait(&full);
    … // empty a slot
    sem_post(&empty);
}
```

Solving Producer-Consumer problem: final

- Three semaphores
  - sem_t full; // # of filled slots
  - sem_t empty; // # of empty slots
  - sem_t mutex; // mutual exclusion

```
sem_init(&full, 0, 0);
sem_init(&empty, 0, N);
sem_init(&mutex, 0, 1);
```

```
producer() {
    sem_wait(&empty);
    sem_wait(&mutex);
    … // fill a slot
    sem_post(&mutex);
    sem_post(&full);
}
```

```
consumer() {
    sem_wait(&full);
    sem_wait(&mutex);
    … // empty a slot
    sem_post(&mutex);
    sem_post(&empty);
}
```

Monitors

- Background: concurrent programming meets object-oriented programming
  – When concurrent programming became a big deal, object-oriented programming too
  – People started to think about ways to make concurrent programming more structured

- Monitor: object with a set of monitor procedures and only one thread may be active (i.e. running one of the monitor procedures) at a time

How to implement monitor?

Compiler automatically inserts lock and unlock operations upon entry and exit of monitor procedures

```
class account {
    int balance;
    public synchronized void deposit() {
        ++balance;
    }
    public synchronized void withdraw() {
        --balance;
    }
};
```

```
lock(this.m);
++balance;
unlock(this.m);
```

```
lock(this.m);
--balance;
unlock(this.m);
```

Condition Variables

- Condition variable operations
  - wait(): suspends the calling thread and releases the lock. When it resumes, reacquire the lock.
  - signal(): resumes one thread waiting in wait() if any.
  - broadcast(): resumes all threads waiting in wait().
- A monitor is 1 mutex + N cond var in a class object
  - In Java, it’s 1 mutex + 1 condition variable

Condition variables vs. semaphores

- Semaphores are sticky: they have memory, sem_post() will increment the semaphore counter, even if no one has called sem_wait()
- Condition variables are not: if no one is waiting for a signal(), this signal() is not saved
- Despite the difference, they are as powerful
  - Easy to implement semaphore with cond var
  - Can implement cond var with semaphore, but tricky

RCU: Lock-free Synchronozation

- Reader-writer lock still too slow, even for reading
  - Counter variable access needs expensive atomic instructions and memory barriers
  - Does not scale with large number of CPUs
- Can we just get rid of locks?
  - Sometimes we get lucky when we forget to lock
  - Can we just replicate the luck all the time?
- Read-Copy-Update (RCU):
  - Many readers + one writer can run simultaneously
  - Readers may read old, but consistent data
  - No lock!

RCU in a Nutshell: Add Spatial Dimension

```
struct foo {
    int a;
    int b;
} *global_foo;

// global_foo initialized elsewhere

DEFINE_SPINLOCK(foo_lock);
```

```
void get(int *p, int *q) {
    struct foo *copy_foo;

    // 1) begin reading (no lock)

    // 2) copy pointer once
    copy_foo = global_foo;

    // 3) access data using copy_foo
    *p = copy_foo->a;
    *q = copy_foo->b;

    // 4) end reading (no unlock)
}
```

```
void set(int x, int y){
    struct foo *new_foo = kmalloc(...);
    struct foo *old_foo;

    // 1) synchronize multiple writers
    spin_lock(&foo_lock);

    // 2) copy old pointer once
    old_foo = global_foo;

    // 3) update data
    new_foo->a = old_foo->a + x;
    new_foo->b = old_foo->b + y;

    // 4) switch pointer
    global_foo = new_foo;

    spin_unlock(&foo_lock);

    // 5) wait a bit for old readers

    // 6) free old struct
    kfree(old_foo);
}
```

RCU Core API

```
struct foo {
    int a;
    int b;
} *global_foo;

// global_foo initialized elsewhere

DEFINE_SPINLOCK(foo_lock);
```

```
void get(int *p, int *q) {
    struct foo *copy_foo;

    // 1) begin reading (no lock)
    rcu_read_lock();
    // 2) copy pointer once
    copy_foo =
        rcu_dereference(global_foo);
    // 3) access data using copy_foo
    *p = copy_foo->a;
    *q = copy_foo->b;

    // 4) end reading (no unlock)
    rcu_read_unlock();
}
```

```
void set(int x, int y){
    struct foo *new_foo = kmalloc(...);
    struct foo *old_foo;

    // 1) synchronize multiple writers
    spin_lock(&foo_lock);

    // 2) copy old pointer once
    old_foo = rcu_dereference_protected(
        global_foo, lockdep_is_held(&foo_lock));
    // 3) update data
    new_foo->a = old_foo->a + x;
    new_foo->b = old_foo->b + y;

    // 4) switch pointer
    rcu_assign_pointer(global_foo, new_foo);

    spin_unlock(&foo_lock);

    // 5) wait a bit for old readers
    synchronize_rcu();
    // 6) free old struct
    kfree(old_foo);
}
```

RCU (Toy) Implementations

#1: Using RW Lock

```
DEFINE_RWLOCK(global_rw_lock);

void rcu_read_lock(void) {
    read_lock(&global_rw_lock);
}

void rcu_read_unlock(void) {
    read_unlock(&global_rw_lock);
}

void synchronize_rcu(void) {
    write_lock(&global_rw_lock);
    write_unlock(&global_rw_lock);
}
```

#2: “Classic” RCU

```
void rcu_read_lock(void) {
    prermpt_disable[cpu_id()]++;
}

void rcu_read_unlock(void) {
    prermpt_disable[cpu_id()]--;
}

void synchronize_rcu(void)
{
    int cpu;

    for_each_possible_cpu(cpu)
        run_on(cpu);
}
```

RCU Today

- Linux kernel
  - TREE_RCU: high perf, super complex implementation of grace period handling
    - https://twitter.com/joel_linux/status/1175700053056512000/photo/1
  - Rich set of API
    - https://www.kernel.org/doc/html/latest/RCU/whatisRCU.html#full-list-of-rcu-apis
- User-space implementations
  - Ex) C++ standard library
- Use cases beyond reader-writer paradigm
- References:
  - Paul McKenney's RCU home page: http://www2.rdrop.com/users/paulmck/RCU/
  - Kernel RCU doc: https://www.kernel.org/doc/html/latest/RCU/index.html
  - Linux RCU API as of 2019: https://lwn.net/Articles/777036/