CS 202: Advanced Operating Systems

Synchronization, Memory Consistency, and Cache Coherence *(some cache coherence slides adapted from Ian Watson; some memory consistency slides from Sarita Adve)*

Classic Example

- Suppose we have to implement a function to handle withdrawals from a bank account:

```
withdraw (account, amount) {
    balance = get_balance(account);
    balance = balance – amount;
    put_balance(account, balance);
    return balance;
}
```

- Now suppose that you and your father share a bank account with a balance of $1000
- Then you each go to separate ATM machines and simultaneously withdraw $100 from the account

Interleaved Schedules

- The problem is that the execution of the two threads can be interleaved:

Execution sequence seen by CPU

```
balance = get_balance(account);
balance = balance – amount;
```

```
balance = get_balance(account);
balance = balance – amount;
put_balance(account, balance);
```

Context switch

```
put_balance(account, balance);
```

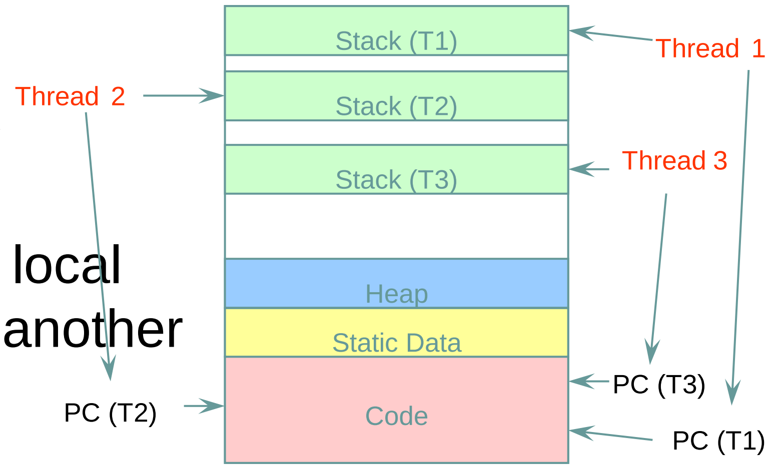
- What is the balance of the account now?

Shared Resources

- Problem: two threads accessed a shared resource
  - Known as a race condition (remember this buzzword!)
- Need mechanisms to control this access
  - So we can reason about how the program will operate
- Our example was updating a shared bank account
- Also necessary for synchronizing access to any shared data structure
  - Buffers, queues, lists, hash tables, etc.

When Are Resources Shared?

- Local variables?
  - Not shared: refer to data on the stack
  - Each thread has its own stack
  - Never pass/share/store a pointer to a local variable on the stack for thread T1 to another thread T2



- Global variables and static objects?
  - Shared: in static data segment, accessible by all threads

- Dynamic objects and other heap objects?
  - Shared: Allocated from heap with malloc/free or new/delete

How Interleaved Can It Get?

How contorted can the interleavings be?

- We'll assume that the only atomic operations are reads and writes of individual memory locations
  - Some architectures don't even give you that!

- We'll assume that a context switch can occur at any time

- We'll assume that you can delay a thread as long as you like as long as it's not delayed forever

```
............... get_balance(account);
balance = get_balance(account);
balance = ...................................
balance = balance – amount;
balance = balance – amount;
put_balance(account, balance);
put_balance(account, balance);
```

Mutual Exclusion

- Mutual exclusion to synchronize access to shared resources
  - This allows us to have larger atomic blocks
  - What does atomic mean?
- Code that uses mutual called a critical section
  - Only one thread at a time can execute in the critical section
  - All other threads are forced to wait on entry
  - When a thread leaves a critical section, another can enter
  - Example: sharing an ATM with others
- What requirements would you place on a critical section?

Using Locks

```
withdraw (account, amount) {
    acquire(lock);
    balance = get_balance(account);
    balance = balance – amount;
    put_balance(account, balance);
    release(lock);
    return balance;
}
```

Critical Section

```
acquire(lock);
balance = get_balance(account);
balance = balance – amount;
```

```
acquire(lock);
```

```
put_balance(account, balance);
release(lock);
```

```
balance = get_balance(account);
balance = balance – amount;
put_balance(account, balance);
release(lock);
```

Using Test-And-Set

- Here is our lock implementation with test-and-set:

```
struct lock {
    int held = 0;
}
void acquire (lock) {
    while (test-and-set(&lock->held));
}
void release (lock) {
    lock->held = 0;
}
```

```
//Atomic!!!
test-and-set(lock) {
    boolean initial = lock;
    lock = true;
    return initial;
}
```

- When will the while return? What is the value of held?
- Does it satisfy critical region requirements? (mutex, progress, bounded wait, performance?)

Another solution: Disabling Interrupts

- Another implementation of acquire/release is to disable interrupts:

```
struct lock {
}
void acquire (lock) {
    disable interrupts;
}
void release (lock) {
    enable interrupts;
}
```

- Note that there is no state associated with the lock
- Can two threads disable interrupts simultaneously?

On Disabling Interrupts

- Disabling interrupts blocks notification of external events that could trigger a context switch (e.g., timer)
- In a “real” system, this is only available to the kernel
  - Why?
- Disabling interrupts is insufficient on a multiprocessor
  - Back to atomic instructions
- Like spinlocks, only want to disable interrupts to implement higher-level synchronization primitives
  - Don’t want interrupts disabled between acquire and release

Summarize Where We Are

- Goal: Use mutual exclusion to protect critical sections of code that access shared resources
- Method: Use locks (spinlocks or disable interrupts)
- Problem: Critical sections can be long

Spinlocks:

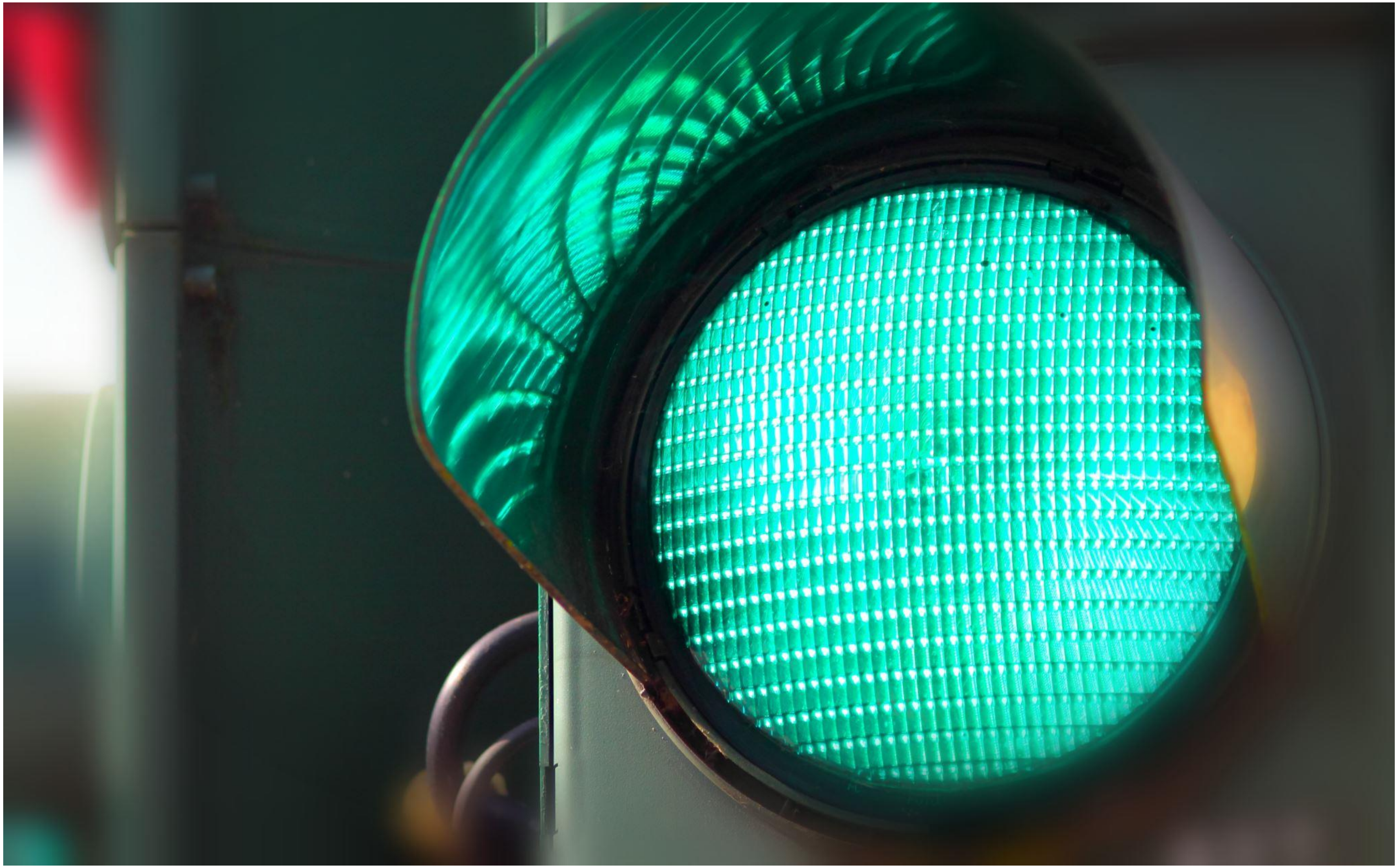
- Threads waiting to acquire lock spin in test-and-set loop
- Wastes CPU cycles
- Longer the CS, the longer the spin
- Greater the chance for lock holder to be interrupted
- Memory consistency model causes problems (out of scope of this class)

```
acquire(lock)
…
Critical section
…
release(lock)
```

Disabling Interrupts:

- Should not disable interrupts for long periods of time
- Can miss or delay important events (e.g., timer, I/O)
- Doesn't work for multiprocessor

Semaphore



Higher-Level Synchronization

- Locks so far inefficient when critical sections are long
  - Spinlocks – inefficient
  - Disabling interrupts – can miss or delay important events
- Instead, we want synchronization mechanisms that
  - Block waiters
  - Leave interrupts enabled inside the critical section
- Plan:
  - Semaphores: binary (mutex) and counting
  - Use them to solve common synchronization problems

Semaphores

- Semaphores are an abstract data type that provide mutual exclusion to critical sections
  - Block waiters, interrupts enabled within critical section
  - Described by Dijkstra in THE system in 1968
- Semaphores are integers that support two operations:
  - sem_wait(sem_t *s): wait if the value is zero; otherwise, decrement
    - Also P(), after the Dutch word for test, or down()
  - sem_post(sem_t *s): if one thread waiting, wake it; otherwise, increment
    - Also V() after the Dutch word for increment, or up()
  - That's it! No other operations – not even just reading its value – exist
- Semaphore safety property: the semaphore value is always greater than or equal to 0

Semaphore Types

- Semaphores come in two types
- Mutex semaphore (or binary semaphore)
  - Represents single access to a resource
  - Guarantees mutual exclusion to a critical section
- Counting semaphore (or general semaphore)
  - Multiple threads pass the semaphore determined by count
    - mutex has count = 1, counting has count = N
  - Represents a resource with many units available
  - or a resource allowing some unsynchronized concurrent access (e.g., reading)

Protecting a critical region

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

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

Figure 31.3: **A Binary Semaphore (That Is, A Lock)**

A parent waiting for its child

```
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;
}
```

Figure 31.6: **A Parent Waiting For Its Child**

Producer/ Consumer (Bounded Buffer)

```
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;
}
```

Figure 31.9: The Put And Get Routines

```
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);
    }
}

int main(int argc, char *argv[]) {
    // ...
    sem_init(&empty, 0, MAX); // MAX are empty
    sem_init(&full, 0, 0);    // 0 are full
    // ...
}
```

Figure 31.10: Adding The Full And Empty Conditions

Second Attempt (Add Mutual Exclusion)

```
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)
    }
}

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);
    }
}
```

Third Attempt

```
void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        sem_wait(&empty);         // Line P1
        sem_wait(&mutex);         // Line P1.5 (MUTEX HERE)
        put(i);                   // Line P2
        sem_post(&mutex);         // Line P2.5 (AND HERE)
        sem_post(&full);          // Line P3
    }
}

void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        sem_wait(&full);          // Line C1
        sem_wait(&mutex);         // Line C1.5 (MUTEX HERE)
        int tmp = get();          // Line C2
        sem_post(&mutex);         // Line C2.5 (AND HERE)
        sem_post(&empty);         // Line C3
        printf("%d\n", tmp);
    }
}
```

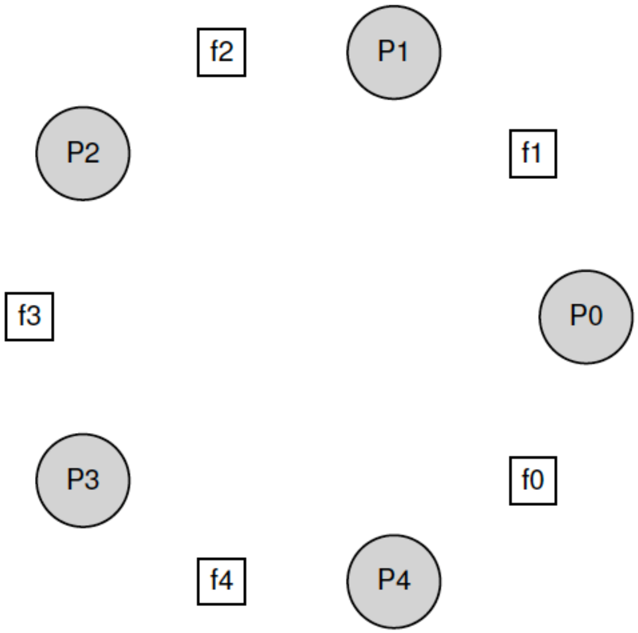
Any more improvement?

Reader-Writer Lock

```
typedef struct _rwlock_t {
  sem_t lock;       // binary semaphore (basic lock)
  sem_t writelock; // allow ONE writer/MANY readers
  int   readers;    // #readers 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);
  rw->readers++;
  if (rw->readers == 1) // first reader gets writelock
    sem_wait(&rw->writelock);
  sem_post(&rw->lock);
}
```

```
void rwlock_release_readlock(rwlock_t *rw) {
  sem_wait(&rw->lock);
  rw->readers--;
  if (rw->readers == 0) // last reader lets it go
    sem_post(&rw->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);
}
```

Dining Philosophers




```
while (1) {
    think();
    get_forks(p);
    eat();
    put_forks(p);
}

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


void get_forks(int p) {
    sem_wait(&forks[left(p)]);
    sem_wait(&forks[right(p)]);
}

void put_forks(int p) {
    sem_post(&forks[left(p)]);
    sem_post(&forks[right(p)]);
}
```

What is wrong?

How to fix it?

Solution: Break Dependency

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

Can you think of another solution?

Semaphore Summary

- Semaphores can be used to solve any of the traditional synchronization problems
- However, they have some drawbacks
  - They are essentially shared global variables
    - Can potentially be accessed anywhere in program
  - No connection between the semaphore and the data being controlled by the semaphore
  - Used both for critical sections (mutual exclusion) and coordination (scheduling)
    - Note that I had to use comments in the code to distinguish
  - No control or guarantee of proper usage
- Sometimes hard to use and prone to bugs
  - Another approach: Use programming language support

Overview

- Before we talk deeply about synchronization
  - Need to get an idea about the memory model in shared memory systems
  - Is synchronization only an issue in multi-processor systems?
- What is a shared memory processor (SMP)?
- Shared memory processors
  - Two primary architectures:
    - Bus-based/local network shared-memory machines (small-scale)
    - Directory-based shared-memory machines (large-scale)