CSE 153
Design of Operating Systems

Winter 2023

Lecture 9: Semaphores

Last time

- Introduced hardware support for synchronization
  - Two flavors:
    - » Atomic instructions that read and update a variable
      - E.g., test-and-set, xchange, …
    - » Disable interrupts
- Blocking locks
  - Spin lock only around acquire of lock
- Introduced Semaphores

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:
  - wait(semaphore): decrement, block until semaphore is open
    - » Also P(), after the Dutch word for test, or down()
  - signal(semaphore): increment, allow another thread to enter
    - » 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

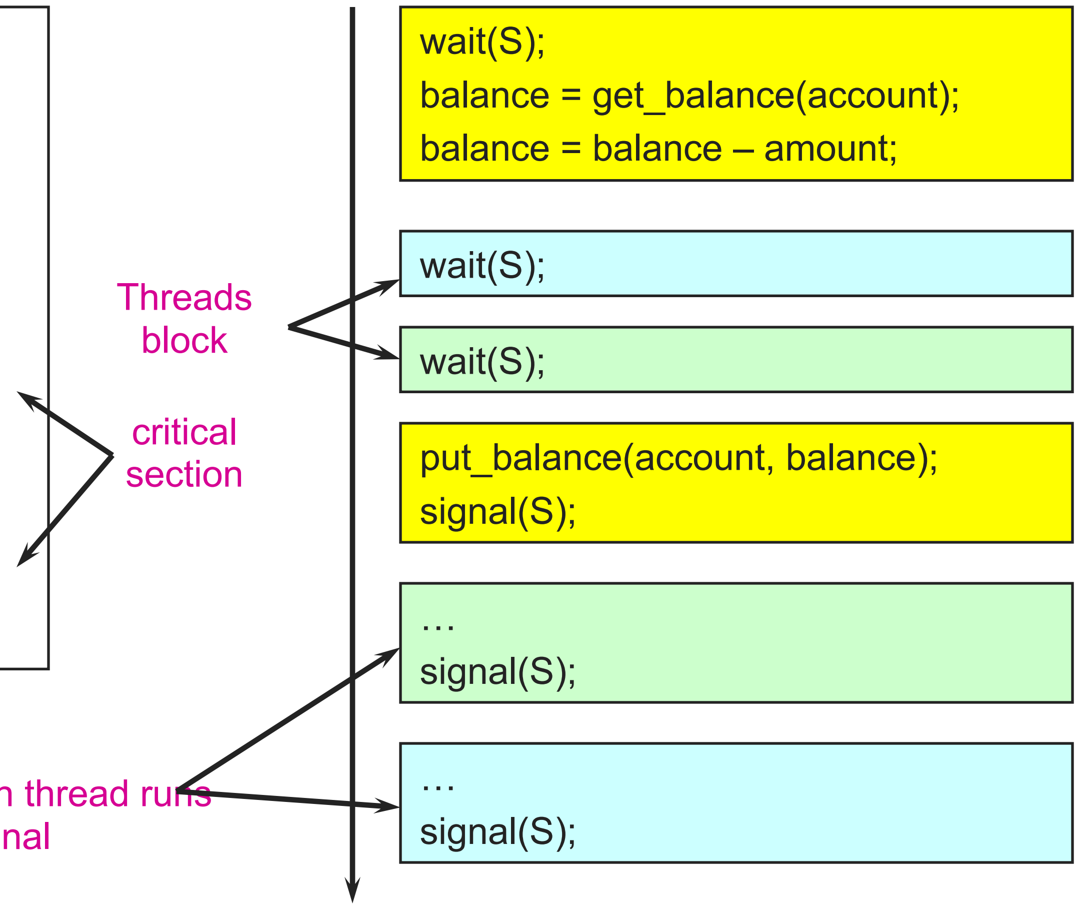
Semaphore Types

- 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)

Using Semaphores

- Use is similar to our locks, but semantics are different

```
struct Semaphore {
    int value;
    Queue q;
} S;
withdraw (account, amount) {
    wait(S);
    balance = get_balance(account);
    balance = balance – amount;
    put_balance(account, balance);
    signal(S);
    return balance;
}
```



It is undefined which thread runs after a signal

Beyond Mutual Exclusion

- We've looked at a simple example for using synchronization
  - Mutual exclusion while accessing a bank account
- We're going to use semaphores to look at more interesting examples
  - Counting critical region
  - Ordering threads
  - Readers/Writers
  - Producer consumer with bounded buffers
  - More general examples

Readers/Writers Problem

- Readers/Writers Problem:
  - An object is shared among several threads
  - Some threads only read the object, others only write it
  - We can allow multiple readers but only one writer
    - » Let #r be the number of readers, #w be the number of writers
    - » Safety: $(\#r \geq 0) \wedge (0 \leq \#w \leq 1) \wedge ((\#r > 0) \Rightarrow (\#w = 0))$
- Use three variables
  - int readcount – number of threads reading object
  - Semaphore mutex – control access to readcount
  - Semaphore w_or_r – exclusive writing or reading

Readers/Writers

```
// number of readers
int readcount = 0;
// mutual exclusion to readcount
Semaphore mutex = 1;
// exclusive writer or reader
Semaphore w_or_r = 1;

writer {
    wait(w_or_r); // lock out readers
    Write;
    signal(w_or_r); // up for grabs
}
```

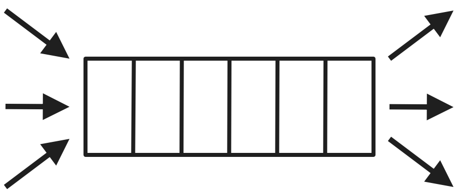
```
reader {
    wait(mutex);       // lock readcount
    readcount += 1; // one more reader
    if (readcount == 1)
        wait(w_or_r); // synch w/ writers
    signal(mutex);   // unlock readcount
    Read;
    wait(mutex);      // lock readcount
    readcount -= 1; // one less reader
    if (readcount == 0)
        signal(w_or_r); // up for grabs
    signal(mutex);   // unlock readcount
}
```

Readers/Writers Notes

- w_or_r provides mutex between readers and writers
  - Readers wait/signal when readcount goes from 0 to 1 or 1 to 0
- If a writer is writing, where will readers be waiting?
- Once a writer exits, all readers can fall through
  - Which reader gets to go first?
  - Is it guaranteed that all readers will fall through?
- If readers and writers are waiting, and a writer exits, who goes first?
- Why do readers use mutex?
- What if the signal is above "if (readcount == 1)"?
- If read in progress when writer arrives, when can writer get access?

Bounded Buffer

- Problem: Set of buffers shared by producer and consumer threads
  - Producer inserts jobs into the buffer set
  - Consumer removes jobs from the buffer set



- Producer and consumer execute at different rates
  - No serialization of one behind the other
  - Tasks are independent (easier to think about)
  - The buffer set allows each to run without explicit handoff
- Data structure should not be corrupted
  - Due to race conditions
  - Or producer writing when full
  - Or consumer deleting when empty

Bounded Buffer (2)

- $0 \leq np - nc \leq N$
- Use three semaphores:
  - full – count of full buffers
    - Counting semaphore
    - full = ?
      - $(np - nc)$
  - empty – count of empty buffers
    - Counting semaphore
    - empty = ?
      - $N - (np - nc)$
  - mutex – mutual exclusion to shared set of buffers
    - Binary semaphore

Bounded Buffer (3)

```
Semaphore mutex = 1;   // mutual exclusion to shared set of buffers
Semaphore empty = N;  // count of empty buffers (all empty to start)
Semaphore full = 0;      // count of full buffers (none full to start)
```

```
producer {
  while (1) {
    Produce new resource;
    wait(empty); // wait for empty buffer
    wait(mutex); // lock buffer list
    Add resource to an empty buffer;
    signal(mutex); // unlock buffer list
    signal(full);      // note a full buffer
  }
}
```

```
consumer {
  while (1) {
    wait(full);          // wait for a full buffer
    wait(mutex);      // lock buffer list
    Remove resource from a full buffer;
    signal(mutex); // unlock buffer list
    signal(empty); // note an empty buffer
    Consume resource;
  }
}
```

Bounded Buffer (4)

- Why need the mutex at all?
- The pattern of signal/wait on full/empty is a common construct often called an interlock
- Producer-Consumer and Bounded Buffer are classic examples of synchronization problems
  - We will see and practice others

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