Semaphores

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Synchronization Types

• Mutual exclusion
  – Only one thread in a critical section at a time

• Waiting for events
  – One thread waits for another to complete some action before it continues
  – Producer/consumer
    • Multiple producers, multiple consumers
  – Pipeline
    • A series of producer and consumer
  – Defer work with background thread
    • Non-critical work in the background when CPU is idle
Higher-level Synchronization

- Spinlocks and disabling interrupts are not enough
  - Useful only for very short and simple critical sections
  - Need to block threads when lock is held by others (mutexes)
  - Need to block threads until a certain condition is met

- Higher-level synchronization mechanisms
  - Semaphores
    - Simple, yet powerful
    - Hard to program with
  - Mutexes and condition variables
    - Used in Pthreads
Semaphores

• A synchronization primitive higher level than locks
  – Invented by Dijkstra in 1968, as part of the THE OS
  – Does not require busy waiting
  – A semaphore is an object with an integer value (state)
  – State cannot be directly accessed by user program, but it determines the behavior of semaphore operations

• Manipulated atomically through two operations
  – `Wait()`: decrement the value, and wait until the value is $\geq 0$
    = $P()$ (after Dutch word for test), $\text{down()}$, or $\text{sem\_wait()}$
  – `Signal()`: increment the value, then wake up a single waiter
    = $V()$ (after Dutch word for increment), $\text{up()}$, or $\text{sem\_post()}$
Implementing Semaphores

typedef struct {
    int value;
    struct process *Q;
} semaphore;

void wait (semaphore *S) {
    S->value--;
    if (S->value < 0) {
        add this process to S->Q;
        block ();
    }
}

void signal (semaphore *S) {
    S->value++;
    if (S->value <= 0) {
        remove a process P from S->Q;
        wakeup (P);
    }
}

wait() / signal() are critical sections! Hence, they must be executed atomically with respect to each other.

HOW??
Types of Semaphores

• **Binary semaphore (≈ mutex)**
  – Semaphore value is initialized to 1
  – Guarantees mutually exclusive access to resource
  – Only one thread allowed entry at a time

• **Counting semaphore**
  – Semaphore value is initialized to N
  – Represents a resource with many units available
  – Allows threads to enter as long as more units are available
Bounded Buffer Problem (1)

- **Producer/consumer problem**
  - There is a set of resource buffers shared by producers and consumers
  - Producer inserts resources into the buffer
    - Output, disk blocks, memory pages, etc.
  - Consumer removes resources from the buffer
    - Whatever is generated by the producer
  - Producer and consumer execute in different rates
    - No serialization of one behind the other
    - Tasks are independent
    - The buffer allows each to run without explicit handoff
  - pipes: single producer, single consumer
Bounded Buffer Problem (2)

• No synchronization

```c
void produce (data)
{
    while (count==N);
    buffer[in] = data;
    in = (in+1) % N;
    count++;
}

void consume (data)
{
    while (count==0);
    data = buffer[out];
    out = (out+1) % N;
    count--;
}
```
Bounded Buffer Problem (3)

- Implementation with semaphores

```c
void produce (data) {
    wait (&empty);
    wait (&mutex);
    buffer[in] = data;
    in = (in+1) % N;
    signal (&mutex);
    signal (&full);
}

void consume (data) {
    wait (&full);
    wait (&mutex);
    data = buffer[out];
    out = (out+1) % N;
    signal (&mutex);
    signal (&empty);
}
```

Semaphore
mutex = 1;
empty = N;
full = 0;
Readers-Writers Problem (1)

• Sharing resource among multiple readers and writers
  – An object is shared among several threads
  – Some threads only read the object, others only write it
  – We can allow multiple readers at a time
  – We can only allow one writer at a time

• Implementation with semaphores
  – readcount: # of threads reading object
  – mutex: control access to readcount
  – rw: exclusive writing or reading
Readers-Writer Problem (2)

```c
// number of readers
int readcount = 0;
// mutex for readcount
Semaphore mutex = 1;
// mutex for reading/writing
Semaphore rw = 1;

void Writer ()
{
    wait (&rw);
    ...
    Write
    ...
    signal (&rw);
}

void Reader ()
{
    wait (&mutex);
    readcount++;
    if (readcount == 1)
    {
        wait (&rw);
        signal (&mutex);
    }
    Read
    ...
    wait (&mutex);
    readcount--;
    if (readcount == 0)
    {
        signal (&rw);
        signal (&mutex);
    }
}
```
Readers-Writers Problem (3)

• If there is a writer
  – The first reader blocks on \( rw \)
  – All other readers will then block on mutex

• Once a writer exits, all readers can fall through
  – Which reader gets to go first?

• The last reader to exit signals waiting writer
  – Can new readers get in while writer is waiting?

• When a writer exits, if there is both a reader and writer waiting, which one goes next is up to scheduler
Dining Philosophers Problem (1)

• A classic synchronization problem by Dijkstra, 1965

• Modeled after the lives of five philosophers sitting around a round table

• Each philosopher repeats forever
  – Thinking
  – Pick up two forks
  – Eating
  – Put down two forks

• Pick one fork at a time
Dining Philosophers Problem (2)

- A simple solution

```c
// initialized to 1
Semaphore forks[N];

#define L(i)  (i)
#define R(i)  ((i + 1) % N)

void philosopher (int i) {
    while (1) {
        think ();
        pickup (i);
        eat ();
        putdown (i);
    }
}

void pickup (int i) {
    wait (&forks[L(i)]);
    wait (&forks[R(i)]);
}

void putdown (int i) {
    signal (&forks[L(i)]);
    signal (&forks[R(i)]);
}
```
Dining Philosophers Problem (3)

- A deadlock-free solution

```c
// initialized to 1
Semaphore forks[N];

#define L(i)  (i)
#define R(i)  ((i + 1) % N)

void philosopher (int i) {
    while (1) {
        think ();
        pickup (i);
        eat ();
        putdown (i);
    }
}

void pickup (int i) {
    if (i == (N-1)) {
        wait (&forks[R(i)]);
        wait (&forks[L(i)]);
    } else {
        wait (&forks[L(i)]);
        wait (&forks[R(i)]);
    }
}

void putdown (int i) {
    signal (&forks[L(i)]);
    signal (&forks[R(i)]);
}
```
Semaphores

• Pros
  – One primitive can be used for both critical sections (mutual exclusion) and coordination among threads (scheduling)

• Cons
  – They are essentially shared global variables; can be accessed from anywhere (bad software engineering)
  – There is no connection between the semaphore and the data being controlled by it
  – No control over their use, no guarantee of proper usage; thus, hard to use and prone to bugs