Previous lecture overview

- *Concurrently* executing threads often share data structures.
- If multiple threads are allowed to access shared data structures unhindered *race condition* may occur
- To protect shared data structure from race conditions the thread's access to it should be *mutually exclusive*
- MX may be implemented in software:
  - for two threads - Peterson's algorithm
  - for multiple threads - bakery algorithm
- MX may be implemented using hardware support
- Writing efficient MX algorithms is not trivial and OS usually provides MX primitives for a programmer (as well as uses them internally)

Lecture 10: Semaphores

- Definition of a semaphore
- using semaphores for MX
- semaphore solutions for common concurrency problems:
  - producer/consumer
  - readers/writers
  - dining philosophers
- implementation of semaphores
  - using spinlocks
  - using test-and-set instructions
  - semaphores without busy waiting
- evaluation of semaphores

Semaphores — OS support for mutual exclusion

- Semaphores were invented by Dijkstra in 1965, and can be thought of as a generalized locking mechanism.
- semaphore supports two **<u>atomic</u>** operations **P / wait** and **V / signal.** The atomicity means that no two P or V operations on the same semaphore can overlap
  - The semaphore initialized to 1
  - Before entering the critical section, a thread calls "**P(semaphore)**", or sometimes "**wait(semaphore)**"
  - After leaving the critical section, a thread calls "**V(semaphore)**", or sometimes "**signal(semaphore)**"

Semaphores — details

- P and V manipulate an integer variable the value of which is originally "1"
- Before entering the critical section, a thread calls "**P(s)**" or "**wait(s)**"
  - wait (s):
    - s = s – 1
    - if (s < 0)
      block the thread that called wait(s) on a queue associated with semaphore s
    - otherwise
      let the thread that called wait(s) continue into the critical section
- After leaving the critical section, a thread calls "**V(s)**" or "**signal(s)**"
  - signal (s):
    - s = s + 1
    - if (s ≤ 0), then
      wake up one of the threads that called wait(s), and run it so that it can continue into the critical section
- *Bounded wait condition* (not specified originally): if signal is continuously executed each individual blocked process is eventually woken up

Using semaphores for MX

```
t1 () {
   while (true) {
         wait(s);
         /* CS */
         signal(s);
         /* non-CS */
   }
}

t2 ()   {
   while (true) {
         wait(s);
         /* CS */
         signal(s);
         /* non-CS */
   }
}
```

- The semaphore **s** is used to protect critical section ***CS***
- before entering CS a thread executes **wait(s)**
- by definition of **wait** it:
  - decrements **s**
  - checks if **s** is less than 0; if it is then the thread is blocked. If not then the thread proceeds to ***CS*** excluding the other from reaching it
- after executing ***CS*** the thread does **signal(s)**
- by definition of signal it:
  - increments **s**
  - checks if **s≤0;** if it is then the other thread is woken up

Semaphore values

- Semaphores (again):

<u>wait (s):</u>	<u>signal (s):</u>
s = s – 1	s = s + 1
if (s < 0) block the thread that called wait(s)	if (s ≤ 0) wake up & run one of the waiting threads
otherwise continue into CS	

- Semaphore values:
  - Positive semaphore = number of (additional) threads that can be allowed into the critical section
  - Negative semaphore = number of threads blocked (note — there's also one in CS)
  - *Binary semaphore* has an initial value of 1
  - *Counting semaphore* has an initial value greater than 1

“Too much milk” with semaphores

Too much milk

Thread A	Thread B

`P(fridge);`
`if (noMilk){`
`buy milk;`
`noMilk=false;`
`}`
`V(fridge);`
	`P(fridge);`
	`if (noMilk){`
	`buy milk;`
	`noMilk=false;`
	`}`
	`V(fridge);`

- “fridge” is a semaphore initialized to 1, noMilk is a shared variable

Execution:

After:	s	queue	A	B
	1			
A: **P(fridge);**	0		in CS	
B: **P(fridge);**	-1	B	in CS	waiting
A: **V(fridge);**	0		finish	ready, in CS
B: **V(fridge);**	1			finish

Producer/consumer problem

```
int p, c, buff[B],
front=0, rear=0;
semaphore empty(B),
          full(0),
          mutex(1);

producer() {
   while (true) {
       /* produce p */
       wait(empty);
       wait(mutex);
       buff[rear]=p;
       rear=(rear+1) % B;
       signal(mutex);
       signal(full);
   }
}

consumer () {
   while (true) {
       wait(full);
       wait(mutex);
       c=buff[front];
       front=(front+1) % B;
       signal(mutex);
       signal(empty);
       /* consume c */
   }
}
```

- bounded **buff** holds items added by **producer** and removed by **consumer**
- this variant – single producer, single consumer, producer and consumer have to have exclusive access to the buffer
- **p** - item generated by producer
- **c** - item utilized by consumer
- **mutex** - protects **buffer** manipulations
- **empty** - if open - **producer** may proceed
- **full** - if open - **consumer** may proceed

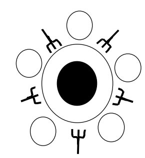
Readers/writers problem

```
int readcount;
semaphore wrt(1),mutex(1);

writer() {
       wait(wrt);
       /* perform write */
       signal(wrt);
}

reader() {
       wait(mutex);
       readcount++;
       if(readcount==1)
          wait(wrt);
       signal(mutex);
       /* perform read */
       wait(mutex);
       readconut--;
       if(readcount==0)
          signal(wrt);
       signal(mutex);
}
```

- Readers and writers perform operations concurrently on a certain item
- writers cannot concurrently access items, readers can
- **readcount** - number of readers wishing to access /accessing the item
- **mutex** - protects manipulation with **readcount**
- **wrt** - writer can get to item if open
- two version of this problem:
  - readers preference - if reader wants to get to item - writers wait
  - writers preference - if writer wants to get to item - readers wait
- which version is this code?

Dining philosophers problem

- The problem was first defined and solved by Dijkstra in 1972: five philosophers sit at the table and alternate between thinking and eating from a bowl of spaghetti in the middle of the table. They have five forks. A philosopher needs 2 forks to eat. Picking up and laying down a fork is an atomic operation. Philosophers can talk (share variables) only to their neighbors



- **Objective:** design an algorithm to ensure that any “hungry” philosopher eventually eats
- one solution - protect each fork by a semaphore.
- what’s wrong with this solution?
  - there is a possibility of deadlock
  - fix: make odd philosophers pick even forks first
  - can we use the bakery algorithm?

```
semaphore fork[5](1);
philosopher(int i) {
   while(true){
       wait(fork[i]);
       wait(fork[(i+1) % 5]);
       /* eat */
        signal(fork[i]);
       signal(fork[(i+1) % 5]);
       /* think */
   }
}
```


Two versions of Semaphores

- Semaphores from last time (simplified):

wait (s):	signal (s):
s = s – 1 if (s < 0) block the thread that called wait(s) otherwise continue into CS	s = s + 1 if (s ≤ 0) wake up one of the waiting threads

- "Classical" version of semaphores:

wait (s):	signal (s):
if (s ≤ 0) block the thread that called wait(s) s = s – 1 continue into CS	if (a thread is waiting) wake up one of the waiting threads s = s + 1

- Do both work? What is the difference?

Implementing semaphores: busy waiting (spinlocks)

```
wait(semaphore s) {
    while (s <= 0)
        ; /* do nothing */
    s--;
}

signal(semaphore s) {
     s++;
}
```

- idea: inside **wait** continuously check the semaphore variable (spins) until unblocked
- Problem: wait and signal operations are **not** atomic

Implementing semaphores: busy waiting (spinlocks)

```
wait(semaphore s) {
   /* disable interrupts */
   while (s <=0)
       ; /* do nothing */
   s--;
   /* enable interrupts
}

signal(semaphore s) {
   /* disable interrupts */
   s++;
   /* enable interrupts */
}
```

- adv: may be efficient on multiprocessors – no need for context switch
- disadvantages
  - does not support bounded wait condition
  - waiting thread wastes time *busy-waiting* (doing nothing useful, wasting CPU time)
    - how long can a thread wait?
  - can interfere with timer (interrupts)

Read-modify-write (RMW) instructions

```
int testnset(boolean *i){
   if (*i==FALSE)
      *i=TRUE;
      return(FALSE);
   else
      return(TRUE);
}
```

- RMW instructions atomically read a value from memory, modify it, and write the new value to memory
  - Test&set — on most CPUs
  - Exchange — Intel x86 — swaps values between register and memory
  - Compare&swap — Motorola 68xxx — read value, if value matches value in register r1, exchange register r1 and value
  - Compare,compare&swap - SPARC
- RMW is not provided by “pure” RISC processors!

Semaphores using hardware support

This is a partial implementation

If lock is free (**lock==false**), test&set atomically:
- reads **false**, sets value to **true**, and returns **false**
- loop test fails, meaning lock is now busy

If lock is busy, test&set atomically:
- reads **true** and returns **true**
- loop test is true, so loop continues until someone releases the lock

Why is this implementation incomplete?

Adv: ensures atomicity of operation

Dis: does not support bounded wait

```
bool lock=false;
wait(semaphore s){
     while (testnset(lock)){
         ; /* do nothing */
     while ( s <= 0 )
         ; /* do nothing */
     s--;
     lock=false;
}

signal(semaphore s){
      while(testnset(lock))
          ; /* do nothing */
      s++;
      lock=false;
}
```


Semaphores (almost) without busy waiting

```
struct semaphore {
public:
   int v;
   struct queue q;
} *s;
thread *ct;

wait(s){
   s->v--;
   if(s->v < 0){
       enqueue(ct,s->q);
       block(ct);
   }
}

signal(s){
   thread *t;
   s->v++;
   if(s->v <= 0) {
       t=dequeue(s->q);
       wakeup(t);
   }
}
```

`*ct` pointer to current thread

`*s` pointer to semaphore

`v` semaphore value

`q` queue of blocked threads waiting for semaphore

`block` blocks thread

`wakeup` wakes up a thread

- This is an incomplete implementation. Why?
- adv:
  - no busy waiting,
  - supports bounded wait
- dis: requires context switch

Semaphores - evaluation

- Semaphores provide the first high-level synchronization abstraction that is possible to implement efficiently in OS.
  - this allows avoid using ad hoc Kernel synchronization techniques like non-preemptive kernel
  - allows to implement in multiprocessors
- problems
  - programming with semaphores is error prone - the code is often cryptic
  - for signal and wait to be atomic on multiprocessor architecture - a low level locking primitives (like test&set instruction) need to be available
  - efficient blocking and unblocking require context switch - performance degradation
  - no means of finding out whether the thread will block on semaphore