CSE 451: Operating Systems
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Lecture 8
Semaphores and Monitors

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Semaphores

- semaphore = a synchronization primitive
  - higher level than locks
  - invented by Dijkstra in 1968, as part of the THE os
- A semaphore is:
  - a variable that is manipulated atomically through two operations, signal and wait
  - wait(semaphore): decrement, block until semaphore is open
    - also called P(), after Dutch word for test, also called down()
  - signal(semaphore): increment, allow another to enter
    - also called V(), after Dutch word for increment, also called up()

Blocking in Semaphores

- Each semaphore has an associated queue of processes/threads
  - when wait() is called by a thread,
    - if semaphore is “available”, thread continues
    - if semaphore is “unavailable”, thread blocks, waits on queue
  - signal() opens the semaphore
    - if thread(s) are waiting on a queue, one thread is unblocked
    - if no threads are on the queue, the signal is remembered for next time a wait() is called
- In other words, semaphore has history
  - this history is a counter
  - if counter falls below 0 (after decrement), then the semaphore is closed
    - wait decrements counter
    - signal increments counter

Hypothetical Implementation

```
type semaphore = record
    value: integer:
    L: list of processes;
end

wait(S):
    S.value = S.value - 1;
    if S.value < 0
    then begin
            add this process to S.L;
            block;
            end;

signal(S):
    S.value = S.value + 1;
    if S.value <= 0
    then begin
            remove a process P from S.L;
            wakeup P
            end;
```

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

Two types of semaphores

- Binary semaphore (aka mutex semaphore)
  - guarantees mutually exclusive access to resource
  - only one thread/process allowed entry at a time
  - counter is initialized to 1
- Counting semaphore (aka counted semaphore)
  - represents a resources with many units available
  - allows threads/process to enter as long as more units are available
  - counter is initialized to N
    - N = number of units available

Example: bounded buffer problem

- AKA producer/consumer problem
  - there is a buffer in memory
    - with finite size N entries
  - a producer process inserts an entry into it
  - a consumer process removes an entry from it
- Processes are concurrent
  - so, we must use synchronization constructs to control access to shared variables describing buffer state

Bounded Buffer using Semaphores

```
var mutex: semaphore = 1    ;mutual exclusion to shared data
    empty: semaphore = n    ;count of empty buffers (all empty to start)
    full: semaphore = 0     ;count of full buffers (none full to start)

producer:
    wait(empty)     ; one fewer buffer, block if none available
    wait(mutex)     ; get access to pointers
        <add item to buffer>
    signal(mutex) ; done with pointers
    signal(full) ; note one more full buffer

consumer:
    wait(full) ;wait until there's a full buffer
    wait(mutex) ;get access to pointers
        <remove item from buffer>
    signal(mutex) ; done with pointers
    signal(empty) ; note there's an empty buffer
        <use the item>
```


Example: Readers/Writers

- Basic problem:
  - object is shared among several processes
  - some read from it
  - others write to it
- We can allow multiple readers at a time
  - why?
- We can only allow one writer at a time
  - why?

Readers/Writers using Semaphores

```
var mutex: semaphore        ; controls access to readcount
    wrt: semaphore  ; control entry to a writer or first reader
    readcount: integer      ; number of readers

write process:
    wait(wrt)       ; any writers or readers?
      <perform write operation>
    signal(wrt)     ; allow others

read process:
    wait(mutex)     ; ensure exclusion
        readcount = readcount + 1 ; one more reader
        if readcount = 1 then wait(wrt) ; if we're the first, synch with writers
    signal(mutex)
        <perform reading>
    wait(mutex)     ; ensure exclusion
        readcount = readcount - 1 ; one fewer reader
        if readcount = 0 then signal(wrt) ; no more readers, allow a writer
    signal(mutex)
```


Readers/Writers notes

- Note:
  - the first reader blocks if there is a writer
    - any other readers will then block on mutex
  - if a writer exists, last reader to exit signals waiting writer
    - can new readers get in while writer is waiting?
  - when writer exits, if there is both a reader and writer waiting, which one goes next is up to scheduler

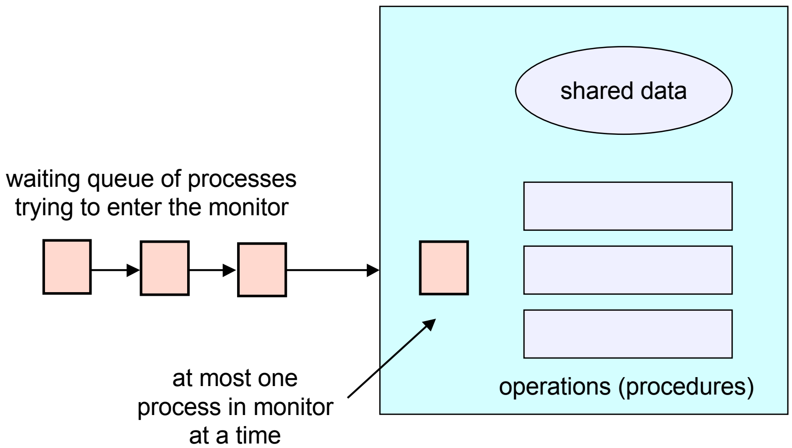
Problems with Semaphores

- They can be used to solve any of the traditional synchronization problems, but:
  - semaphores 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
  - used for both critical sections (mutual exclusion) and for coordination (scheduling)
  - no control over their use, no guarantee of proper usage
- Thus, they are prone to bugs
  - another (better?) approach: use programming language support

Monitors

- A programming language construct that supports controlled access to shared data
  - synchronization code added by compiler, enforced at runtime
  - why does this help?
- Monitor is a software module that encapsulates:
  - shared data structures
  - procedures that operate on the shared data
  - synchronization between concurrent processes that invoke those procedures
- Monitor protects the data from unstructured access
  - guarantees only access data through procedures, hence in legitimate ways

A monitor



Monitor facilities

- Mutual exclusion
  - only one process can be executing inside at any time
    - thus, synchronization implicitly associated with monitor
  - if a second process tries to enter a monitor procedure, it blocks until the first has left the monitor
    - more restrictive than semaphores!
    - but easier to use most of the time
- Once inside, a process may discover it can't continue, and may wish to sleep
  - or, allow some other waiting process to continue
  - condition variables provided within monitor
    - processes can wait or signal others to continue
    - condition variable can only be accessed from inside monitor

Condition Variables

- A place to wait; sometimes called a rendezvous point
- Three operations on condition variables
  - wait(c)
    - release monitor lock, so somebody else can get in
    - wait for somebody else to signal condition
    - thus, condition variables have wait queues
  - signal(c)
    - wake up at most one waiting process/thread
    - if no waiting processes, signal is lost
    - this is different than semaphores: no history!
  - broadcast(c)
    - wake up all waiting processes/threads

Bounded Buffer using Monitors

```
Monitor bounded_buffer {
  buffer resources[N];
  condition not_full, not_empty;

  procedure add_entry(resource x) {
    while(array “resources” is full)
      wait(not_full);
    add “x” to array “resources”
    signal(not_empty);
  }
  procedure get_entry(resource *x) {
    while (array “resources” is empty)
      wait(not_empty);
    *x = get resource from array “resources”
    signal(not_full);
  }
```

Two Kinds of Monitors

- Hoare monitors: signal(c) means
  - run waiter immediately
  - signaller blocks immediately
    - condition guaranteed to hold when waiter runs
    - but, signaller must restore monitor invariants before signalling!
- Mesa monitors: signal(c) means
  - waiter is made ready, but the signaller continues
    - waiter runs when signaller leaves monitor (or waits)
    - condition is not necessarily true when waiter runs again
  - signaller need not restore invariant until it leaves the monitor
  - being woken up is only a hint that something has changed
    - must recheck conditional case

Examples

- Hoare monitors
  - if (notReady)
    - wait(c)
- Mesa monitors
  - while(notReady)
    - wait(c)

- Mesa monitors easier to use
  - more efficient
  - fewer switches
  - directly supports broadcast
- Hoare monitors leave less to chance
  - when wake up, condition guaranteed to be what you expect

Condition Variables and Mutex

- Yet another construct:
  - condition variables can be used with mutexes

```
pthread_mutex_t mu;
pthread_cond_t co;
boolean ready;
void foo( ) {
 pthread_mutex_lock(&mu);
 if (!ready)
   pthread_cond_wait(&co, &mu);
 …
 ready = TRUE;
 pthread_cond_signal(&co);  // unlock and signal atomically
 pthread_mutex_unlock(&mu);
}
```

- Think of a monitor as a language feature
  - under the covers, compiler knows about monitors
  - compiler inserts a mutex to control entry and exit of processes to the monitor's procedures