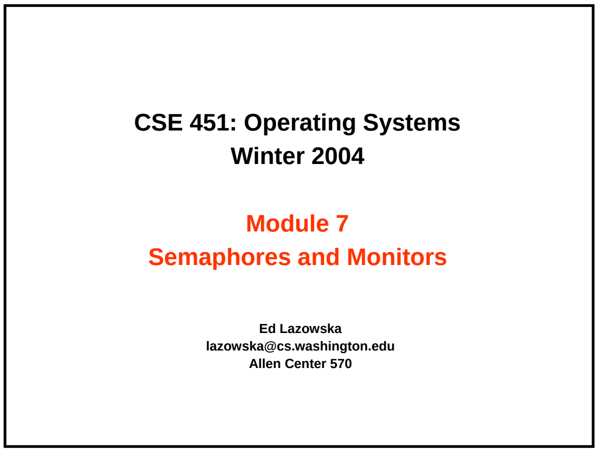
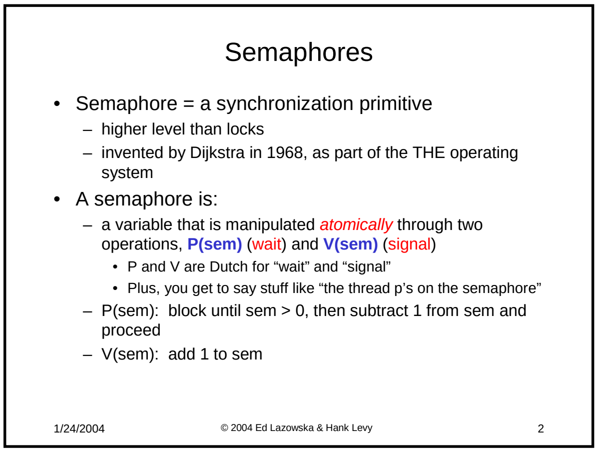


CSE 451: Operating Systems
Winter 2004

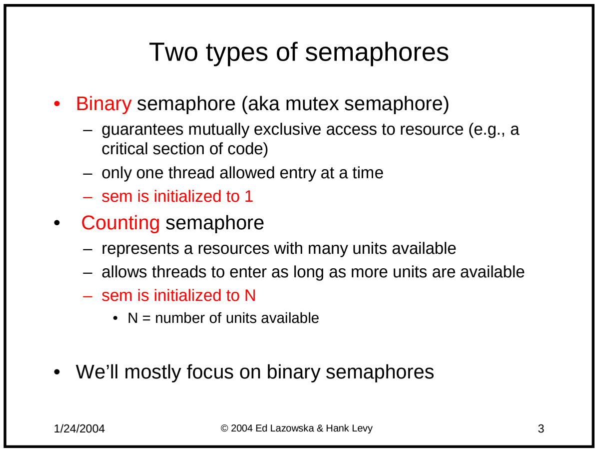
Module 7
Semaphores and Monitors

Ed Lazowska
lazowska@cs.washington.edu
Allen Center 570



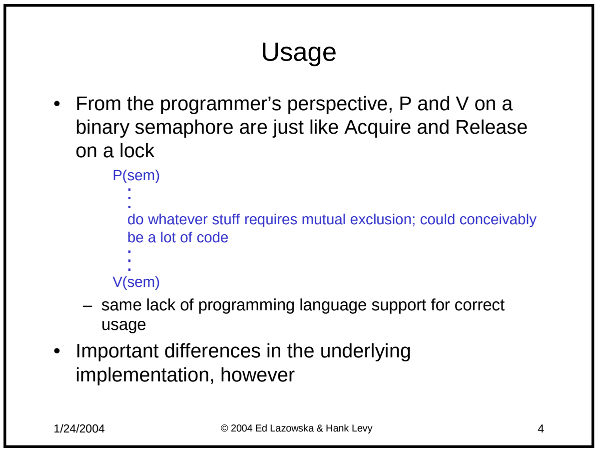
Semaphores

- Semaphore = a synchronization primitive
  - higher level than locks
  - invented by Dijkstra in 1968, as part of the THE operating system
- A semaphore is:
  - a variable that is manipulated *atomically* through two operations, **P(sem)** (wait) and **V(sem)** (signal)
    - P and V are Dutch for “wait” and “signal”
    - Plus, you get to say stuff like “the thread p’s on the semaphore”
  - P(sem): block until sem > 0, then subtract 1 from sem and proceed
  - V(sem): add 1 to sem



Two types of semaphores

- Binary semaphore (aka mutex semaphore)
  - guarantees mutually exclusive access to resource (e.g., a critical section of code)
  - only one thread allowed entry at a time
  - sem is initialized to 1
- Counting semaphore
  - represents a resources with many units available
  - allows threads to enter as long as more units are available
  - sem is initialized to N
    - N = number of units available
- We’ll mostly focus on binary semaphores

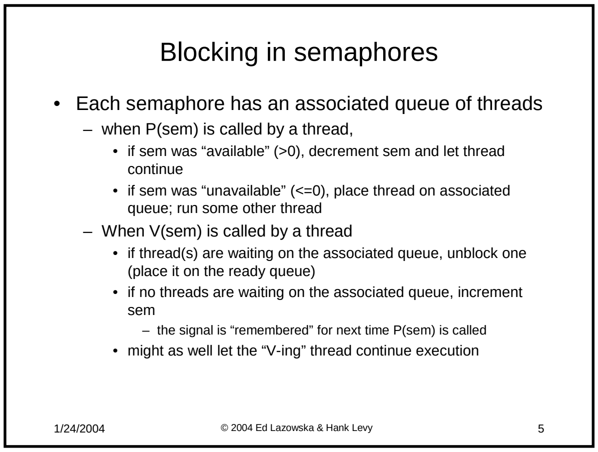


Usage

- From the programmer’s perspective, P and V on a binary semaphore are just like Acquire and Release on a lock

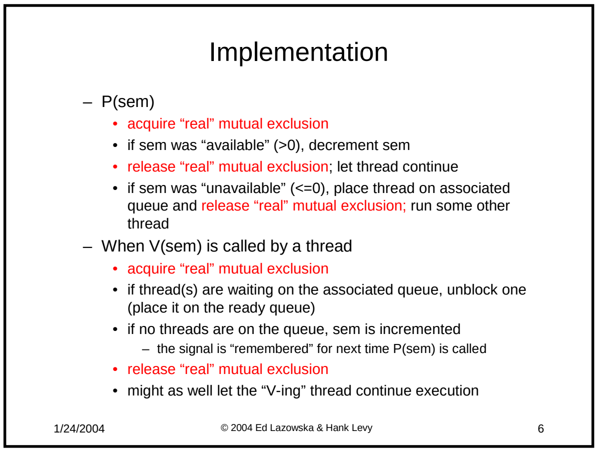
```
P(sem)
   :
   do whatever stuff requires mutual exclusion; could conceivably
   be a lot of code
   :
V(sem)
```

  - same lack of programming language support for correct usage
- Important differences in the underlying implementation, however



Blocking in semaphores

- Each semaphore has an associated queue of threads
  - when P(sem) is called by a thread,
    - if sem was “available” (>0), decrement sem and let thread continue
    - if sem was “unavailable” (<=0), place thread on associated queue; run some other thread
  - When V(sem) is called by a thread
    - if thread(s) are waiting on the associated queue, unblock one (place it on the ready queue)
    - if no threads are waiting on the associated queue, increment sem
      - the signal is “remembered” for next time P(sem) is called
    - might as well let the “V-ing” thread continue execution



Implementation

- P(sem)
  - acquire “real” mutual exclusion
  - if sem was “available” (>0), decrement sem
  - release “real” mutual exclusion; let thread continue
  - if sem was “unavailable” (<=0), place thread on associated queue and release “real” mutual exclusion; run some other thread
- When V(sem) is called by a thread
  - acquire “real” mutual exclusion
  - if thread(s) are waiting on the associated queue, unblock one (place it on the ready queue)
  - if no threads are on the queue, sem is incremented
    - the signal is “remembered” for next time P(sem) is called
  - release “real” mutual exclusion
  - might as well let the “V-ing” thread continue execution

Pressing questions

- How do you acquire “real” mutual exclusion?
- Why is this any better than using a spinlock (test-and-set) or disabling interrupts (assuming you’re in the kernel) in lieu of a semaphore?
- What if some bozo issues an extra V?
- What if some bozo forgets to P?

Example: Bounded buffer problem

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

Bounded buffer using semaphores (both binary and counting)

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

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

Note 1: I have spared you a repeat of the clip-art!

Note 2: I have elided all the code concerning which is the first full buffer, which is the last full buffer, etc.

Note 3: Try to figure out how to do this without using counting semaphores!

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
    clear: semaphore        ; control entry for a writer or first reader
    readcount: integer      ; number of active readers

writer:
    P(clear)                ; any writers or readers?
        <perform write operation>
    V(clear)                ; allow others

reader:
    P(mutex)                ; ensure exclusion
        readcount = readcount + 1     ; one more reader
        if readcount = 1 then P(clear)  ; if we’re the first, synch with writers
    V(mutex)
        <perform reading>
    P(mutex)                ; ensure exclusion
        readcount = readcount – 1     ; one fewer reader
        if readcount = 0 then V(clear) ; no more readers, allow a writer
    V(mutex)
```

Readers/Writers notes

- Note:
  - the first reader blocks if there is a writer
    - any other readers will then block on mutex
  - if a waiting 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

Semaphores vs. locks

- Threads that are blocked at the level of program logic are placed on queues, rather than busy-waiting
- Busy-waiting is used for the “real” mutual exclusion required to implement P and V, but these are very short critical sections – totally independent of program logic
- In the not-very-interesting case of a thread package implemented in an address space “powered by” only a single kernel thread, it’s even easier that this

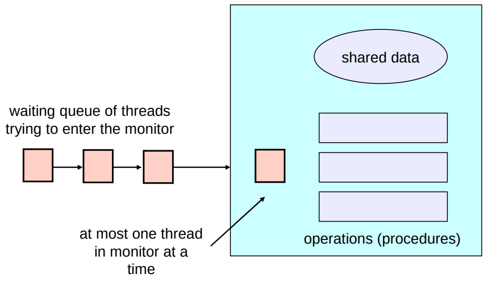
Problems with semaphores

- 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
  - – a 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 threads that invoke those procedures
- Monitor protects the data from unstructured access
  - – guarantees data can only be accessed through procedures, hence in legitimate ways

A monitor



Monitor facilities

- Mutual exclusion
  - – only one thread can be executing inside at any time
    - thus, synchronization implicitly associated with monitor
  - – if a second thread tries to execute a monitor procedure, it blocks until the first has left the monitor
- Once inside, a thread may discover it can’t continue, and may wish to sleep
  - – or, allow some other waiting process to continue
  - – condition variables provided within monitor
    - threads can wait, or can signal others to continue
    - condition variables can only be accessed from within monitor
    - a thread that waits “steps outside” the monitor
    - what happens to a thread that signals depends on the precise monitor semantics that are used

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 associated wait queues
  - – signal(c)
    - wake up at most one waiting thread
    - if no waiting threads, signal is lost
      - – this is different than semaphores: no history!
  - – broadcast(c)
    - wake up all waiting 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);
    insert “x” in 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
      - can use “if” rather than “while” in previous example
    - 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
      - must use “while” as in previous example
  - 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

Hoare vs. Mesa

- 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

A monitor is a language feature

- Language supports monitors
- Compiler understands them
  - compiler inserts calls to runtime routines for
    - monitor entry
    - monitor exit
    - signal
    - wait
- Runtime system implements these routines
  - moves threads on and off queues
  - *ensures mutual exclusion!*