Threading and Synchronization

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Parallelism

- Parallelism and Pseudo-parallelism
- Why parallelize?
- Finding parallelism
  - Advantages: better load balancing, better scalability
  - Disadvantages: process/thread overhead and communication

Parrallelism – Cont'd

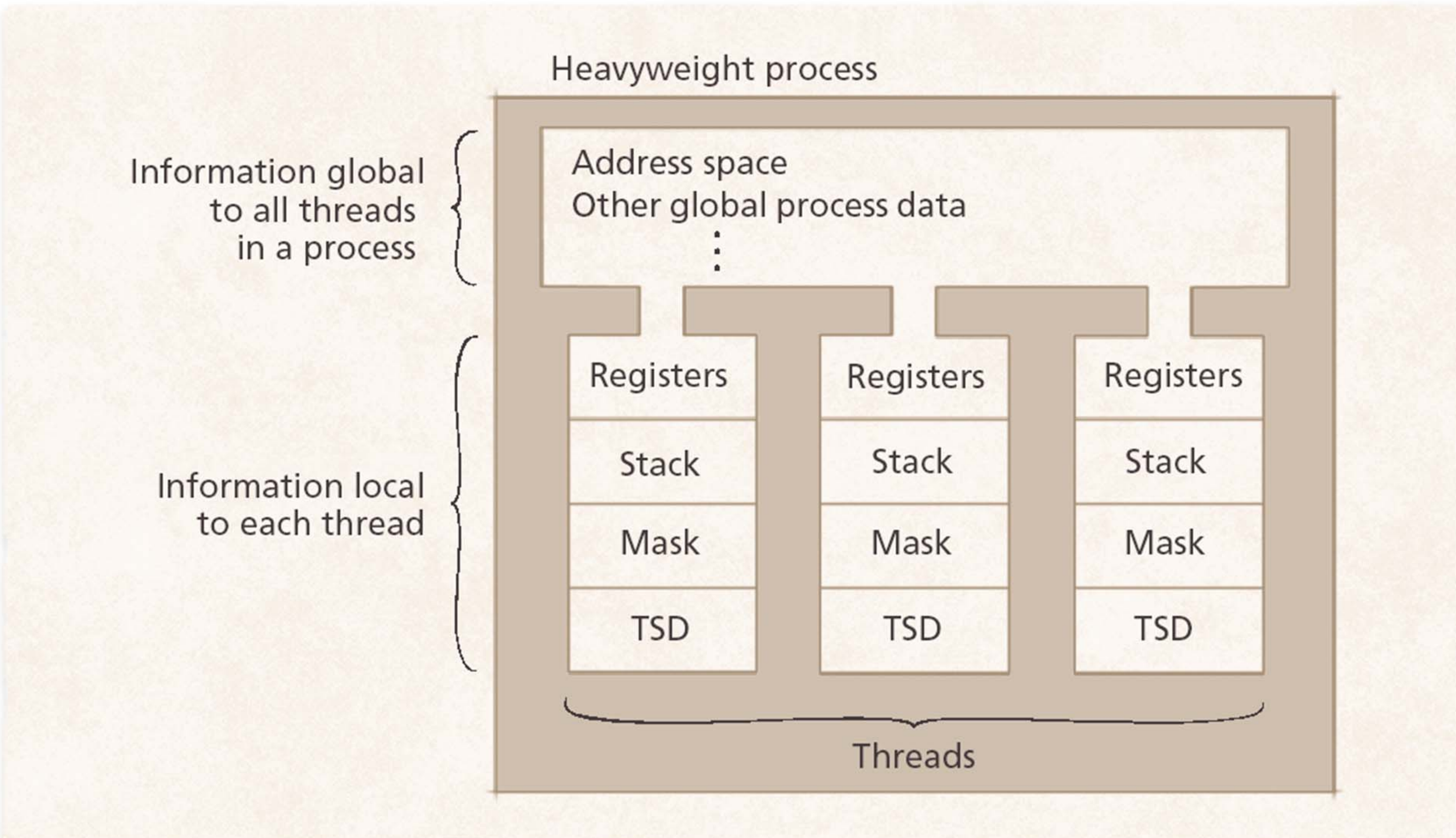
- distribute computation and data
  - Assign which processor does which computation
  - If memory is distributed, decide which processor stores which data (why is this?)
    - Data can be replicated also
  - Goals: minimize communication and balance the computational workload
    - Often conflicting goals

Parallelism – Cont'd

- synchronize and/or communicate
  - If shared-memory machine, synchronize
    - Both mutual exclusion and sequence control
      - Locks, semaphores, condition variables, barriers, reductions
  - If distributed-memory machine, communicate
    - Message passing
    - Usually communication involves implicit synchronization

Definition of Thread

- Thread
  - Lightweight process (LWP)
  - Threads of instructions or thread of control
  - Shares address space and other global information with its process
  - Registers, stack, signal masks and other thread-specific data are local to each thread
- Threads may be managed by the operating system or by a user application
- Examples: Win32 threads, C-threads, Pthreads


Heavyweight process
Information global to all threads in a process
Address space
Other global process data
Information local to each thread
Registers
Stack
Mask
TSD
Registers
Stack
Mask
TSD
Registers
Stack
Mask
TSD
Threads

- Threads have become prominent due to trends in
  - Software design
    - More naturally expresses inherently parallel tasks
  - Performance
    - Scales better to multiprocessor systems
  - Cooperation
    - Shared address space incurs less overhead than IPC

- Thread states
  - *Born* state
  - *Ready* state (*runnable* state)
  - *Running* state
  - *Dead* state
  - *Blocked* state
  - *Waiting* state
  - *Sleeping* state
    - Sleep interval specifies for how long a thread will sleep

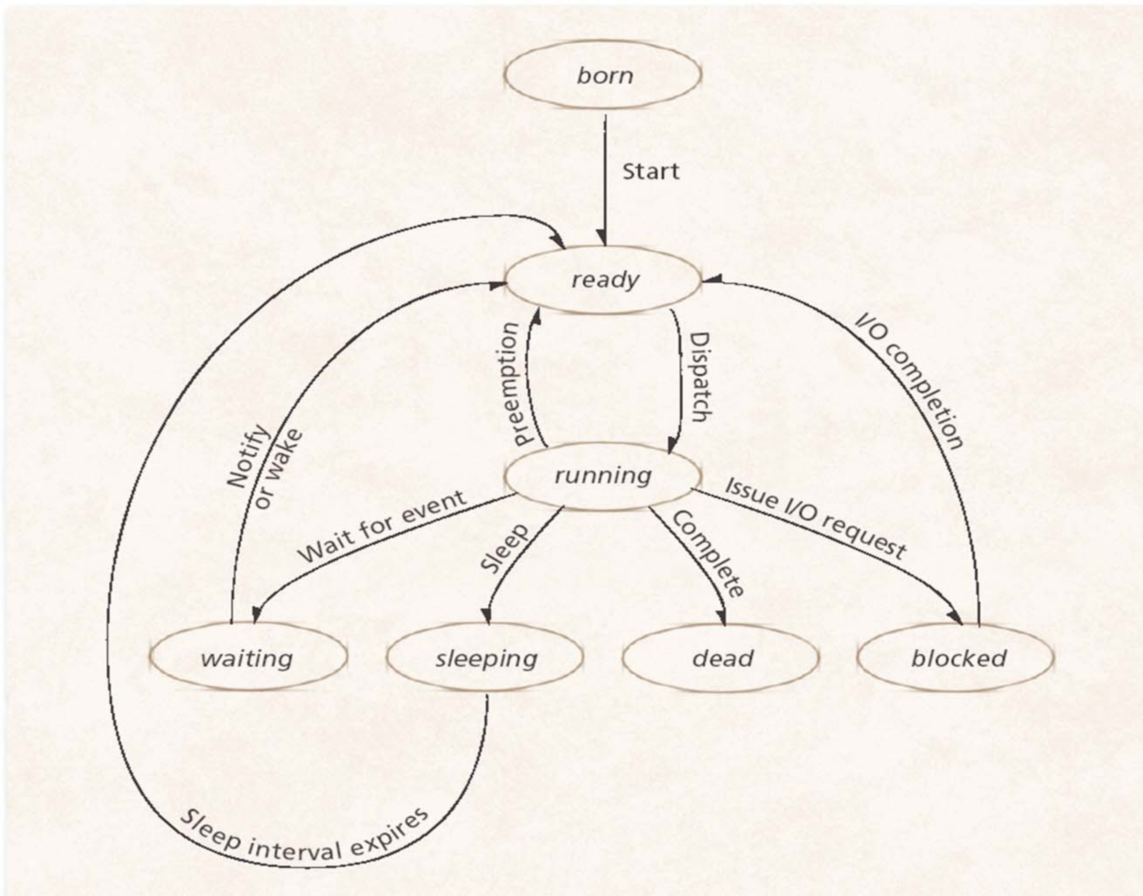
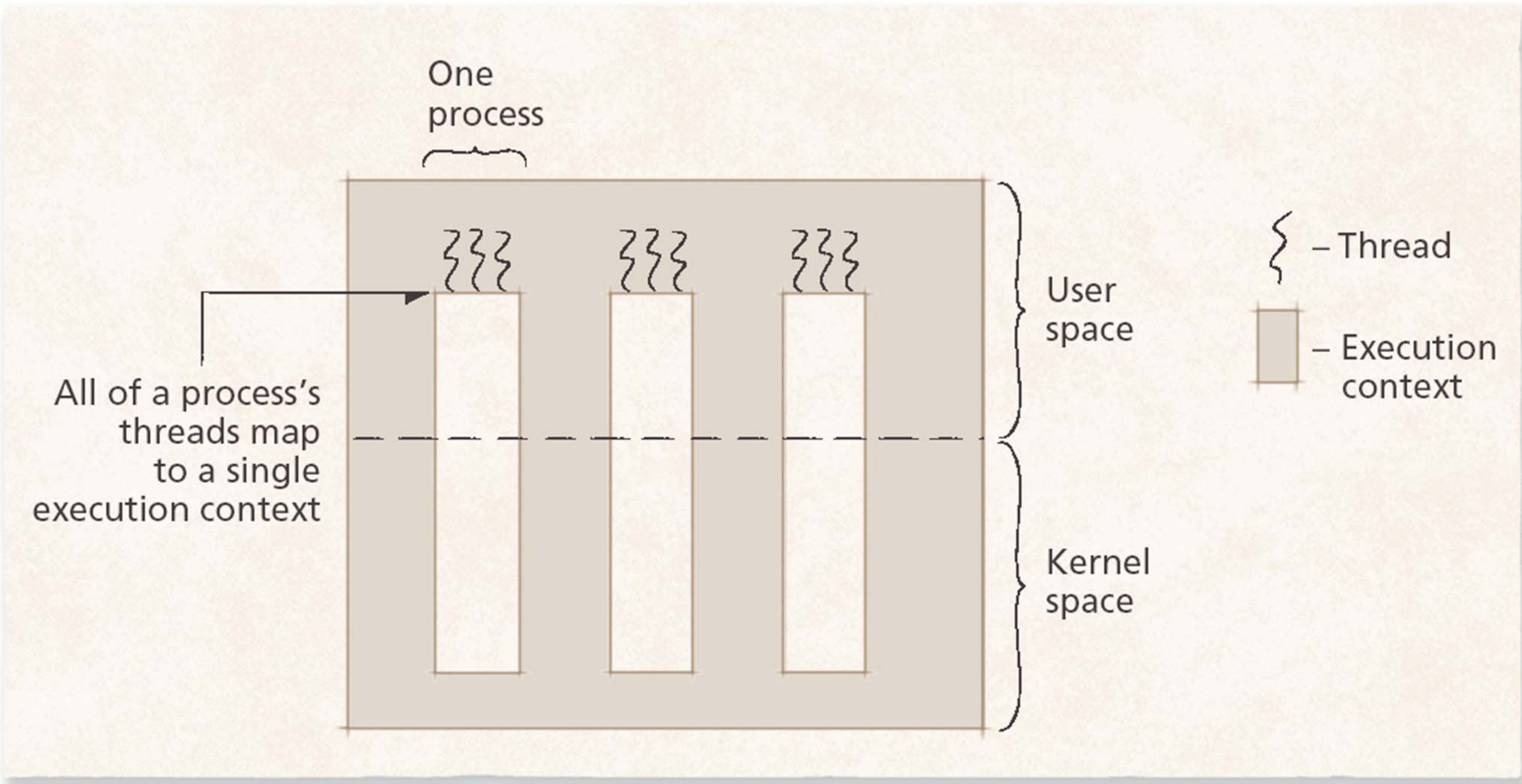

born
Start
ready
Preemption
Dispatch
I/O completion
Notify
or wake
running
Wait for event
Sleep
Complete
Issue I/O request
waiting
sleeping
dead
blocked
Sleep interval expires

Figure 4.3 User-level threads.



- User-level threads perform threading operations in user space
  - Threads are created by runtime libraries that cannot execute privileged instructions or access kernel primitives directly
- User-level thread implementation
  - Many-to-one thread mappings
    - Operating system maps all threads in a multithreaded process to single execution context
    - Advantages
      - User-level libraries can schedule its threads to optimize performance
      - Synchronization performed outside kernel, avoids context switches
      - More portable
    - Disadvantage
      - Kernel views a multithreaded process as a single thread of control
        - » Can lead to suboptimal performance if a thread issues I/O
        - » Cannot be scheduled on multiple processors at once

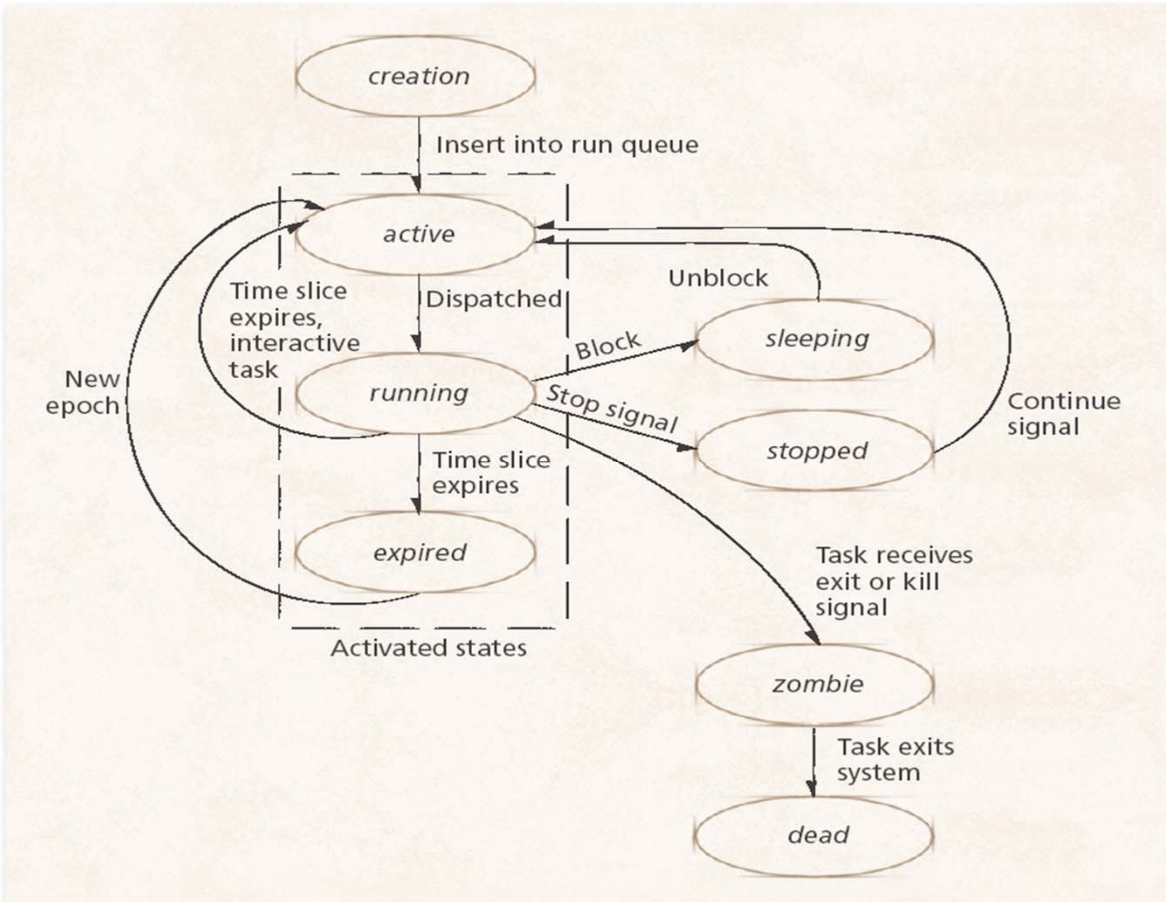
Thread Signal Delivery

- Two types of signals
  - Synchronous:
    - Occur as a direct result of program execution
    - Should be delivered to currently executing thread
  - Asynchronous
    - Occur due to an event typically unrelated to the current instruction
    - Threading library must determine each signal’s recipient so that asynchronous signals are delivered properly
- Each thread is usually associated with a set of pending signals that are delivered when it executes
- Thread can mask all signals except those that it wishes to receive

Thread Termination

- Thread termination (cancellation)
  - Differs between thread implementations
  - Prematurely terminating a thread can cause subtle errors in processes because multiple threads share the same address space
  - Some thread implementations allow a thread to determine when it can be terminated to prevent process from entering inconsistent state

Linux task state-transition diagram.



Example Concurrent Program

(x is shared, initially 0)

- code for Thread 0

  foo( )

  x := x+1

- code for Thread 1

  bar( )

  x := x+2

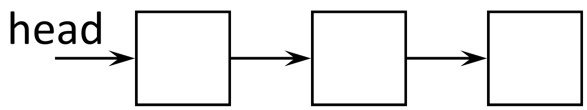
Assume both threads execute at about the same time.

What's the output?

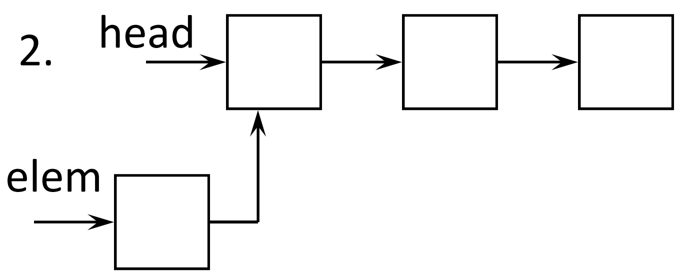
Example Concurrent Program (cont.)

- One possible execution order is:
  - Thread 0: R1 := x (R1 == 0)
  - Thread 1: R2 := x (R2 == 0)
  - Thread 1: R2 := R2 + 2 (R2 == 2)
  - Thread 1: x := R2 (x == 2)
  - Thread 0: R1 := R1 + 1 (R1 == 1)
  - Thread 0: x := R1 (x == 1)
- Final value of x is 1 (!!)
- Question: what if Thread 1 also uses R1?

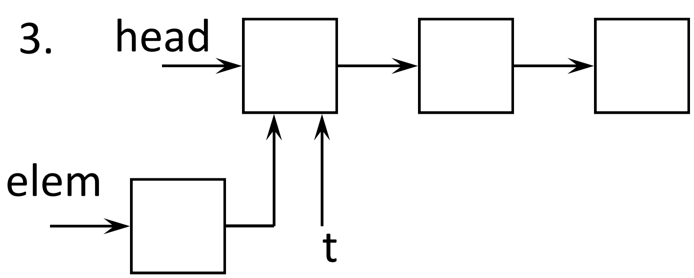
Example Execution

1. 

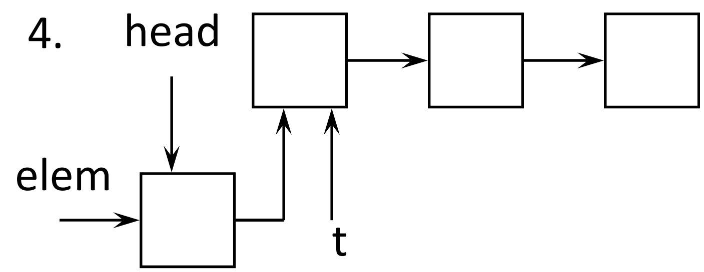
Insert: elem->next := head;

2. 

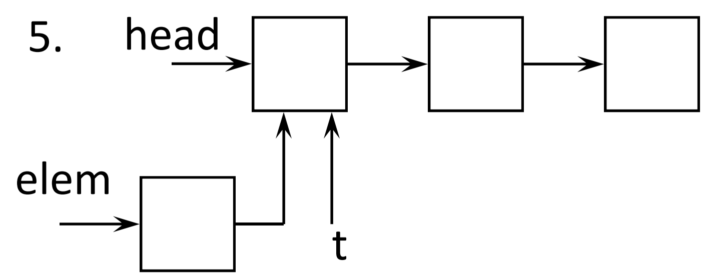
Delete: t := head;

3. 

Insert: head := elem;

4. 

Delete: head := head->next;

5. 

Delete: return t;

Some Definitions

- Race condition
  - when output depends on ordering of thread execution
  - more formally:
    - (1) two or more threads access a shared variable with no synchronization, and
    - (2) at least one of the threads writes to the variable

More Definitions

- Atomic Operation
  - an operation that, once started, runs to completion
    - **note: more precisely, logically runs to completion**
  - indivisible
  - in this class: loads and stores
    - meaning: if thread A stores “1” into variable x and thread B stores “2” into variable x about about the same time, result is either “1” or “2”
  - <await (B) S>
    - atomically (evaluate B, wait until true, execute S)

Critical Section

- section of code that:
  - must be executed by one thread at a time
  - if more than one thread executes at a time, have a race condition
  - ex: linked list from before
    - Insert/Delete code forms a critical section
    - What about just the Insert *or* Delete code?
      - is that enough, or do both procedures belong in a single critical section?

Critical Section (CS) Problem

- Provide entry and exit routines:
  - all threads must call entry before executing CS
  - all threads must call exit after executing CS
  - thread must not leave entry routine until it's safe
- CS solution properties
  - Mutual exclusion: at most one thread is executing CS
  - Absence of deadlock: two or more threads trying to get into CS => at least one succeeds
  - Absence of uneccessary delay: if only one thread trying to get into CS, it succeeds
  - Eventual entry: thread eventually gets into CS

Structure of threads for Critical Section problem

Threads do the following:

```
while (1) {
   do other stuff (non-critical section)
   call enter
   execute CS
   call exit
   do other stuff (non-critical section)
}
```

Critical Section Assumptions

- Threads must call enter and exit
- Threads must not die or quit inside a critical section
- Threads **can** be context switched inside a critical section
  - this does **not** mean that the newly running thread may enter the critical section

Hardware Support

- Provide instruction that is:
  - atomic
  - fairly easy for hardware designer to implement
- Read/Modify/Write
  - atomically read value from memory, modify it in some way, write it back to memory
- Use to develop simpler critical section solution for any number of threads

Test-and-Set

Many machines have it

```
function TS(var target: bool) returns bool
    var b: bool := target;  /* return old value */
    target := true;
    return b;
```

Executes atomically

Basic Idea with Atomic Instructions

- Each thread has a local flag
- One variable shared by all threads
- Use the atomic instruction with flag, shared variable
  - on a change, allow thread to go in
  - other threads will not see this change
- When done with CS, set shared var back to initial state

Problems with busy-waiting CS solution

- Complicated
- Inefficient
  - consumes CPU cycles while spinning
- Priority inversion problem
  - low priority thread in CS, high priority thread spinning can end up causing deadlock
  - example: Mars Pathfinder problem

Want to block when waiting for CS

Locks

- Two operations:
  - Acquire (get it, if can’t go to sleep)
  - Release (give it up, possibly wake up a waiter)
- entry( ) is then just Acquire(lock)
- exit( ) is just Release(lock)

Lock is shared among all threads

Problems with Locks

- Not general
  - only solve simple critical section problem
  - can’t do any more general synchronization
  - often must enforce strict orderings betw. threads
- Condition synchronization
  - need to wait until some condition is true
  - example: bounded buffer (next slide)
  - example: thread join

Semaphores (Dijkstra)

- Semaphore is an object
  - contains a (private) value and 2 operations
- **Semaphore value must be nonnegative**
- P operation (atomic):
  - if value is 0, block; else decrement value by 1
- V operation (atomic):
  - if thread blocked, wake up; else value++
- Semaphores are “resource counters”

Critical Sections with Semaphores

sem mutex := 1

entry( )

– P(mutex)

exit( )

– V(mutex)

- Semaphores more powerful than locks
- For mutual exclusion, initialize semaphore to 1

Bounded Buffer (1 producer, 1 consumer)

char buf[n], int front := 0, rear := 0

sem empty := n, full := 0

Producer( )

```
do forever...
produce message m
P(empty)
buf[rear] := m;
rear := rear "+" 1
V(full)
```

Consumer()

```
do forever...
P(full)
m := buf[front]
front := front "+" 1
V(empty)
consume m
```

Bounded Buffer (multiple producers and consumers)

char buf[n], int front := 0, rear := 0

sem empty := n, full := 0, mutexC := 1, mutexP := 1

Producer( )

```
do forever...
 produce message m
 P(empty); P(mutexP)
 buf[rear] := m;
 rear := rear "+" 1
 V(mutexP); V(full)
```

Consumer()

```
do forever...
 P(full); P(mutexC)
 m := buf[front]
 front := front "+" 1
 V(mutexC); V(empty)
consume m
```

Scratching the surface

- Readers/Writers
- Barriers
- Monitors
- Fairness/Enforcing ordering