

## Concurrency

- On multiprocessors, several threads can execute simultaneously, one on each processor.
- On uniprocessors, only one thread executes at a time. However, because of preemption and timesharing, threads appear to run concurrently.

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Concurrency and synchronization are important even on uniprocessors.

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## Thread Synchronization

- Concurrent threads can interact with each other in a variety of ways:
  - Threads share access (through the operating system) to system devices.
  - Threads in the same process share access to program variables in their process's address space.
- A common synchronization problem is to enforce *mutual exclusion*, which means making sure that only one thread at a time uses a shared object, e.g., a variable or a device.
- The part of a program in which the shared object is accessed is called a *critical section*.

## Critical Section Example (Part 1)

```
int IntList::RemoveFront() {
    ListElement *element = first;
    ASSERT(!IsEmpty());
    int num = first->item;
    if (first == last) { first = last = NULL; }
    else { first = element->next; }
    numInList--;
    delete element;
    return num;
}
```

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The RemoveFront method is a critical section. It may not work properly if two threads call it at the same time on the same IntList. (Why?)

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## Critical Section Example (Part 2)

```
void IntList::Append(int item) {
    ListElement *element = new ListElement(item);
    ASSERT(!IsInList(item));
    if (IsEmpty()) {
        first = element; last = element;
    } else {
        last->next = element; last = element;
    }
    numInList++;
}
```

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The Append method is part of the same critical section as RemoveFront. It may not work properly if two threads call it at the same time, or if a thread calls it while another has called RemoveFront

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## Peterson's Mutual Exclusion Algorithm

```
boolean flag[2]; /* shared, initially false */
int turn;        /* shared */

flag[i] = true; /* in one process, i = 0 and j = 1 */
turn = j;       /* in the other, i = 1 and j = 0 */
while (flag[j] && turn == j) { } /* busy wait */

    critical section /* e.g., call to RemoveFront */

flag[i] = false;
```

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Ensures mutual exclusion and avoids starvation, but works only for two processes. (Why?)

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## Mutual Exclusion Using Special Instructions

- Software solutions to the critical section problem (e.g., Peterson's algorithm) assume only atomic load and atomic store.
- Simpler algorithms are possible if more complex *atomic* operations are supported by the hardware. For example:
  - Test and Set:** set the value of a variable, and return the old value
  - Swap:** swap the values of two variables
- On uniprocessors, mutual exclusion can also be achieved by disabling interrupts during the critical section. (Normally, user programs cannot do this, but the kernel can.)

## Mutual Exclusion with Test and Set

```
boolean lock; /* shared, initially false */  
  
while (TestAndSet(&lock,true)) { } /* busy wait */  
  
    critical section /* e.g., call to RemoveFront */  
  
lock = false;
```

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Works for any number of threads, but starvation is a possibility.

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## Semaphores

- A semaphore is a synchronization primitive that can be used to solve the critical section problem, and many other synchronization problems too
- A semaphore is an object that has an integer value, and that supports two operations:
  - P:** if the semaphore value is greater than 0, decrement the value. Otherwise, wait until the value is greater than 0 and then decrement it.
  - V:** increment the value of the semaphore
- Two kinds of semaphores:
  - counting semaphores:** can take on any non-negative value
  - binary semaphores:** take on only the values 0 and 1. (V on a binary semaphore with value 1 has no effect.)

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By definition, the P and V operations of a semaphore are *atomic*.

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## Mutual Exclusion Using a Binary Semaphore

```
binarySemaphore s; /* initial value is 1 */  
  
P(s);  
  
    critical section /* e.g., call to RemoveFront */  
  
V(s);
```

## Producer/Consumer Using a Counting Semaphore

```
countingSemaphore s; /* initial value is 0 */  
item buffer[infinite]; /* huge buffer, initially empty */
```

Producer's Pseudo-code:

```
add item to buffer  
V(s);
```

Consumer's Pseudo-code:

```
P(s);  
remove item from buffer
```

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If mutual exclusion is required for adding and removing items from the buffer, this can be provided using a second semaphore. (How?)

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## Producer/Consumer with a Bounded Buffer

```
countingSemaphore full;    /* initial value is 0 */
countingSemaphore empty;  /* initial value is N */
item buffer[N];           /* buffer with capacity N */
```

Producer's Pseudo-code:

```
P(empty);
  add item to buffer
V(full);
```

Consumer's Pseudo-code:

```
P(full);
  remove item from buffer
V(empty);
```

## Implementing Semaphores

```
void P(s) {  
    start critical section  
    while (s == 0) { /* busy wait */  
        end critical section  
        start critical section }  
    s = s - 1;  
    end critical section }  
  
void V(s) {  
    start critical section  
    s = s + 1;  
    end critical section }
```

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Any mutual exclusion technique can be used to protect the critical sections. However, starvation is possible with this implementation.

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## Implementing Semaphores in the Kernel

- Semaphores can be implemented at user level, e.g., as part of a user-level thread library.
- Semaphores can also be implemented by the kernel:
  - for its own use, for synchronizing threads in the kernel
  - for use by application programs, if a semaphore system call interface is provided
- As an optimization, semaphores can be integrated with the thread scheduler (easy to do for semaphores implemented in the kernel):
  - threads can be made to block, rather than busy wait, in the P operation
  - the V operation can make blocked threads ready

## Nachos Semaphore Class

```
class Semaphore {
    public:
        Semaphore(char* debugName, int initialValue);
        ~Semaphore();
        char* getName() { return name;}
        void P();
        void V();
        void SelfTest();
    private:
        char* name;    // useful for debugging
        int value;    // semaphore value, always >= 0
        List<Thread *> *queue;
};
```

## Nachos Semaphore P()

```
void Semaphore::P() {
    Interrupt *interrupt = kernel->interrupt;
    Thread *currentThread = kernel->currentThread;
    IntStatus oldLevel = interrupt->SetLevel(IntOff);
    if(value <= 0) {
        queue->Append(currentThread);
        currentThread->Sleep(FALSE);
    } else { value--; }
    (void) interrupt->SetLevel(oldLevel);
}
```

## Nachos Semaphore V()

```
void Semaphore::V() {
    Interrupt *interrupt = kernel->interrupt;
    IntStatus oldLevel = interrupt->SetLevel(IntOff);
    if (!queue->IsEmpty()) {
        kernel->scheduler->ReadyToRun(queue->RemoveFront());
    } else { value++; }
    (void) interrupt->SetLevel(oldLevel);
}
```



## Monitors

- a monitor is a programming language construct that supports synchronized access to data
- a monitor is essentially an object for which
  - object state is accessible only through the object's methods
  - only one method may be active at a time
- if two threads attempt to execute methods at the same time, one will be blocked until the other finishes
- inside a monitor, so called *condition variables* can be declared and used

## Condition Variable

- a condition variable is an object that support two operations:
  - wait:** causes the calling thread to block, and to release the monitor
  - signal:** if threads are blocked on the signaled condition variable then unblock one of them, otherwise do nothing
- a thread that has been unblocked by *signal* is outside of the monitor and it must wait to re-enter the monitor before proceeding.
- in particular, it must wait for the thread that signalled it

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This describes Mesa-type monitors. There are other types on monitors, notably Hoare monitors, with different semantics for `wait` and `signal`.

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## Bounded Buffer Using a Monitor

```
item buffer[N]; /* buffer with capacity N */
int count; /* initially 0 */
condition notfull, notempty;
```

```
Produce(item) {
    while (count == N) { wait(notfull); }
    add item to buffer
    count = count + 1;
    signal(notempty);
}
```

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Produce is implicitly executed atomically, because it is a monitor method.

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## Bounded Buffer Using a Monitor (cont'd)

```
Consume(item) {  
    while (count == 0) { wait(notempty); }  
    remove item from buffer  
    count = count - 1;  
    signal(notfull);  
}
```

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Consume is implicitly executed atomically, because it is a monitor method. Notice that `while`, rather than `if`, is used in both Produce and Consume. This is important. (Why?)

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## Simulating Monitors with Semaphores and Condition Variables

- Use a single binary semaphore (or Nachos “Lock”) to provide mutual exclusion.
- Each method must start by acquiring the mutex semaphore, and must release it on all return paths.
- Signal only while holding the mutex semaphore.
- Re-check the wait condition after each wait.
- Return only (the values of) variables that are local to the method.

## Producer Implemented with Locks and Condition Variables (Example)

```
item buffer[N]; /* buffer with capacity N */
int count; /* initially 0 */
Condition notfull, notempty;
Lock mutex; /* for mutual exclusion */
Produce(item) {
    mutex.Acquire();
    while (count == N) {
        notfull.Wait(mutex);
    }
    add item to buffer
    count = count + 1;
    notempty.Signal(mutex);
    mutex.Release();
}
```

## Deadlocks

- A simple example. Suppose a machine has 64MB of memory. The following sequence of events occurs.
  1. Process *A* starts, using 30MB of memory.
  2. Process *B* starts, also using 30MB of memory.
  3. Process *A* requests an additional 8MB of memory. The kernel blocks process *A*'s thread, since there is only 4 MB of available memory.
  4. Process *B* requests an additional 5MB of memory. The kernel blocks process *B*'s thread, since there is not enough memory available.

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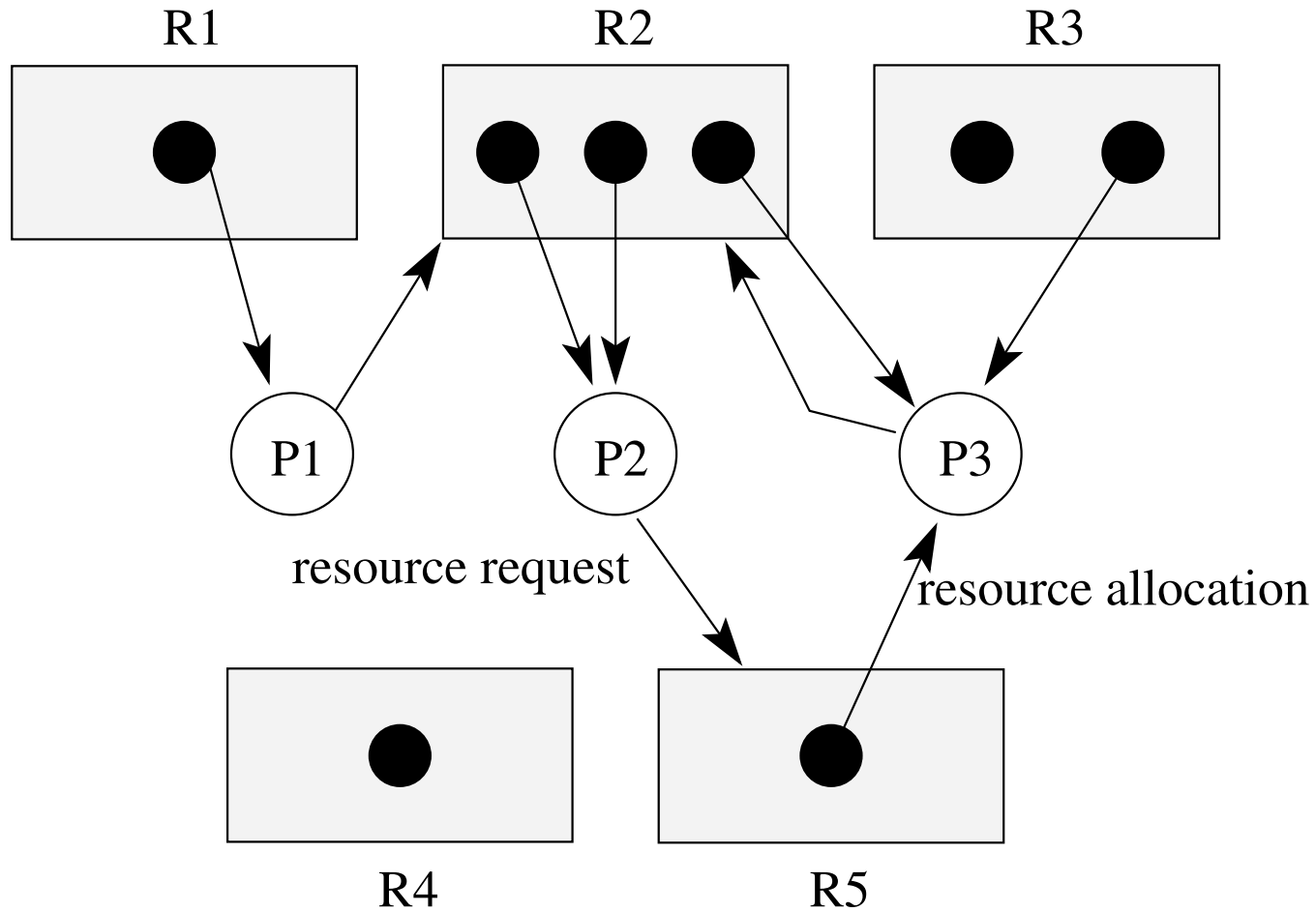
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These two processes are *deadlocked* - neither process can make progress. Waiting will not resolve the deadlock. The processes are permanently stuck.

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## Resource Allocation Graph (Example)



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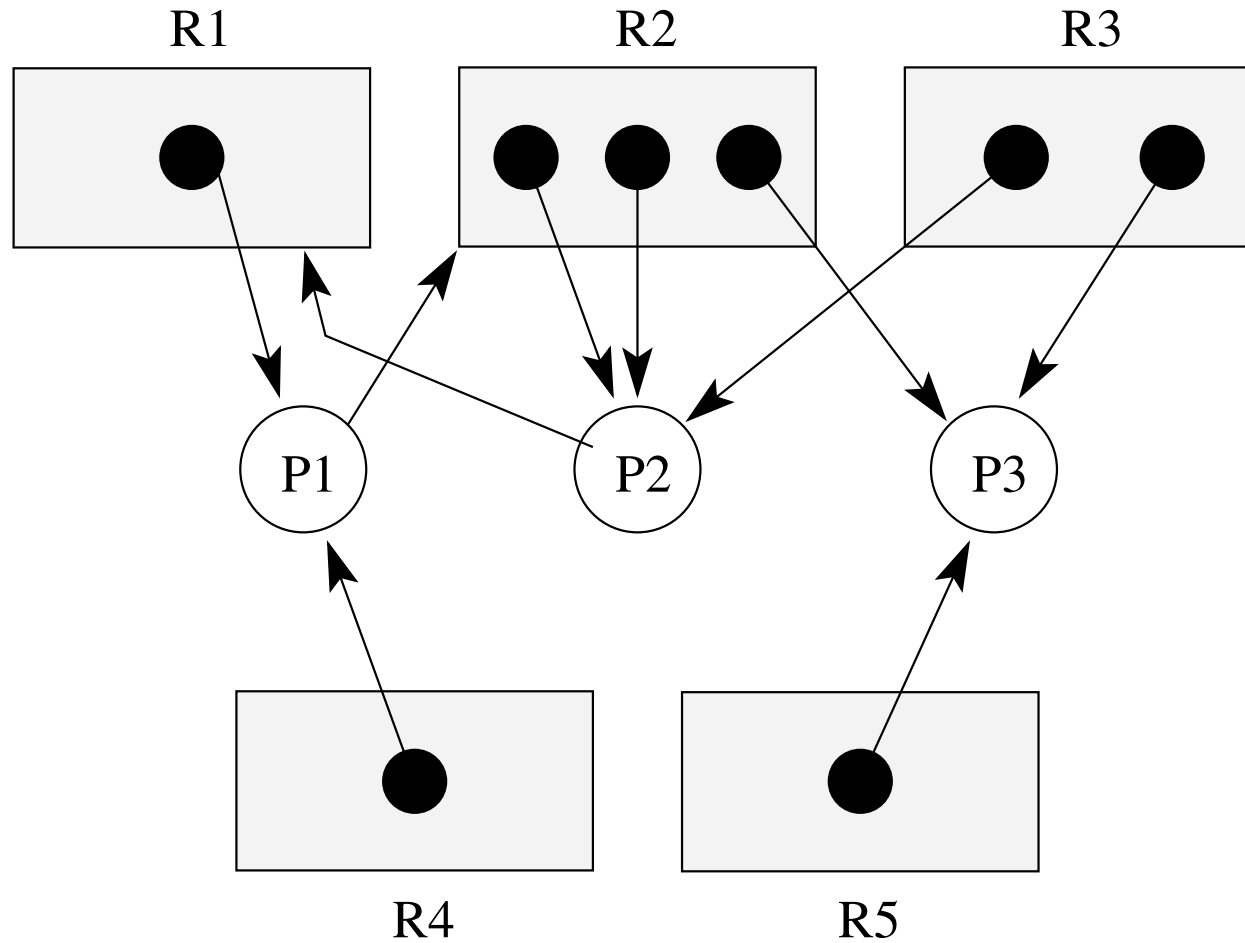
Is there a deadlock in this system?

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## Resource Allocation Graph (Another Example)



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Is there a deadlock in this system?

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## Deadlock Prevention

**No Hold and Wait:** prevent a process from requesting resources if it currently has resources allocated to it. A process may hold several resources, but to do so it must make a single request for all of them.

**Preemption:** take resources away from a process and give them to another (usually not possible). Process is restarted when it can acquire all the resources it needs.

**Resource Ordering:** Order (e.g., number) the resource types, and require that each process acquire resources in increasing resource type order. That is, a process may make no requests for resources of type less than or equal to  $i$  once the process has requested resources of type  $i$ .

## Deadlock Detection and Recovery

- main idea: the system maintains the resource allocation graph and tests it to determine whether there is a deadlock. If there is, the system must recover from the deadlock situation.
- deadlock recovery is usually accomplished by terminating one or more of the processes involved in the deadlock
- when to test for deadlocks? Can test on every blocked resource request, or can simply test periodically. Deadlocks persist, so periodic detection will not “miss” them.

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Deadlock detection and deadlock recovery are both costly. This approach makes sense only if deadlocks are expected to be infrequent.

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## Detecting Deadlock in a Resource Allocation Graph

- System State Notation:
  - $R_i$ : request vector for process  $P_i$
  - $A_i$ : current allocation vector for process  $P_i$
  - $U$ : unallocated (available) resource vector
- Additional Algorithm Notation:
  - $T$ : scratch resource vector
  - $f_i$ : algorithm is finished with process  $P_i$ ? (boolean)

## Detecting Deadlock (cont'd)

```
/* initialization */
T = U
fi is false if Ai > 0, else true
/* can each process finish? */
while ∃ i ( ¬ fi ∧ (Ri ≤ T) ) {
    T = T + Ai;
    fi = true
}
/* if not, there is a deadlock */
if ∃ i ( ¬ fi ) then report deadlock
else report no deadlock
```

## Deadlock Detection, Positive Example

- $R_1 = (0, 1, 0, 0, 0)$
- $R_2 = (0, 0, 0, 0, 1)$
- $R_3 = (0, 1, 0, 0, 0)$
- $A_1 = (1, 0, 0, 0, 0)$
- $A_2 = (0, 2, 0, 0, 0)$
- $A_3 = (0, 1, 1, 0, 1)$
- $U = (0, 0, 1, 1, 0)$

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The deadlock detection algorithm will terminate with  $f_1 == f_2 == f_3 == \text{false}$ , so this system is deadlocked.

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## Deadlock Detection, Negative Example

- $R_1 = (0, 1, 0, 0, 0)$
- $R_2 = (1, 0, 0, 0, 0)$
- $R_3 = (0, 0, 0, 0, 0)$
- $A_1 = (1, 0, 0, 1, 0)$
- $A_2 = (0, 2, 1, 0, 0)$
- $A_3 = (0, 1, 1, 0, 1)$
- $U = (0, 0, 0, 0, 0)$

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This system is not in deadlock. It is possible that the processes will run to completion in the order  $P_3, P_1, P_2$ .

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