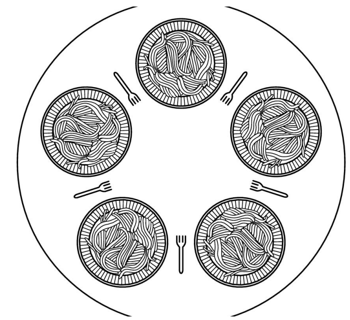
Last Class: Synchronization Problems

- Reader Writer
  - Multiple readers, single writer
  - In practice, use read-write locks
- Dining Philosophers
  - Need to hold multiple resources to perform task

Dining Philosophers

- It's lunch time in the philosophy dept
- Five philosophers, each either eats or thinks
- Share a circular table with five chopsticks
- Thinking: do nothing
- Eating => need two chopsticks, try to pick up two closest chopsticks
  - Block if neighbor has already picked up a chopstick
- After eating, put down both chopsticks and go back to thinking



Dining Philosophers v1

```
Semaphore  chopstick[5];

do{
   wait(chopstick[i]);  // left chopstick
   wait(chopstick[(i+1)%5 ]); // right chopstick
      // eat
   signal(chopstick[i]);  // left chopstick
   signal(chopstick[(i+1)%5 ]); // right chopstick
      // think
   } while(TRUE);
```


Dining Philosophers (semaphores)

```
#define N              5             /* number of philosophers */
#define LEFT           (i+N−1)%N     /* number of i's left neighbor */
#define RIGHT          (i+1)%N       /* number of i's right neighbor */
#define THINKING       0             /* philosopher is thinking */
#define HUNGRY         1             /* philosopher is trying to get forks */
#define EATING         2             /* philosopher is eating */
typedef int semaphore;               /* semaphores are a special kind of int */
int state[N];                        /* array to keep track of everyone's state */
semaphore mutex = 1;                 /* mutual exclusion for critical regions */
semaphore s[N];                      /* one semaphore per philosopher */

void philosopher(int i)              /* i: philosopher number, from 0 to N−1 */
{
    while (TRUE) {                   /* repeat forever */
        think( );                    /* philosopher is thinking */
        take_forks(i);               /* acquire two forks or block */
        eat( );                      /* yum-yum, spaghetti */
        put_forks(i);                /* put both forks back on table */
    }
}
```

Dining Philosophers (contd)

```
void take_forks(int i)          /* i: philosopher number, from 0 to N-1 */
{
    down(&mutex);               /* enter critical region */
    state[i] = HUNGRY;          /* record fact that philosopher i is hungry */
    test(i);                    /* try to acquire 2 forks */
    up(&mutex);                 /* exit critical region */
    down(&s[i]);                /* block if forks were not acquired */
}
void put_forks(i)               /* i: philosopher number, from 0 to N-1 */
{
    down(&mutex);               /* enter critical region */
    state[i] = THINKING;        /* philosopher has finished eating */
    test(LEFT);                 /* see if left neighbor can now eat */
    test(RIGHT);                /* see if right neighbor can now eat */
    up(&mutex);                 /* exit critical region */
}

void test(i)                    /* i: philosopher number, from 0 to N-1 */
{
    if (state[i] == HUNGRY && state[LEFT] != EATING && state[RIGHT] != EATING) {
        state[i] = EATING;
        up(&s[i]);
    }
}
```


Real-world Examples

- Producer-consumer
  - Audio-Video player: network and display threads; shared buffer
  - Web servers: master thread and slave thread
- Reader-writer
  - Banking system: read account balances versus update
- Dining Philosophers
  - Cooperating processes that need to share limited resources
    - Set of processes that need to lock multiple resources
      - Disk and tape (backup),
    - Travel reservation: hotel, airline, car rental databases

Today: Deadlocks

- What are deadlocks?
- Conditions for deadlocks
- Deadlock prevention
- Deadlock detection

Deadlocks

- **Deadlock:** A condition where two or more threads are waiting for an event that can only be generated by these same threads.
- Example:

```
Process A:                  Process B:
printer.Wait();             disk.Wait();
disk.Wait();                printer.Wait();

// copy from disk           // copy from disk
// to printer               // to printer

printer.Signal();           printer.Signal();
disk.Signal();              disk.Signal();
```

Deadlocks: Terminology

- **Deadlock** can occur when several threads compete for a finite number of resources simultaneously
- **Deadlock prevention** algorithms check resource requests and possibly availability to prevent deadlock.
- **Deadlock detection** finds instances of deadlock when threads stop making progress and tries to recover.
- **Starvation** occurs when a thread waits indefinitely for some resource, but other threads are actually using it (making progress).

  => Starvation is a different condition from deadlock

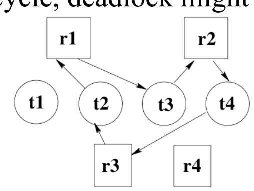
Necessary Conditions for Deadlock

Deadlock can happen if all the following conditions hold.

- **Mutual Exclusion:** at least one thread must hold a resource in non-sharable mode, i.e., the resource may only be used by one thread at a time.
- **Hold and Wait:** at least one thread holds a resource and is waiting for other resource(s) to become available. A different thread holds the resource(s).
- **No Preemption:** A thread can only release a resource voluntarily; another thread or the OS cannot force the thread to release the resource.
- **Circular wait:** A set of waiting threads $\{t_1, ..., t_n\}$ where t_i is waiting on t_{i+1} (i = 1 to n) and t_n is waiting on t_1.

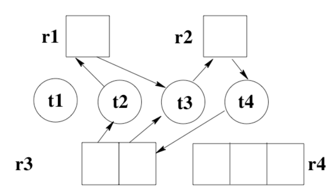
Deadlock Detection Using a Resource Allocation Graph

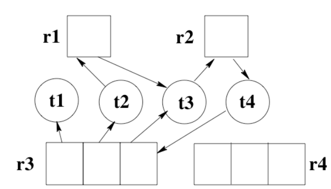
- We define a graph with vertices that represent both resources $\{r_1, ..., r_m\}$ and threads $\{t_1, ..., t_n\}$.
  - A directed edge from a thread to a resource, $t_i \rightarrow r_j$ indicates that t_i has requested that resource, but has not yet acquired it (*Request Edge*)
  - A directed edge from a resource to a thread $r_j \rightarrow t_i$ indicates that the OS has allocated r_j to t_i (*Assignment Edge*)
- If the graph has no cycles, no deadlock exists.
- If the graph has a cycle, deadlock might exist.



Deadlock Detection Using a Resource Allocation Graph

- What if there are multiple interchangeable instances of a resource?
  - Then a cycle indicates only that deadlock *might* exist.
  - If any instance of a resource involved in the cycle is held by a thread not in the cycle, then we can make progress when that resource is released.





Detect Deadlock and Then Correct It

- Scan the resource allocation graph for cycles, and then break the cycles.
- Different ways of breaking a cycle:
  - Kill all threads in the cycle.
  - Kill the threads one at a time, forcing them to give up resources.
  - Preempt resources one at a time rolling back the state of the thread holding the resource to the state it was in prior to getting the resource. This technique is common in database transactions.
- Detecting cycles takes $O(n^2)$ time, where n is $|T| + |R|$. When should we execute this algorithm?
  - Just before granting a resource, check if granting it would lead to a cycle? (Each request is then $O(n^2)$.)
  - Whenever a resource request can't be filled? (Each failed request is $O(n^2)$.)
  - On a regular schedule (hourly or ...)? (May take a long time to detect deadlock)
  - When CPU utilization drops below some threshold? (May take a long time to detect deadlock)
- What do current OS do?
  - Leave it to the programmer/application.

Deadlock Prevention

Prevent deadlock: ensure that at least one of the necessary conditions doesn't hold.

1. **Mutual Exclusion:** make resources sharable (but not all resources can be shared)
2. **Hold and Wait:**
   - Guarantee that a thread cannot hold one resource when it requests another
   - Make threads request all the resources they need at once and make the thread release all resources before requesting a new set.
3. **No Preemption:**
   - If a thread requests a resource that cannot be immediately allocated to it, then the OS preempts (releases) all the resources that the thread is currently holding.
   - Only when all of the resources are available, will the OS restart the thread.
   - *Problem:* not all resources can be easily preempted, like printers.
4. **Circular wait:** impose an ordering (numbering) on the resources and request them in order.

Deadlock Prevention with Resource Reservation

- Threads provide advance information about the maximum resources they may need during execution
- Define a sequence of threads $\{t_1, ..., t_n\}$ as *safe* if for each t_i, the resources that t_i can still request can be satisfied by the currently available resources plus the resources held by all t_j, $j < i$.
- A *safe state* is a state in which there is a safe sequence for the threads.
- An unsafe state is not equivalent to deadlock, it just may lead to deadlock, since some threads might not actually use the maximum resources they have declared.
- Grant a resource to a thread is the new state is safe
- If the new state is unsafe, the thread must wait even if the resource is currently available.
- This algorithm ensures no circular-wait condition exists.

Example

- Threads t_1, t_2, and t_3 are competing for 12 tape drives.
- Currently, 11 drives are allocated to the threads, leaving 1 available.
- The current state is *safe* (there exists a safe sequence, $\{t_1, t_2, t_3\}$ where all threads may obtain their maximum number of resources without waiting)
  - t_1 can complete with the current resource allocation
  - t_2 can complete with its current resources, plus all of t_1's resources, and the unallocated tape drive.
- t_3 can complete with all its current resources, all of t_1 and t_2's resources, and the unallocated tape drive.

	max need	in use	could want
t_1	4	3	1
t_2	8	4	4
t_3	12	4	8

Example (contd)

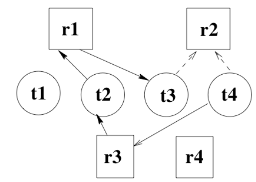
•If t_3 requests one more drive, then it must wait because allocating the drive would lead to an unsafe state.

•There are now 0 available drives, but each thread might need at least one more drive.

	max need	in use	could want
t_1	4	3	1
t_2	8	4	4
t_3	12	5	7

Deadlock Avoidance using Resource Allocation Graph

- Claim edges: an edge from a thread to a resource that may be requested in the future
- Satisfying a request results in converting a claim edge to an allocation edge and changing its direction.
- A cycle in this extended resource allocation graph indicates an unsafe state.
- If the allocation would result in an unsafe state, the allocation is denied even if the resource is available.
  - The claim edge is converted to a request edge and the thread waits.
- This solution does not work for multiple instances of the *same* resource.



Banker's Algorithm

- This algorithm handles multiple instances of the same resource.
- Force threads to provide advance information about what resources they may need for the duration of the execution.
- The resources requested may not exceed the total available in the system.
- The algorithm allocates resources to a requesting thread if the allocation leaves the system in a safe state.
- Otherwise, the thread must wait.

Preventing Deadlock with Banker's Algorithm

```
class ResourceManager {
  int n;        // # threads
  int m;      // # resources
  int avail[m], // # of available resources of each type
  max[n,m],   // # of each resource that each thread may want
  alloc[n,m], //# of each resource that each thread is using
  need[n,m],   // # of resources that each thread might still
   request
```

Banker's Algorithm:Resource Allocation

```
public void synchronized allocate (int request[m], int i) {
  // request  contains the resources being requested
  // i is the thread making the request

  if (request > need[i])  //vector comparison
    error();  // Can't request more than you declared
  else while (request[i] > avail)
    wait();   // Insufficient resources available

  // enough resources exist to satisfy the requests
  // See if the request would lead to an unsafe state
  avail = avail - request;  // vector additions
  alloc[i] = alloc[i] + request;
  need[i] = need[i] - request;

  while ( !safeState () ) {
    // if this is an unsafe state, undo the allocation and wait
    <undo the changes to avail, alloc[i], and need[i]>
    wait ();
    <redo the changes to avail, alloc[i], and need[i]>
 } }
```


Banker's Algorithm: Safety Check

```
private boolean safeState () {
  boolean work[m] = avail[m];  // accommodate all resources
  boolean finish[n] = false;   // none finished yet

  // find a process that can complete its work now
  while (find i such that finish[i] == false
      and need[i] <= work) { // vector operations
    work = work + alloc[i]
    finish[i] = true;
  }

  if (finish[i] == true for all i)
    return true;
  else
    return false;
}
```

- Worst case: requires O(mn^2) operations to determine if the system is safe.

Example using Banker's Algorithm

System snapshot:

	Max	Allocation	Available
	A B C	A B C	A B C
P_0	0 0 1	0 0 1	
P_1	1 7 5	1 0 0	
P_2	2 3 5	1 3 5	
P_3	0 6 5	0 6 3	
Total		2 9 9	1 5 2

Example (contd)

- How many resources are there of type (A,B,C)?
- What is the contents of the Need matrix?

	A B C
P_0	
P_1	
P_2	
P_3	

- Is the system in a safe state? Why?

Example: solutions

- How many resources of type (A,B,C)? (3,14,11)
  resources = total + avail
- What is the contents of the need matrix?
  Need = Max - Allocation.

	A B C
P_0	0 0 0
P_1	0 7 5
P_2	1 0 0
P_3	0 0 2

- Is the system in a safe state? Why?
- Yes, because the processes can be executed in the sequence P_0, P_2, P_1, P_3, even if each process asks for its maximum number of resources when it executes.

Example (contd)

- If a request from process P_1 arrives for additional resources of (0,5,2), can the Banker's algorithm grant the request immediately?
- What would be the new system state after the allocation?

	Max	Allocation	Need	Available
	A B C	A B C	A B C	A B C
P_0	0 0 1			
P_1	1 7 5			
P_2	2 3 5			
P_3	0 6 5			
Total				

- What is a sequence of process execution that satisfies the safety constraint?

Example: solutions

- If a request from process P_1 arrives for additional resources of (0,5,2), can the Banker's algorithm grant the request immediately? Show the system state, and other criteria.

  Yes. Since

  1. (0,5,2) ≤ (1,5,2), the Available resources, and
  2. (0,5,2) + (1,0,0) = (1,5,2) ≤ (1,7,5), the maximum number P_1 can request.
  3. The new system state after the allocation is:

	Allocation	Max	Available
	A B C	A B C	A B C
P_0	0 0 1	0 0 1	
P_1	1 5 2	1 7 5	
P_2	1 3 5	2 3 5	
P_3	0 6 3	0 6 5	
			1 0 0

and the sequence P_0, P_2, P_1, P_3 satisfies the safety constraint.

Summary

- Deadlock: situation in which a set of threads/processes cannot proceed because each requires resources held by another member of the set.
- Detection and recovery: recognize deadlock after it has occurred and break it.
- Avoidance: don't allocate a resource if it would introduce a cycle.
- Prevention: design resource allocation strategies that guarantee that one of the necessary conditions never holds
- Code concurrent programs very carefully. This only helps prevent deadlock over resources managed by the program, not OS resources.
- Ignore the possibility! (Most OSes use this option!!)