CS 318 Principles of Operating Systems

Fall 2020

Lecture 8: Deadlock

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Administrivia

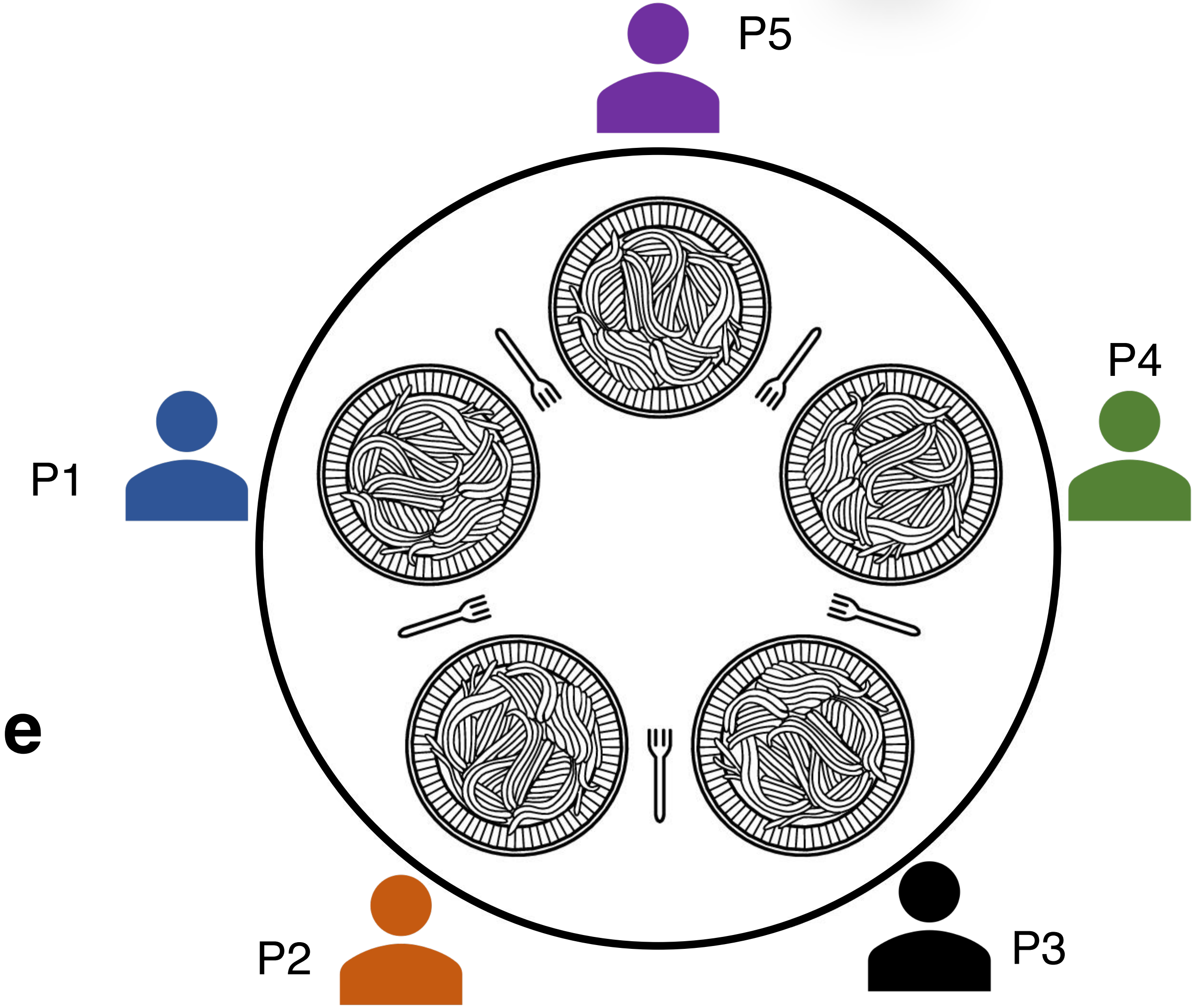
- **Lab 1 deadline is this Sunday noon (Sept 27th 11:59am)**
- **If you decide to use late hours, please send an email to the staff mailing list following the format *before* the deadline.**
- **Reminder about cheating**

Deadlock

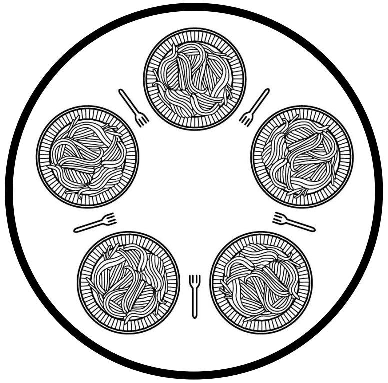
- **Synchronization is a live gun**
  - We can easily shoot ourselves in the foot
  - Incorrect use of synchronization can block all processes
  - You have likely been intuitively avoiding this situation already
- **If one process tries to access a resource that a second process holds, and vice-versa, they can never make progress**
- **We call this situation deadlock, and we'll look at:**
  - Definition and conditions necessary for deadlock
  - Representation of deadlock conditions
  - Approaches to dealing with deadlock

Dining Philosophers Problem

- **Philosophers spend their lives alternating thinking and eating**
- **Don't interact with neighbors, occasionally eat**
  - Need 2 forks to eat
  - Release both when done
- **Can only pick up 1 fork at a time**



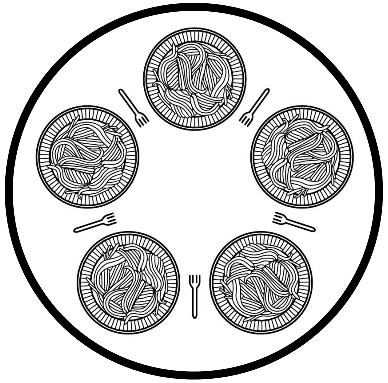
Philosophers in Code (1)



```
#define N 5                /* number of philosophers */


void philosopher(int i) /* i: philosopher id, 0 to 4 */
{
  while (true) {
    think();                    /* philosopher is thinking */
    take_fork(i);               /* take left fork */
    take_fork((i + 1) % N);     /* take right fork */
    eat();                      /* yum-yum, spaghetti */
    put_fork(i);                /* put left fork back on the table */
    put_fork((i + 1) % N);      /* put right fork back on the table */
  }
}
```

Philosophers in Code (2)



```
semaphore forks[N]; /* semaphores for each fork,
                       each initialized to 1 (omitted) */

void take_fork(int i)
{
  forks[i].P();       /* wait for ith fork's semaphore */
}

void put_fork(int i)
{
  forks[i].V();      /* signal ith fork's semaphore */
}
```

- **What is a problem with this algorithm?**

How to Avoid Deadlock Here?

- **Multiple solutions exist**

- **Simple one: allow at most 4 philosophers to sit simultaneously at the table**

- **Another solution: define a partial order for resources (forks)**
  - Number the forks
  - Philosopher must always pick up lower-numbered fork first and then higher-numbered fork
  - What happens if four philosophers all pick up their lower-numbered fork?
  - Disadvantage
    - Not always practical, when the complete list of all resources is not known in advance

- **Third solution: all or none each time**

2nd Attempt to Dining Philosopher Problem

```
#define N 5                            /* number of philosophers */
#define LEFT  (i+N-1) % N              /* i's left neighbor */
#define RIGHT (i+1) % N                /* i's right neighbor */
enum State {THINKING, HUNGRY, EATING}; /* a philosopher's status */
enum State states[N];   /* keep track of each philosopher's status */
semaphore mutex = 1;    /* mutual exclusion for critical section */
semaphore phis[N];      /* semaphore for each philosopher, init to 0 */


void philosopher(int i) /* i: philosopher id, 0 to N-1 */
{
  while (true) {
    think();            /* philosopher is thinking */
    take_forks(i);      /* take both forks */
    eat();              /* yum-yum, spaghetti */
    put_forks(i);       /* put both forks */
  }
}
```

2nd Attempt to Dining Philosopher Problem

```
void take_forks(int i) /* i: philosopher id, 0 to N-1 */
{
  mutex.P();             /* enter critical section */
  states[i] = HUNGRY;    /* indicate philosopher is hungry */
  test(i);               /* try to acquire two forks */
  mutex.V();             /* exit critical section */
  phis[i].P();           /* block if forks not acquired */
}
void put_forks(int i)    /* i: philosopher id, 0 to N-1 */
{
  mutex.P();              /* enter critical section */
  states[i] = THINKING;   /* indicate i finished eating */
  test(LEFT);             /* see if left neighbor can eat now */
  test(RIGHT);            /* see if right neighbor can eat now */
  mutex.V();              /* exit critical section */
}
```

```
void test(int i) /* i: philosopher id,
                    0 to N-1 */
{
  if (states[i] == HUNGRY &&
       states[LEFT] != EATING &&
       states[RIGHT] != EATING) {
    states[i] = EATING; /* philosopher i
                           can eat now */
    phis[i].V(); /* signal i to proceed */
  }
}
```

Notes for the 2^{nd} Attempt Solution

- **What is the purpose of `states` array?**
  - …given that already have the semaphore array?
  - A semaphore doesn’t have operations for checking its value!
- **What if we don’t use the `mutex` semaphore?**
- **Why the semaphore array is for each philosopher?**
  - Our first attempt uses semaphore array for each fork
- **What if we put `phis[i].P();` inside the critical section?**
- **What if we don’t call the two `test` in `put_forks`?**

Deadlock Definition

- **Deadlock is a problem that can arise:**
  - When processes compete for access to limited resources
  - When processes are incorrectly synchronized
- **Definition:**
  - Deadlock exists among a set of processes if every process is waiting for an event that can be caused only by another process in the set.

Deadlock Example

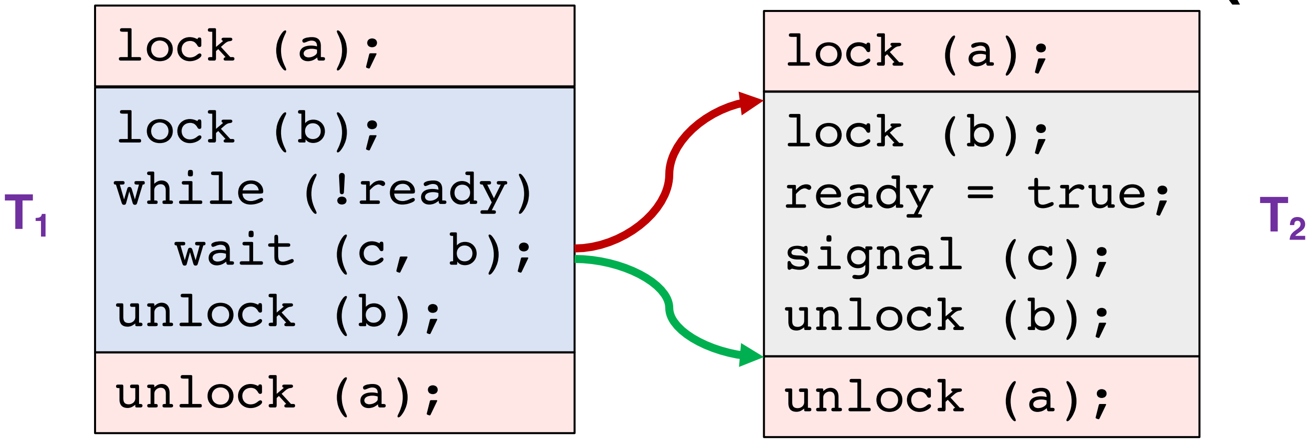
```
      mutex_t m1, m2;
      void p1(void *ignored) {
        lock(m1);
→       lock(m2);
        /* critical section */
        unlock(m2);
        unlock(m1);
      }
      void p2(void *ignored) {
        lock(m2);
→       lock(m1);
        /* critical section */
        unlock(m1);
        unlock(m2);
      }
```

Deadlock Example

- **Can you have deadlock w/o mutexes?**

- **Same problem with condition variables**
  - Suppose resource 1 managed by c_1, resource 2 by c_2
  - A has 1, waits on c_2, B has 2, waits on c_1

- **Or w/ combined mutex/condition variable (tricky)**



T_1

```
lock (a);
lock (b);
while (!ready)
  wait (c, b);
unlock (b);
unlock (a);
```

T_2

```
lock (a);
lock (b);
ready = true;
signal (c);
unlock (b);
unlock (a);
```

Deadlock Example

- **Can you have deadlock w/o mutexes?**

- **Same problem with condition variables**
  - Suppose resource 1 managed by c_1, resource 2 by c_2
  - A has 1, waits on c_2, B has 2, waits on c_1

- **Or with combined mutex/condition variable (tricky)**
  - `lock (a); lock (b); while (!ready) wait (c, b); unlock (b); unlock (a);`
  - `lock (a); lock (b); ready = true; signal (c); unlock (b); unlock (a);`

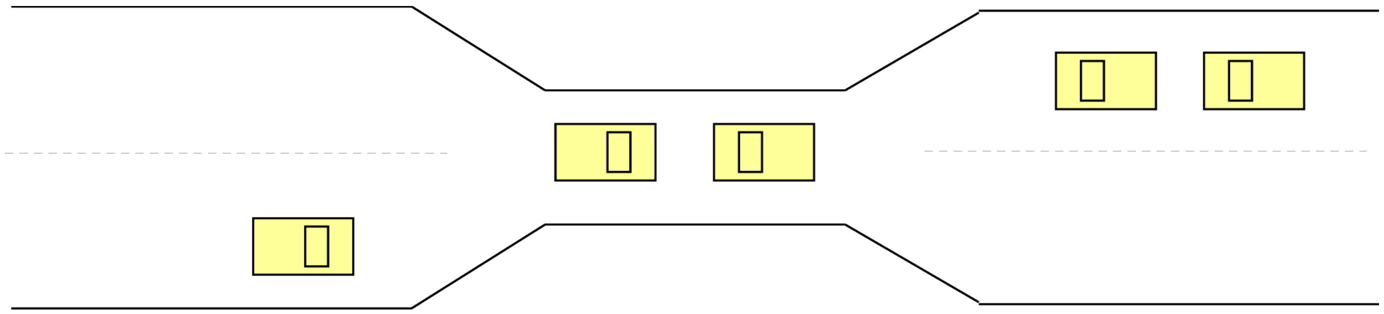
- **Lesson: dangerous to hold locks when crossing boundaries!**

```
lock (a);
foo(x);
unlock (a);
```

internally uses condition variables

```
lock (a);
bar(y);
unlock (a);
```

Deadlocks w/o Computers



- **Real issue is *resources* & how required**
- **E.g., bridge only allows traffic in one direction**
  - Each section of a bridge can be viewed as a resource.
  - If a deadlock occurs, it can be resolved if one car backs up (preempt resources and rollback).
  - Several cars may have to be backed up if a deadlock occurs.
  - Starvation is possible.

Conditions for Deadlock

1. Mutual exclusion – At least one resource must be held in a non-sharable mode
2. Hold and wait – There must be one process holding one resource and waiting for another resource
3. No preemption – Resources cannot be preempted (critical sections cannot be aborted externally)
4. Circular wait – There must exist a set of processes [P_1, P_2, P_3,…,P_n] such that P_1 is waiting for P_2, P_2 for P_3, etc.

- **All of 1–4 necessary for deadlock to occur**
- **Two approaches to dealing with deadlock:**
  - Pro-active: prevention
  - Reactive: detection + corrective action

Prevent by Eliminating One Condition

1. **Mutual exclusion**
   - Buy more resources, split into pieces, or virtualize to make "infinite" copies
   - Threads: threads have copy of registers = no lock

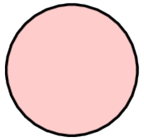
2. **Hold and wait**
   - Wait on all resources at once (must know in advance)

3. **No preemption**
   - Physical memory: virtualized with VM, can take physical page away and give to another process!

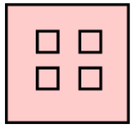
4. **Circular wait**
   - Single lock for entire system: (problems?)
   - Partial ordering of resources (next)

Resource Allocation Graph

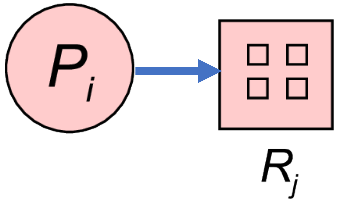
- **View system as graph**
  - Processes and Resources are nodes
  - Resource Requests and Assignments are edges
- **Process:**



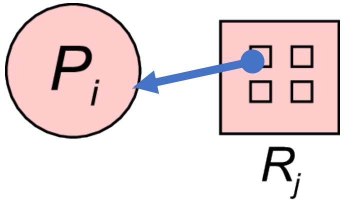
- **Resource with 4 instances:**



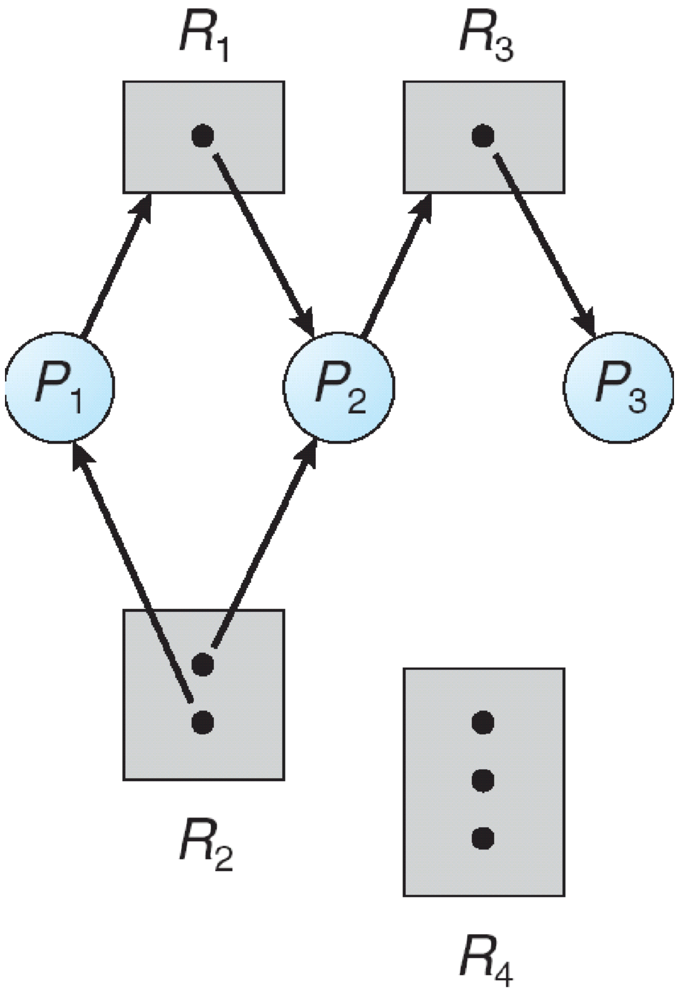
- P_i **requesting** R_j**:**



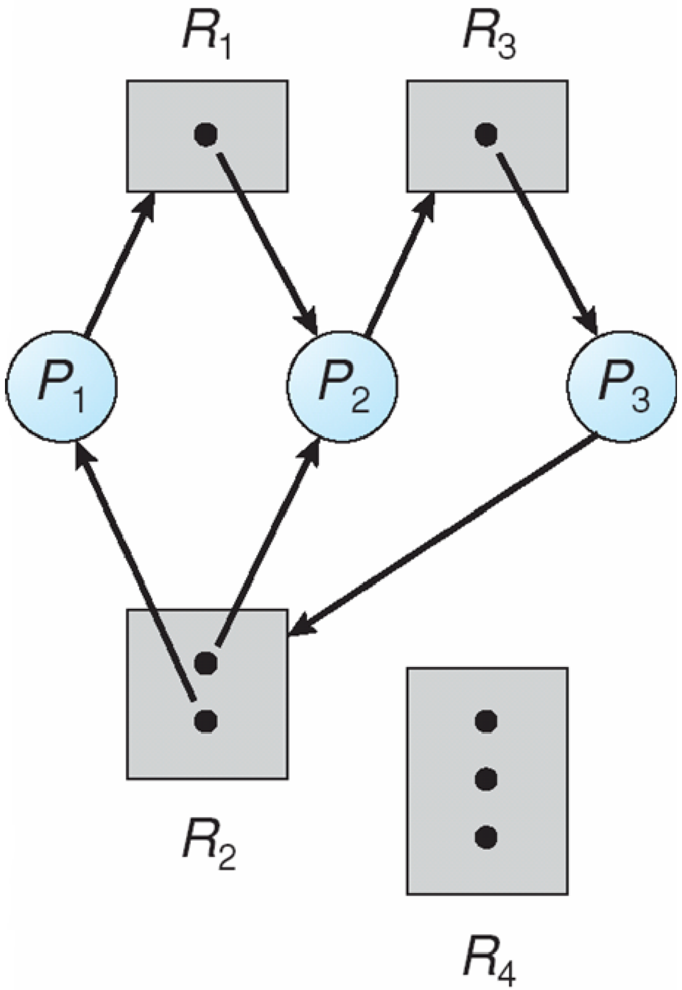
- P_i **holding instance of** R_j**:**



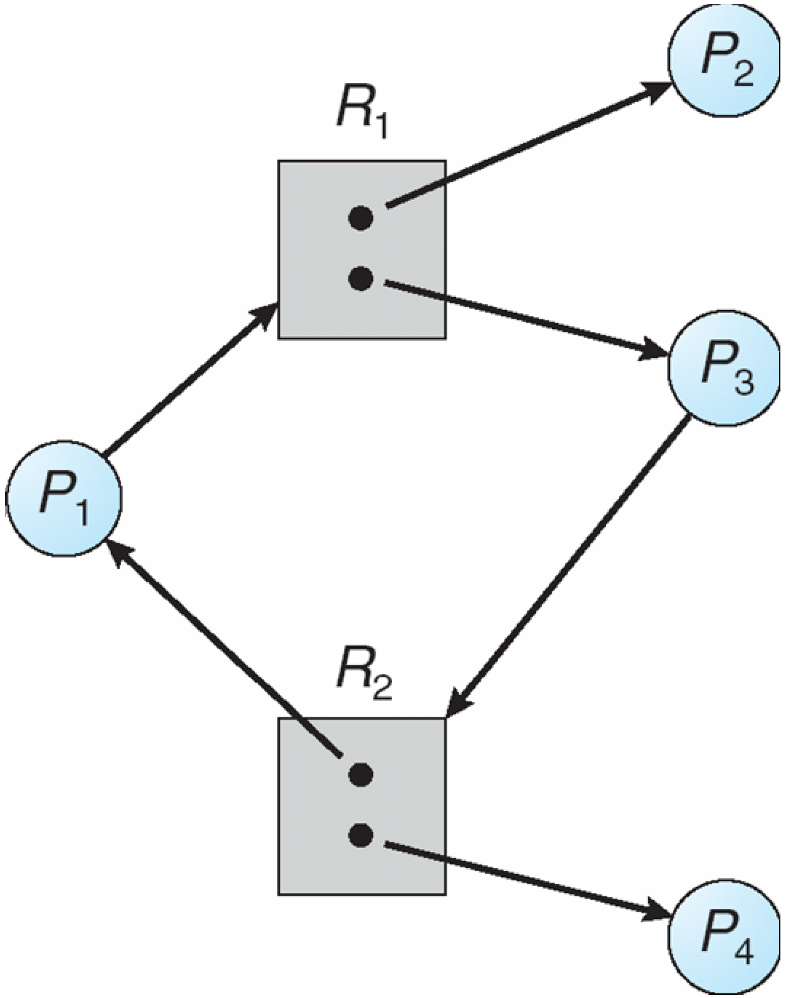
Example Resource Allocation Graph



Resource Allocation Graph with Deadlock



Is This Deadlock?



Cycles and Deadlock

- **If graph has no cycles ⇒ no deadlock**

- **If graph contains a cycle**
  - Definitely deadlock if only one instance per resource (waits-for graph (WFG))
  - Otherwise, maybe deadlock, maybe not

- **Prevent deadlock with partial order on resources**
  - e.g., always acquire mutex m_1 before m_2
  - Usually design locking discipline for application this way

Dealing With Deadlock

- **There are four approaches for dealing with deadlock:**
  - Ignore it – how lucky do you feel?
  - Prevention – make it impossible for deadlock to happen
  - Avoidance – control allocation of resources
  - Detection and Recovery – look for a cycle in dependencies

Deadlock Avoidance

- **Avoidance**
  - Provide information in advance about what resources will be needed by processes to guarantee that deadlock will not happen
  - System only grants resource requests if it knows that the process can obtain all resources it needs in future requests
  - Avoids circularities (wait dependencies)
- **Tough**
  - Hard to determine all resources needed in advance
  - Good theoretical problem, not as practical to use

Banker's Algorithm

- **The Banker's Algorithm is the classic approach to deadlock avoidance for resources with multiple units**

1. Assign a credit limit to each customer (process)

  - Maximum credit claim must be stated in advance

2. Reject any request that leads to a dangerous state

  - A dangerous state is one where a sudden request by any customer for the full credit limit could lead to deadlock
  - A recursive reduction procedure recognizes dangerous states

3. In practice, the system must keep resource usage well below capacity to maintain a resource surplus

  - Rarely used in practice due to low resource utilization

Detection and Recovery

- **Detection and recovery**
  - If we don’t have deadlock prevention or avoidance, then deadlock may occur
  - In this case, we need to detect deadlock and recover from it
- **To do this, we need two algorithms**
  - One to determine whether a deadlock has occurred
  - Another to recover from the deadlock
- **Possible, but expensive (time consuming)**
  - Implemented in VMS
  - Run detection algorithm when resource request times out

Deadlock Detection

- **Detection**
  - Traverse the resource graph looking for cycles
  - If a cycle is found, preempt resource (force a process to release)
- **Expensive**
  - Many processes and resources to traverse
- **Only invoke detection algorithm depending on**
  - How often or likely deadlock is
  - How many processes are likely to be affected when it occurs

Deadlock Recovery

Once a deadlock is detected, we have two options…

1. Abort processes

- Abort all deadlocked processes
  - Processes need to start over again
- Abort one process at a time until cycle is eliminated
  - System needs to rerun detection after each abort

2. Preempt resources (force their release)

- Need to select process and resource to preempt
- Need to rollback process to previous state
- Need to prevent starvation

Deadlock Summary

- **Deadlock occurs when processes are waiting on each other and cannot make progress**
  - Cycles in Resource Allocation Graph (RAG)
- **Deadlock requires four conditions**
  - Mutual exclusion, hold and wait, no resource preemption, circular wait
- **Four approaches to dealing with deadlock:**
  - Ignore it – Living life on the edge
  - Prevention – Make one of the four conditions impossible
  - Avoidance – Banker's Algorithm (control allocation)
  - Detection and Recovery – Look for a cycle, preempt or abort

Next time…

- **Read Chapter 15, 16, 18**