Deadlocks

System Model

- There are non-shared computer resources
  - Maybe more than one instance
  - Printers, Semaphores, Tape drives, CPU
- Processes need access to these resources
  - Acquire resource
    - If resource is available, access is granted
    - If not available, the process is blocked
  - Use resource
  - Release resource
- Undesirable scenario:
  - Process A acquires resource 1, and is waiting for resource 2
  - Process B acquires resource 2, and is waiting for resource 1
  - ⇒ Deadlock!

For example: Semaphores

```
semaphore:     mutex1 = 1    /* protects resource 1 */
               mutex2 = 1    /* protects resource 2 */
```

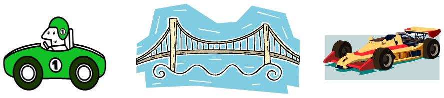
```
Process A code:
 {
    /* initial compute */
   P(mutex1)
   P(mutex2)

  /* use both resources */

   V(mutex2)
   V(mutex1)
}
```

```
Process B code:
 {
    /* initial compute */
   P(mutex2)
   P(mutex1)

  /* use both resources */

   V(mutex2)
   V(mutex1)
}
```

Deadlocks

Definition:

Deadlock exists among a set of processes if
- Every process is waiting for an event
- This event can be caused only by another process in the set
  - Event is the acquire of release of another resource



One-lane bridge

Four Conditions for Deadlock

- Coffman et. al. 1971
- Necessary conditions for deadlock to exist:
  - **Mutual Exclusion**
    - At least one resource must be held is in non-sharable mode
  - **Hold and wait**
    - There exists a process holding a resource, and waiting for another
  - **No preemption**
    - Resources cannot be preempted
  - **Circular wait**
    - There exists a set of processes $\{P_1, P_2, \dots P_N\}$, such that
      - P_1 is waiting for P_2, P_2 for P_3, …. and P_N for P_1

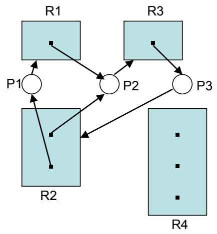
All four conditions must hold for deadlock to occur

Resource Allocation Graph

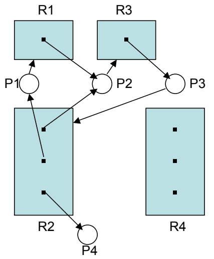
- Deadlock can be described using a *resource allocation graph, RAG*
- The RAG consists of:
  - set of vertices $V = P \cup R$,
    - where $P=\{P_1,P_2,\dots,P_n\}$ of processes and $R=\{R_1,R_2,\dots,R_m\}$ of resources.
  - Request edge: directed edge from a process to a resource,
    - $P_i \rightarrow R_j$, implies that P_i has requested R_j.
  - Assignment edge: directed edge from a resource to a process,
    - $R_j \rightarrow P_i$, implies that R_j has been allocated to P_i.

- If the graph has no cycles, deadlock cannot exist.
- If the graph has a cycle, deadlock may exist.

RAG Example



Cycles:
P1-R1-P2-R3-P3-R2-P1
P2-R3-P3-R2-P2
and there is *deadlock*.



Same cycles, but no deadlock

Dealing with Deadlocks

- Proactive Approaches:
  - Deadlock Prevention
    - Negate one of 4 necessary conditions
    - Prevent deadlock from occurring
  - Deadlock Avoidance
    - Carefully allocate resources based on future knowledge
    - Deadlocks are prevented
- Reactive Approach:
  - Deadlock detection and recovery
    - Let deadlock happen, then detect and recover from it
- Ignore the problem
  - Pretend deadlocks will never occur
  - Ostrich approach (real OSs!!!)

Deadlock Prevention

- Can the OS prevent deadlocks?
- Prevention: Negate one of necessary conditions
  - Mutual exclusion:
    - Make resources sharable
    - Not always possible (spooling?)
  - Hold and wait
    - Do not hold resources when waiting for another
    - ⇒ Request all resources before beginning execution
    - ➩ Processes do not know what all they will need
    - ➩ Starvation (if waiting on many popular resources)
    - ➩ Low utilization (Need resource only for a bit)
    - Alternative: Release all resources before requesting anything new
      - Still has the last two problems

Deadlock Prevention

- Prevention: Negate one of necessary conditions
  - No preemption:
    - Make resources preemptable (2 approaches)
    - Preempt requesting processes' resources if all not available
    - Preempt resources of waiting processes to satisfy request
    - Good when easy to save and restore state of resource
      - CPU registers, memory virtualization
  - Circular wait: (2 approaches)
    - Single lock for entire system? (Problems)
    - Impose partial ordering on resources, request them in order

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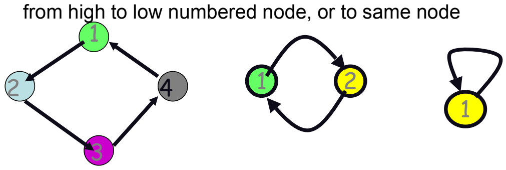
Breaking Circular Wait

- Order resources (lock1, lock2, …)
- Acquire resources in strictly increasing/decreasing order
- When requests to multiple resources of same order:
  - Make the request a single operation
- Intuition: Cycle requires an edge from low to high, and from high to low numbered node, or to same node



➩ Ordering not always possible, low resource utilization

Two phase locking

- Acquire all resources, if block on any, release all, and retry

```
print_file:
        lock(file);
        acquire printer
        acquire disk;
        …do work…
        release all
```

- Pro: dynamic, simple, flexible
- Con:
  - Cost with number of resources?
  - Length of critical section?
  - Hard to know what's needed a priori

Deadlock Avoidance

- If we have future information
  - Max resource requirement of each process before they execute
- Can we guarantee that deadlocks will never occur?
- Avoidance Approach:
  - Before granting resource, check if state is **safe**
  - If the state is safe ⇒ no deadlock!

Safe State

- A state is said to be **safe**, if it has a process sequence $\{P_1, P_2, \ldots, P_n\}$, such that for each P_i, the resources that P_i can still request can be satisfied by the currently available resources plus the resources held by all P_j, where $j < i$
- State is safe because OS can definitely avoid deadlock
  - by blocking any new requests until safe order is executed
- This avoids circular wait condition
  - Process waits until safe state is guaranteed

Safe State Example

- Suppose there are 12 tape drives

	max need	current usage	could ask for
p0	10	5	5
p1	4	2	2
p2	9	2	7

3 drives remain

- current state is safe because a safe sequence exists: <p1,p0,p2>
  p1 can complete with current resources
  p0 can complete with current+p1
  p2 can complete with current +p1+p0
- if p2 requests 1 drive, then it must wait to avoid unsafe state.

Safe State Example

(One resource class only)

process	holding	max claims
A	4	6
B	4	11
C	2	7

unallocated: 2

safe sequence: A,C,B

If C should have a claim of 9 instead of 7,
there is no safe sequence.

Safe State Example

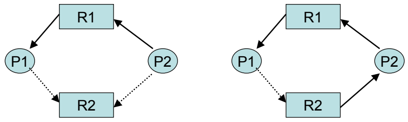
process	holding	max claims
A	4	6
B	4	11
C	2	9

unallocated: 2
deadlock-free sequence: A,C,B
if C makes only 6 requests

However, this sequence is not safe:
If C should have 7 instead of 6 requests, deadlock exists.

RAG Algorithm

- Works if only **one** instance of each resource type
- Algorithm:
  - Add a **claim edge**, $P_i \rightarrow R_j$ if P_i can request R_j in the future
    - Represented by a dashed line in graph
  - A request $P_i \rightarrow R_j$ can be granted only if:
    - Adding an assignment edge $R_j \rightarrow P_i$ does not introduce cycles
      - Since cycles imply unsafe state



Banker's Algorithm

- Decides whether to grant a resource request.
- Data structures:

n: integer	# of processes
m: integer	# of resources
available[1..m]	available[i] is # of avail resources of type i
max[1..n,1..m]	max demand of each Pi for each Ri
allocation[1..n,1..m]	current allocation of resource Rj to Pi
need[1..n,1..m]	max # resource Rj that Pi may still request

let request[i] be vector of # of resource Rj Process Pi wants

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Basic Algorithm

```
1. If request[i] > need[i] then
      error (asked for too much)
2. If request[i] > available[i] then
      wait (can't supply it now)
3. Resources are available to satisfy the request
   Let's assume that we satisfy the request. Then we would have:
      available = available - request[i]
      allocation[i] = allocation [i] + request[i]
      need[i] = need [i] - request [i]
   Now, check if this would leave us in a safe state:
      if yes, grant the request,
      if no, then leave the state as is and cause process to wait.
```

Safety Check

```
free[1..m] = available          /* how many resources are available */
finish[1..n] = false (for all i)  /* none finished yet */

Step 1: Find an i such that finish[i]=false and need[i] <= work
          /* find a proc that can complete its request now */
        if no such i exists, go to step 3   /* we're done */

Step 2: Found an i:
        finish [i] = true  /* done with this process */
        free = free + allocation [i]
        /* assume this process were to finish, and its allocation
        back to the available list */
        go to step 1

Step 3: If finish[i] = true for all i, the system is safe. Else Not
```

Banker's Algorithm: Example

	Allocation			**Max**			**Available**		
	A	B	C	A	B	C	A	B	C
P0	0	1	0	7	5	3	3	3	2
P1	2	0	0	3	2	2			
P2	3	0	2	9	0	2			
P3	2	1	1	2	2	2			
P4	0	0	2	4	3	3			

this is a safe state: safe sequence <P1, P3, P4, P2, P0>

Suppose that P1 requests (1,0,2)

- add it to P1's allocation and subtract it from Available

Banker's Algorithm: Example

	Allocation			**Max**			**Available**		
	A	B	C	A	B	C	A	B	C
P0	0	1	0	7	5	3	2	3	0
P1	3	0	2	3	2	2			
P2	3	0	2	9	0	2			
P3	2	1	1	2	2	2			
P4	0	0	2	4	3	3			

This is still safe: safe seq <P1, P3, P4, P0, P2>

In this new state,
P4 requests (3,3,0)
not enough available resources

P0 requests (0,2,0)
let's check resulting state

Banker's Algorithm: Example

	Allocation			**Max**			**Available**		
	A	B	C	A	B	C	A	B	C
P0	0	3	0	7	5	3	2	1	0
P1	3	0	2	3	2	2			
P2	3	0	2	9	0	2			
P3	2	1	1	2	2	2			
P4	0	0	2	4	3	3			

This is unsafe state (why?)
So P0's request will be denied

Problems with Banker's Algorithm?

Deadlock Detection & Recovery

- If none of these approaches are used, deadlock can occur
- This scheme requires:
  - Detection: finding out if deadlock has occurred
    - Keep track of resource allocation (who has what)
    - Keep track of pending requests (who is waiting for what)
  - Ways to recover from it
- Expensive to detect, as well as recover

RAG Algorithm

- Suppose there is only one instance of each resource
- Example 1: Is this a deadlock?
  - P1 has R2 and R3, and is requesting R1
  - P2 has R4 and is requesting R3
  - P3 has R1 and is requesting R4
- Example 2: Is this a deadlock?
  - P1 has R2, and is requesting R1 and R3
  - P2 has R4 and is requesting R3
  - P3 has R1 and is requesting R4
- Use a **wait-for graph:**
  - Collapse resources
  - An edge $P_i \rightarrow P_k$ exists only if RAG has $P_i \rightarrow R_j$ & $R_j \rightarrow P_k$
  - Cycle in wait-for graph ⇒ deadlock!

2nd Detection Algorithm

- What if there are multiple resource instances?
- Data structures:

n: integer	# of processes
m: integer	# of resources
available[1..m]	available[i] is # of avail resources of type i
request[1..n,1..m]	max demand of each Pi for each Ri
allocation[1..n,1..m]	current allocation of resource Rj to Pi
finish[1..n]	true if Pi's request can be satisfied

let request[i] be vector of # instances of each resource Pi wants

---

2nd Detection Algorithm

```
1. work[]=available[]
   for all i < n, if allocation[i] ≠ 0
       then finish[i]=false else finish[i]=true
2. find an index i such that:
       finish[i]=false;
       request[i]<=work
   if no such i exists, go to 4.
3. work=work+allocation[i]
   finish[i] = true, go to 2
4. if finish[i] = false for some i,
   then system is deadlocked with Pi in deadlock
```

Example

Finished = {F, F, F, F};
Work = Available = (0, 0, 1);

	R_1	R_2	R_3
P_1	1	1	1
P_2	2	1	2
P_3	1	1	0
P_4	1	1	1

Allocation

	R_1	R_2	R_3
P_1	3	2	1
P_2	2	2	1
P_3	0	0	1
P_4	1	1	1

Request

Example

Finished = {F, F, T, F};
Work = (1, 1, 1);

	R_1	R_2	R_3
P_1	1	1	1
P_2	2	1	2
P_3	1	1	0
P_4	1	1	1

Allocation

	R_1	R_2	R_3
P_1	3	2	1
P_2	2	2	1
P_3			
P_4	1	1	1

Request

Example

Finished = {F, F, T, T};
Work = (2, 2, 2);

	R_1	R_2	R_3
P_1	1	1	1
P_2	2	1	2
P_3	1	1	0
P_4	1	1	1

Allocation

	R_1	R_2	R_3
P_1	3	2	1
P_2	2	2	1
P_3			
P_4			

Request

Example

Finished = {F, T, T, T};
Work = (4, 3, 2);

	R_1	R_2	R_3
P_1	1	1	1
P_2	2	1	2
P_3	1	1	0
P_4	1	1	1

Allocation

	R_1	R_2	R_3
P_1	3	2	1
P_2			
P_3			
P_4			

Request

When to run Detection Algorithm?

- For every resource request?
- For every request that cannot be immediately satisfied?
- Once every hour?
- When CPU utilization drops below 40%?

Deadlock Recovery

- Killing one/all deadlocked processes
  - Crude, but effective
  - Keep killing processes, until deadlock broken
  - Repeat the entire computation
- Preempt resource/processes until deadlock broken
  - Selecting a victim (# resources held, how long executed)
  - Rollback (partial or total)
  - Starvation (prevent a process from being executed)

What happens today?

- **Ostrich Approach**
- Deadlock avoidance and prevention is often impossible
- Thorough detection of all scenarios too expensive
- All operating systems have potential deadlocks
- Engineering philosophy:

  The price of infrequent crashes in exchange for performance and user convenience is worth it

SQL Server

- Runs detection algorithm:
  - Periodically, or
  - On demand
- Recovers by terminating:
  - Least expensive process, or
  - User specified priority

Transaction (Process ID xxx) was deadlocked on (xxx) resources with another process and has been chosen as the deadlock victim. Rerun the transaction.

Windows DDK Driver Verifier

- DDK = Device Driver Kit
- Added in XP and later
- Uses Deadlock Prevention, by breaking circular-wait
  - Checks for a hierarchy in your locking mechanism
- Will bugcheck even if your system has not deadlocked!
  - (0xc4), fatal error

- You would not use it in a production system
  - Useful in development