Deadlock (part II)

Ken Birman

Revisiting *resource deadlocks*

- 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: Locks

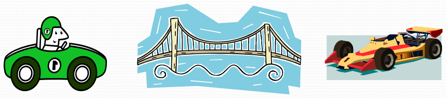
```
Object X, Y;

   Process A code:
    {
       /* initial compute */
      X.acquire();
      Y.acquire();

      … use X and Y …

      Y.release();
      X.release();
    }

                                        Process B code:
                                         {
                                            /* initial compute */
                                           Y.acquire();
                                           X.acquire();

                                           … use X and Y …

                                           X.release();
                                           Y.release();
                                         }
```

Deadlocks with resources

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

Reminder: Conditions for Process-Wait Deadlocks to arise

- **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 $\{P_1, P_2, \ldots P_N\}$, such that
    - P_1 is waiting for P_2, P_2 for P_3, …. and P_N for P_1

Can we do this for resource wait?

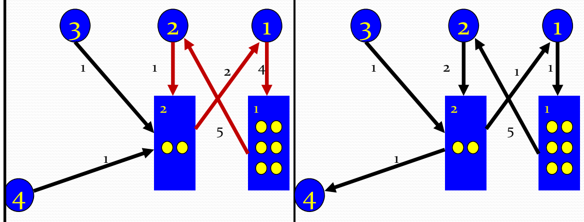
- Observation: the conditions won't be identical
- In particular, a resource-wait cycle might not imply that a deadlock has occurred

Reminder: 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 $P=\{P_1,P_2,\ldots,P_n\}$ of processes and $R=\{R_1,R_2,\ldots,R_m\}$ 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.

Res. Alloc. Graph Example



Cycle:
P1-R1-P2-R2-P1
and there is *deadlock*.

Same cycle, but no deadlock

Dealing with Deadlocks

- "Reactive" Approaches: break deadlocks if they arise
  - Periodically check for evidence of deadlock
    - For example, using a graph reduction algorithm
    - Or just using timeout on the lock acquire operations
  - Then need a way to recover
    - Could blue screen and reboot the computer
    - Perhaps a thread can give up on what it was trying to do
- Database systems always have a way to "back out" by "aborting" (rolling back) uncompleted activities
  - This lets them abort and then retry if a deadlock arises

Deadlock Prevention

- Can the OS prevent deadlocks?
- Prevention: Negate one of necessary conditions.

- Let's try one by one… ***Mutual exclusion***
  - Make resources sharable
  - Not always possible: concurrency conflicts may arise

- Example of a way to "share" a resource
  - "Initiate work to be done asynchronously
  - Later the O/S will do a notification when task finishes

Deadlock Prevention

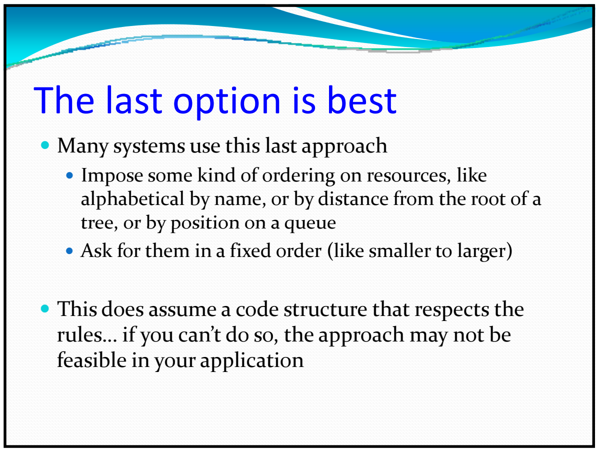
- **Hold and wait**
  - One option: if you need to wait, must release resources, then re-acquire them after wait is finished (very awkward)
  - Or simply request everything all at once in one shot

- These both have issues
  - First approach is inefficient (endlessly acquires/releases the same things. Also attempt to reacquire a resource may fail)
  - In second, what if you don't know what resources will be needed until you actually run the code?
  - Starvation (if you request lots of very popular resources)
  - Low utilization (Might ask for things you don't end up needing)

Deadlock Prevention

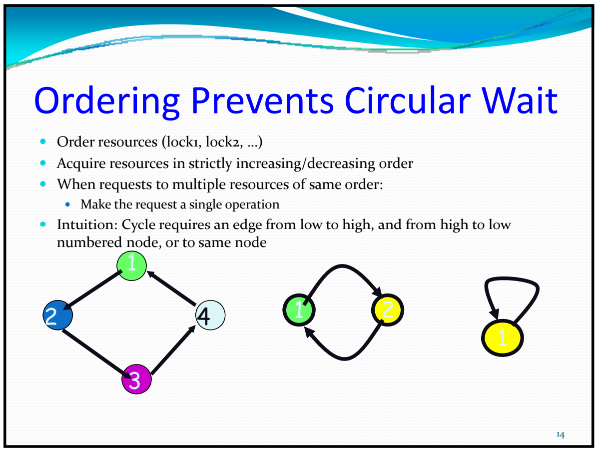
- **No preemption:**
  - Make resources preemptable (2 approaches)
  - Preempt requesting processes' resources if all not available
  - Preempt resources of waiting processes to satisfy request
  - Good when easy to save and restore state of resource
    - CPU registers, memory virtualization

- **Circular wait: (2 approaches)**
  - Single lock for entire system? (Problems)
  - Impose partial ordering on resources, request them in order



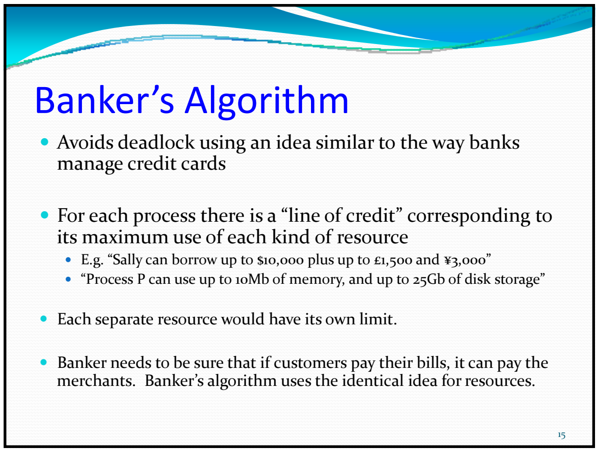
The last option is best

- Many systems use this last approach
  - Impose some kind of ordering on resources, like alphabetical by name, or by distance from the root of a tree, or by position on a queue
  - Ask for them in a fixed order (like smaller to larger)
- This does assume a code structure that respects the rules… if you can't do so, the approach may not be feasible in your application



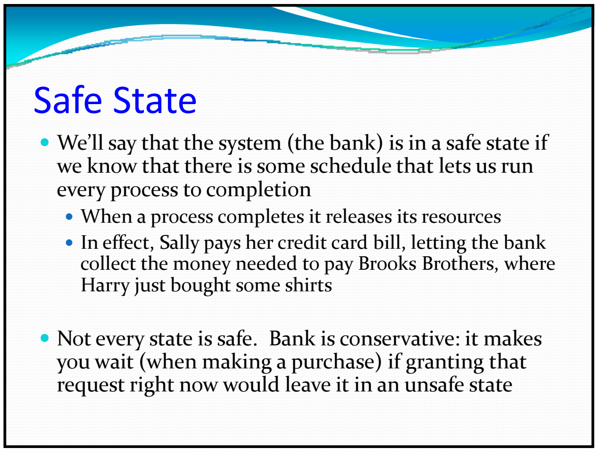
Ordering Prevents Circular Wait

- 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



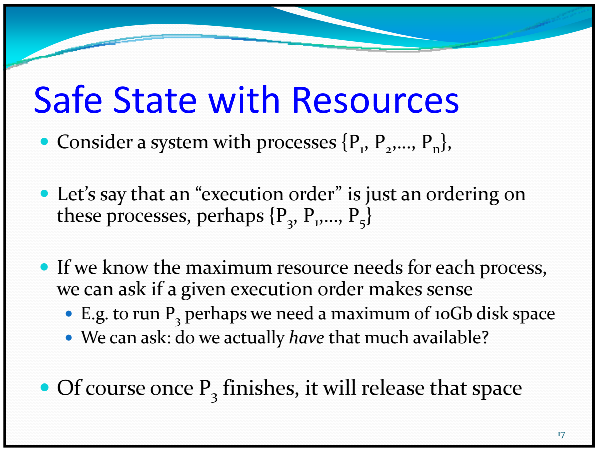
Banker's Algorithm

- Avoids deadlock using an idea similar to the way banks manage credit cards
- For each process there is a "line of credit" corresponding to its maximum use of each kind of resource
  - E.g. "Sally can borrow up to $10,000 plus up to £1,500 and ¥3,000"
  - "Process P can use up to 10Mb of memory, and up to 25Gb of disk storage"
- Each separate resource would have its own limit.
- Banker needs to be sure that if customers pay their bills, it can pay the merchants. Banker's algorithm uses the identical idea for resources.



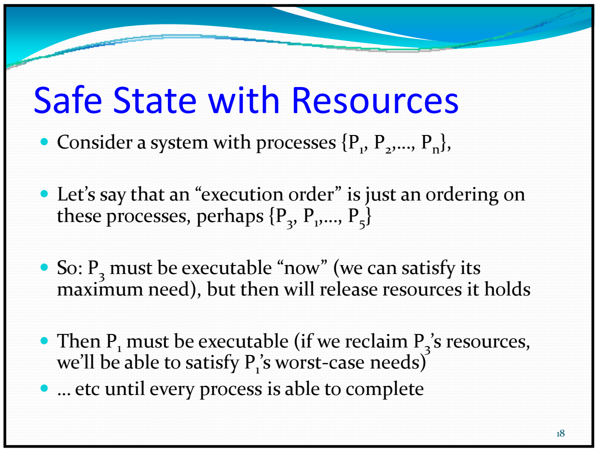
Safe State

- We'll say that the system (the bank) is in a safe state if we know that there is some schedule that lets us run every process to completion
  - When a process completes it releases its resources
  - In effect, Sally pays her credit card bill, letting the bank collect the money needed to pay Brooks Brothers, where Harry just bought some shirts
- Not every state is safe. Bank is conservative: it makes you wait (when making a purchase) if granting that request right now would leave it in an unsafe state



Safe State with Resources

- Consider a system with processes {P_1, P_2,…, P_n},
- Let's say that an "execution order" is just an ordering on these processes, perhaps {P_3, P_1,…, P_5}
- If we know the maximum resource needs for each process, we can ask if a given execution order makes sense
  - E.g. to run P_3 perhaps we need a maximum of 10Gb disk space
  - We can ask: do we actually *have* that much available?
- Of course once P_3 finishes, it will release that space



Safe State with Resources

- Consider a system with processes {P_1, P_2,…, P_n},
- Let's say that an "execution order" is just an ordering on these processes, perhaps {P_3, P_1,…, P_5}
- So: P_3 must be executable "now" (we can satisfy its maximum need), but then will release resources it holds
- Then P_1 must be executable (if we reclaim P_3's resources, we'll be able to satisfy P_1's worst-case needs)
- … etc until every process is able to complete

Safe State with Resources

- A state is said to be **safe**, if it has an execution sequence
  $\{P_a, P_b, \ldots, P_k\}$, 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 $j < I$
- How do we turn this definition into an algorithm?
  - The idea is simple: keep track of resource allocations
  - If a process makes a request
    - Grant it if (and only if) the resulting state is safe
    - Delay it if the resulting state would be unsafe

Confusing because…

- Keep in mind that the actual execution may not be the one that the bank used to convince itself that the state is safe
- For example, the banker's algorithm might be looking at a request for disk space by process P_7.
  - So it thinks "What if I grant this request?"
  - Computes the resulting resource allocation state
  - Then finds that $\{P_3, P_1, \ldots, P_5\}$ is a possible execution
  - … so it grants P_7's request. Yet the real execution doesn't have to be $\{P_3, P_1, \ldots, P_5\}$ – this was just a worst case option

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

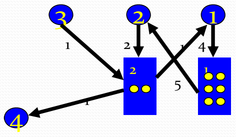
process	holding	max claims
A	4	6
B	4	11
C	2	9

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.

Res. Alloc. Graph Algorithm

- Recall our resource allocation graphs… in fact the Banker's Algorithm works by finding a graph reduction sequence:
  - For a requested resource it computes the resulting resource allocation graph in which every process requests its maximum need
  - Then checks to see if that graph can be reduced. If so the state is safe and the request is granted. If not the request must wait.
  - Graph reduction order is the "safe schedule"



Banker's Algorithm

- So…
  - A process pre-declares its worst-case needs
  - Then it asks for what it "really" needs, a little at a time
  - The algorithm decides when to grant requests
- It delays a request unless:
  - It can find a sequence of processes…
  - …. such that it could grant their outstanding need…
  - … so they would terminate…
  - … letting it collect their resources…
  - … and in this way it can execute everything to completion!

Banker's Algorithm

- How will it really do this?
  - The algorithm will just implement the graph reduction method for resource graphs
  - Graph reduction is "like" finding a sequence of processes that can be executed to completion
- So: given a request
  - Build a resource graph
  - See if it is reducible, only grant request if so
  - Else must delay the request until someone releases some resources, at which point can test again

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
```

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, Po>

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?

Problems with Banker's Alg.

- May be hard to figure out the maximum needs
  - If too conservative, Bank doesn't allow any parallelism
  - But if too optimistic, a process could exceed its limit
    - It can request a bigger limit (a bigger "line of credit")
    - We can grant that request if the state would still be safe
    - But we might not be able to do so, and in that case the process would have to wait, or be terminated
- Some real systems use Banker's Algorithm but it isn't very common. Many just impose limits
  - If resource exhaustion occurs, they blue screen

Deadlock summary

- We've looked at two kinds of systems
  - Process-wait situations, where "process P is waiting for process Q" – common when using locks
  - Resource-wait situations, where "Process P needs resource R" – more general
- We identified necessary conditions for deadlock in the process-wait case
- We found ways to test for deadlock
- And we developed ways to build deadlock-free systems, such as ordered requests and Bankers Algorithm

Real systems?

- Some real systems use these techniques
- Others just recommend that you impose time-limits whenever you wait, for anything
  - But you need to decide what you'll do when a timeout expires!
- Database transactions are a very effective option, but only if you are working with databases or files.