Deadlocks

But crises and deadlocks when they occur have at least this advantage, that they force us to think.

— *Jawaharlal Nehru*

Overview

- Resources
- Why do deadlocks occur?
- Dealing with deadlocks
  - Ignoring them: ostrich algorithm
  - Detecting & recovering from deadlock
  - Avoiding deadlock
  - Preventing deadlock

Resources

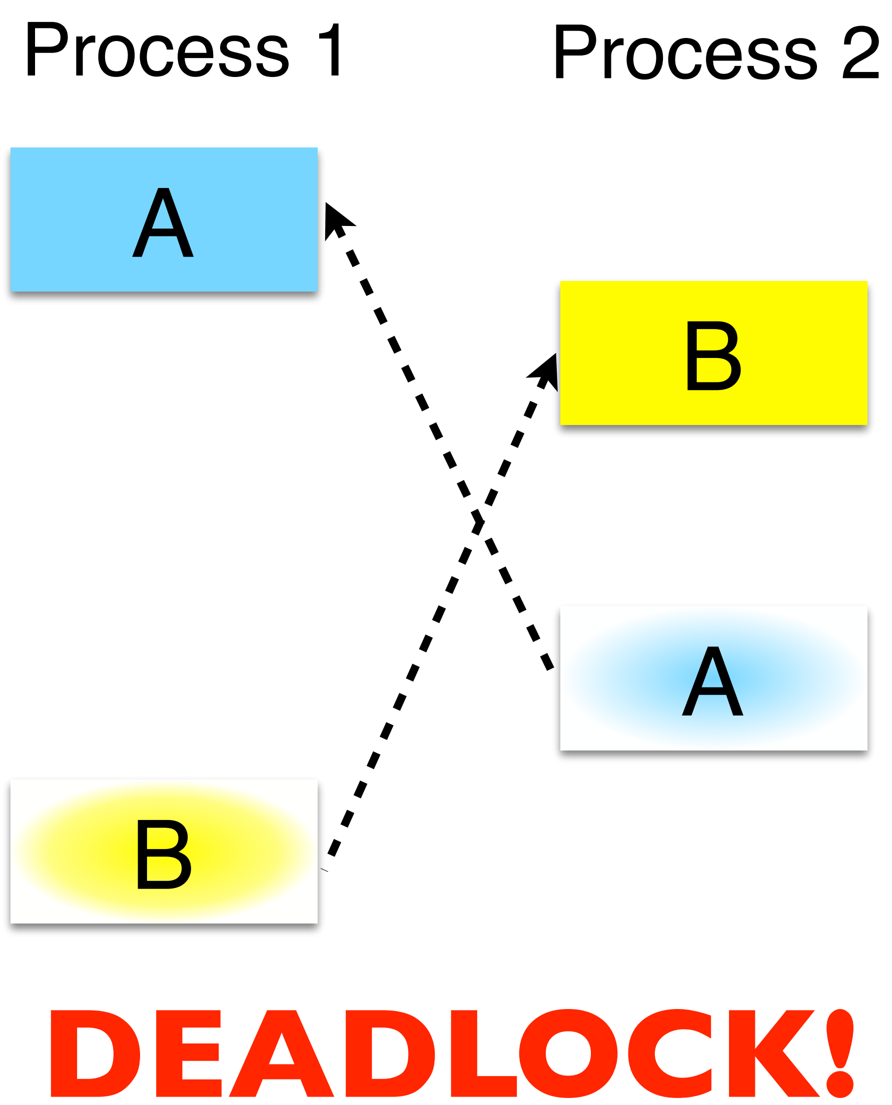
- Resource: something a process uses
  - Usually limited (at least somewhat)
- Examples of computer resources
  - Printers
  - Semaphores / locks
  - Memory
  - Tables (in a database)
- Processes need access to resources in reasonable order
- Two types of resources:
  - Preemptable resources: can be taken away from a process with no ill effects
  - Nonpreemptable resources: will cause the process to fail if taken away

Using resources

- Sequence of events required to use a resource
  - Request the resource
  - Use the resource
  - Release the resource
- Can't use the resource if request is denied
  - Requesting process has options
    - Block and wait for resource
    - Continue (if possible) without it: may be able to use an alternate resource
    - Process fails with error code
  - Some of these may be able to prevent deadlock…

When do deadlocks happen?

- Suppose
  - Process 1 holds resource A and requests resource B
  - Process 2 holds B and requests A
  - Both can be blocked, with neither able to proceed
- Deadlocks occur when …
  - Processes are granted exclusive access to devices or software constructs (resources)
  - Each deadlocked process needs a resource held by another deadlocked process

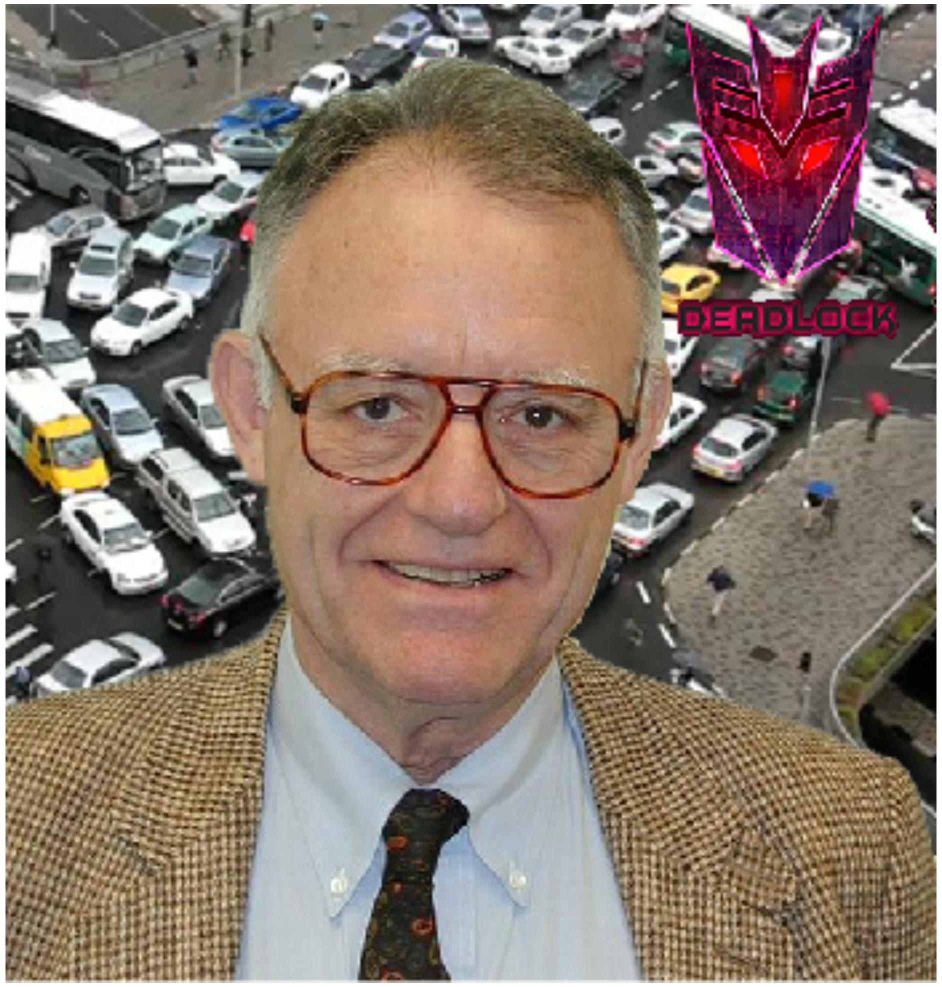


What is a deadlock?

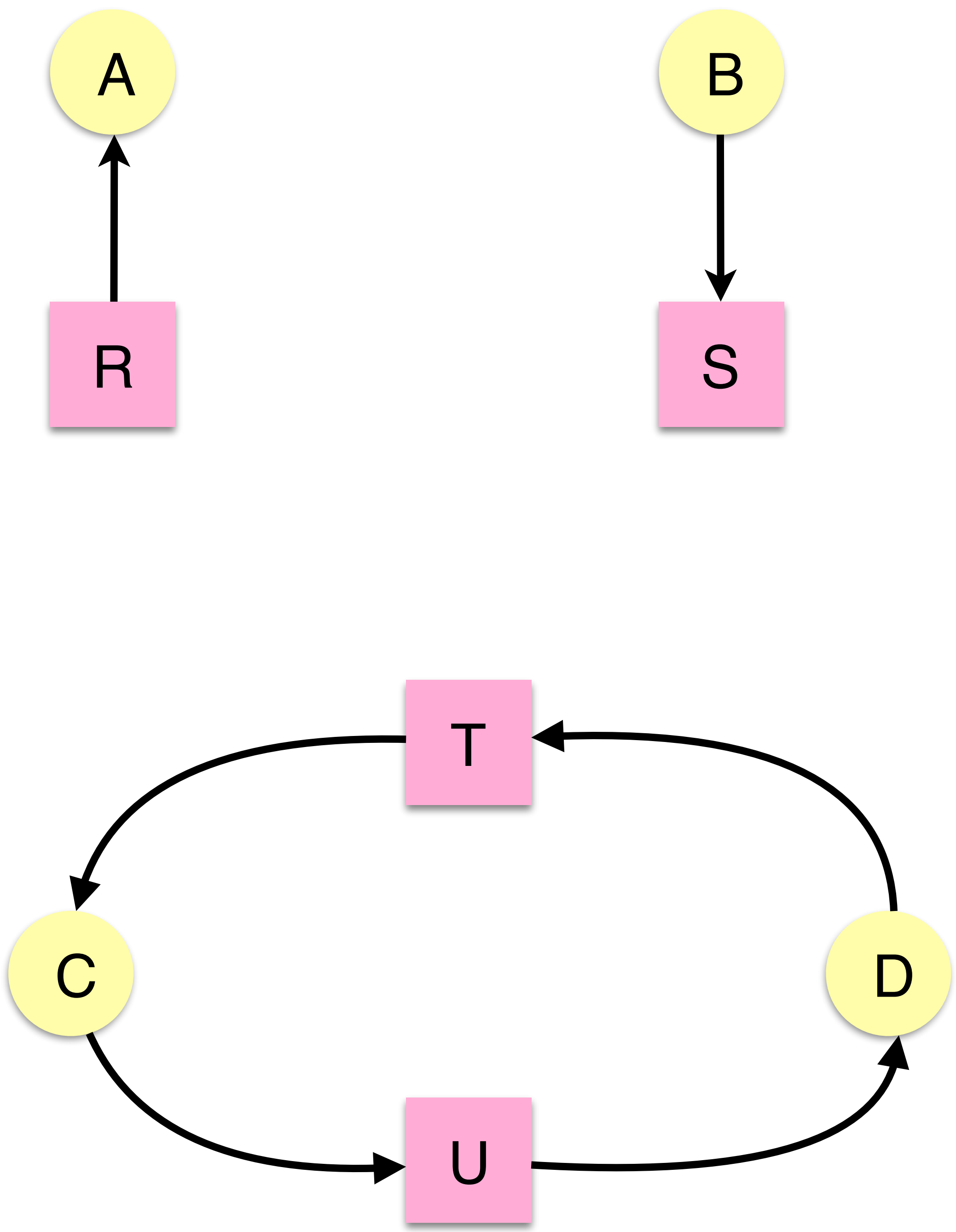
- Formal definition:
  "A set of processes is deadlocked if each process in the set is waiting for an event that only another process in the set can cause."
- Usually, the event is release of a currently held resource
- In deadlock, none of the processes can
  - Run
  - Release resources
  - Be awakened

Four conditions for deadlock

- Mutual exclusion
  - Each resource is assigned to at most one process
- Hold and wait
  - A process holding resources can request more resources
- No preemption
  - Previously granted resources cannot be forcibly taken away
- Circular wait
  - There must be a circular chain of 2 or more processes where each is waiting for a resource held by the next member of the chain



Resource allocation graphs



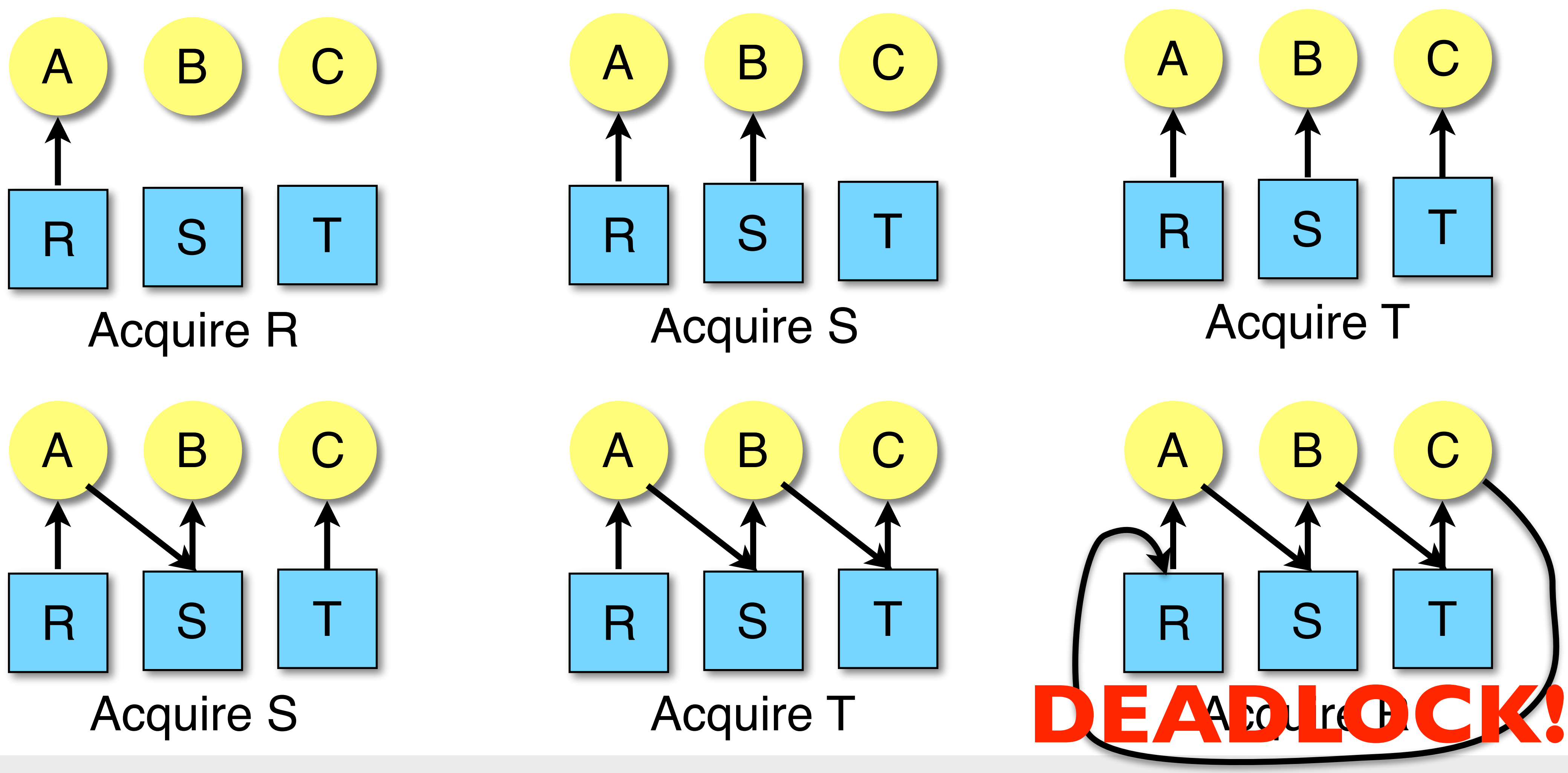
- Resource allocation modeled by directed graphs
- Example 1:
  - Resource R assigned to process A
- Example 2:
  - Process B is requesting / waiting for resource S
- Example 3:
  - Process C holds T, waiting for U
  - Process D holds U, waiting for T
  - C and D are in deadlock!

Dealing with deadlock

- How can the OS deal with deadlock?
  - Ignore the problem altogether!
    - Hopefully, it'll never happen…
  - Detect deadlock & recover from it
  - Dynamically avoid deadlock
    - Careful resource allocation
  - Prevent deadlock
    - Remove at least one of the four necessary conditions
- We'll explore these tradeoffs

Getting into deadlock

A	B	C
Acquire R	Acquire S	Acquire T
Acquire S	Acquire T	Acquire R
Release R	Release S	Release T
Release S	Release T	Release R



The Ostrich Algorithm

- Pretend there's no problem
- Reasonable if
  - Deadlocks occur very rarely
  - Cost of prevention is high
- UNIX and Windows take this approach
  - Resources (memory, CPU, disk space) are plentiful
  - Deadlocks over such resources rarely occur
  - Deadlocks typically handled by rebooting
- Trade off between convenience and correctness

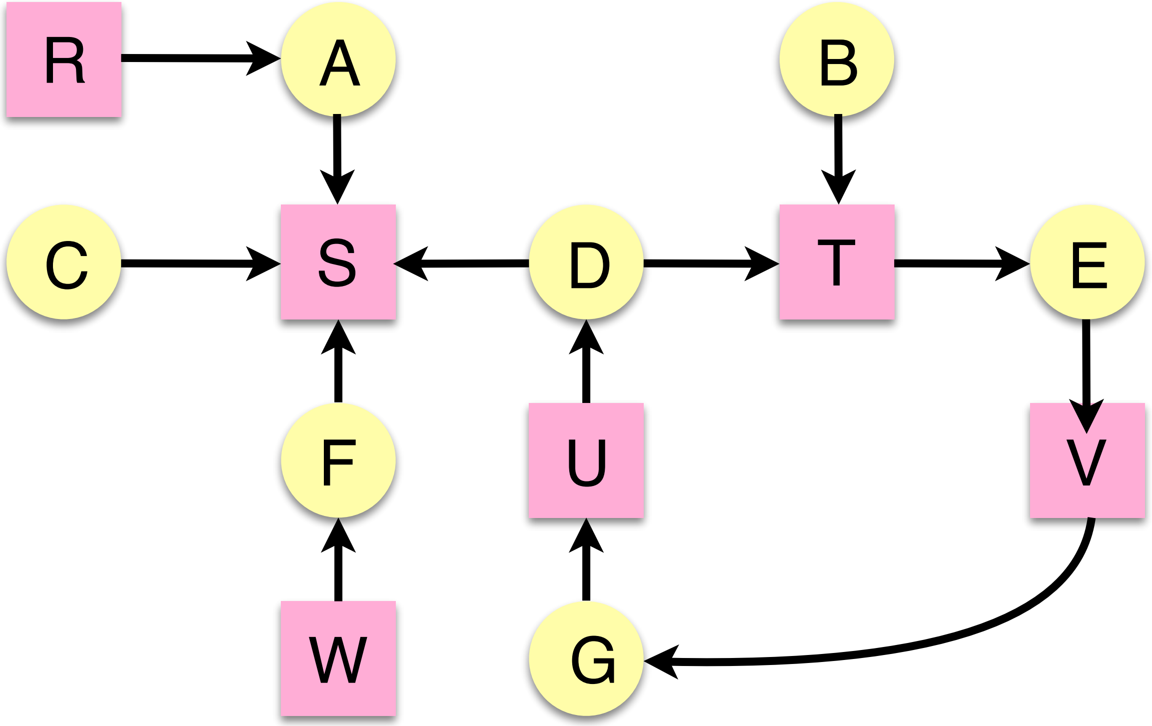
Not getting into deadlock…

- Many situations may result in deadlock (but don't have to)
  - In previous example, A could release R before C requests R, resulting in no deadlock
  - Can we always get out of it this way?
- Find ways to:
  - Detect deadlock and reverse it
  - Stop it from happening in the first place

Detecting deadlocks using graphs

- Process holdings and requests in the table and in the graph (they're equivalent)
- Graph contains a cycle ⇒ deadlock!
  - Easy to pick out by looking at it (in this case)
  - Need to mechanically detect deadlock
- Not all processes are deadlocked (A, C, F not in deadlock)

Process	Holds	Wants
A	R	S
B		T
C		S
D	U	S,T
E	T	V
F	W	S
G	V	U



Deadlock detection algorithm

- General idea: try to find cycles in the resource allocation graph
- Algorithm: depth-first search at each node
  - Mark arcs as they're traversed
  - Build list of visited nodes
  - If node to be added is already on the list, a cycle exists!
- Cycle ⇒ deadlock

```
For each node N in the graph {
  Set L = empty list
  unmark all arcs
  Traverse (N,L)
}
If no deadlock reported by now, there isn't
any

define Traverse (C,L) {
  If C in L, report deadlock!
  Add C to L
  For each unmarked arc from C {
    Mark the arc
    Set A = arc destination
    /* NOTE: L is a
       local variable */
    Traverse (A,L)
  }
}
```

Recovering from deadlock

- Recovery through preemption
  - Take a resource from some other process
  - Depends on nature of the resource and the process
- Recovery through rollback
  - Checkpoint a process periodically
  - Use saved state to restart the process if it's in deadlock
  - May present a problem if the process affects lots of "external" things
- Recovery through killing processes
  - Crudest but simplest way to break a deadlock: kill one of the processes in the deadlock cycle
  - Other processes can get its resources
  - Try to choose a process that can be rerun from the start
    - Pick one that hasn't run too far already

Preventing deadlock

- Deadlock can be completely prevented!
- Ensure that at least one of the conditions for deadlock never occurs
  - Mutual exclusion
  - Circular wait
  - Hold & wait
  - No preemption
- Not always possible…

Eliminating mutual exclusion

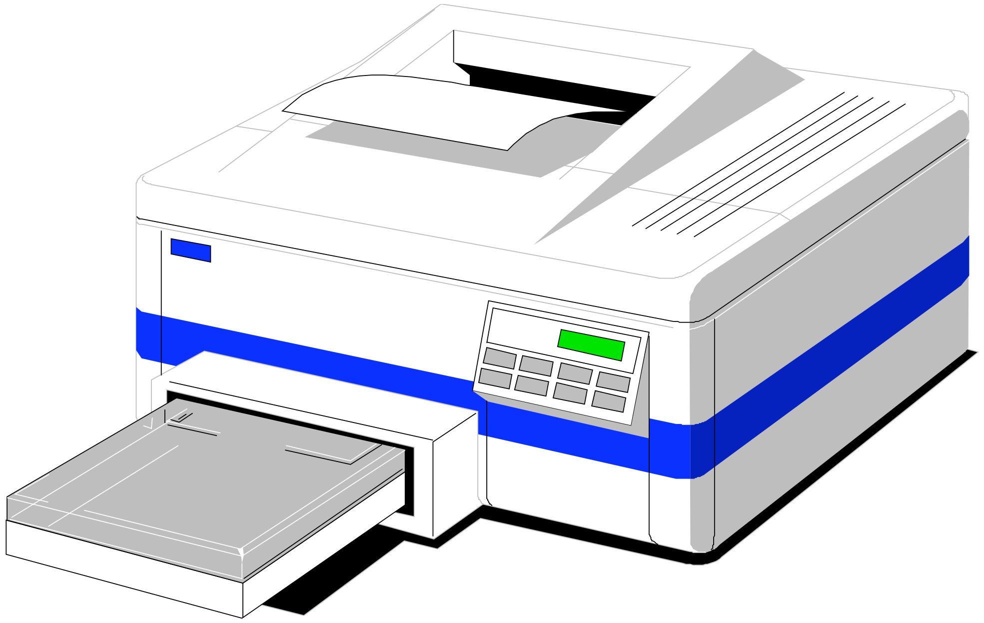
- Some devices (such as printer) can be spooled
  - Only the printer daemon uses printer resource
  - This eliminates deadlock for printer
- Not all devices can be spooled
- Principle:
  - Avoid assigning resource when not absolutely necessary
  - As few processes as possible actually claim the resource

Attacking “hold and wait”

- Require processes to request resources before starting
  - A process never has to wait for what it needs
- This can present problems
  - A process may not know required resources at start of run
  - This also ties up resources other processes could be using
    - Processes will tend to be conservative and request resources they might need
- Variation: a process must give up all resources before making a new request
  - Process is then granted all prior resources as well as the new ones
  - Problem: what if someone grabs the resources in the meantime—how can the process save its state?

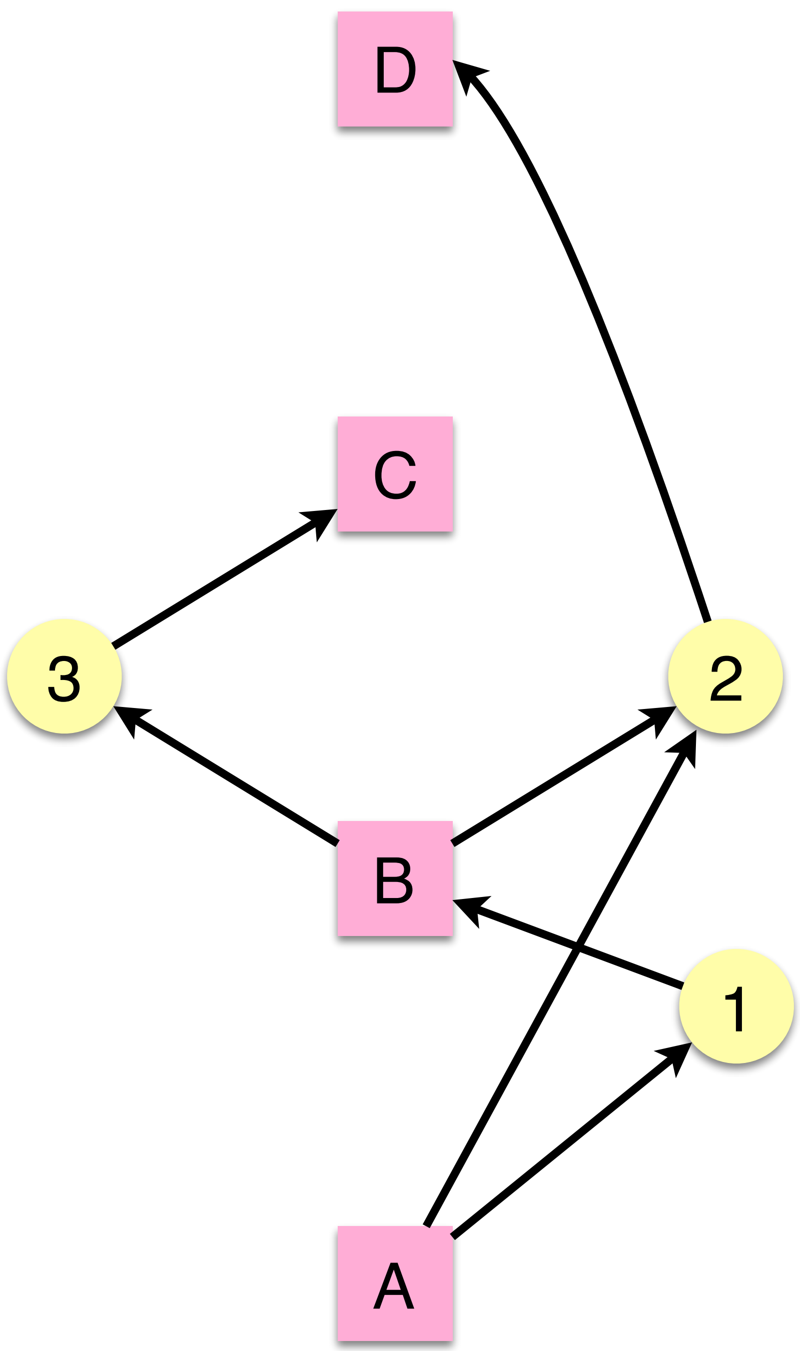
Attacking “no preemption”

- This is not usually a viable option
- Consider a process given the printer
  - Halfway through its job, take away the printer
  - Confusion ensues!
- May work for some resources
  - Forcibly take away memory pages, suspending the process
  - Process may be able to resume with no ill effects



Attacking "circular wait"

- Assign an order to resources
- Always acquire resources in numerical order
  - Need not acquire them all at once!
- Circular wait is prevented
  - A process holding resource *n* can't wait for resource *m* if $m < n$
  - No way to complete a cycle!
    - Place processes above the highest resource they hold and below any they're requesting
    - All arrows point up!



What does FreeBSD do?

- What resources are at issue?
  - Locks & semaphores: one holder at a time!
  - Physical resources: not typically a concern
    - There are millions of (interchangeable) pages
    - Limited resources (*e.g.*, printer) only used for a short time and then released
- Goal: prevent deadlock
  - Mechanism must be low-cost (fast & efficient)
  - Mechanism must be simple & flexible
- Two basic approaches
  - Locks / semaphores: use resource ordering
    - Must acquire resources in "group" order
  - Printers and other "limited" hardware resources: manage with a single process
    - No hold & wait: processes that want to use them queue up requests
    - Manager process is the only one to directly use the device

Deadlock prevention: summary

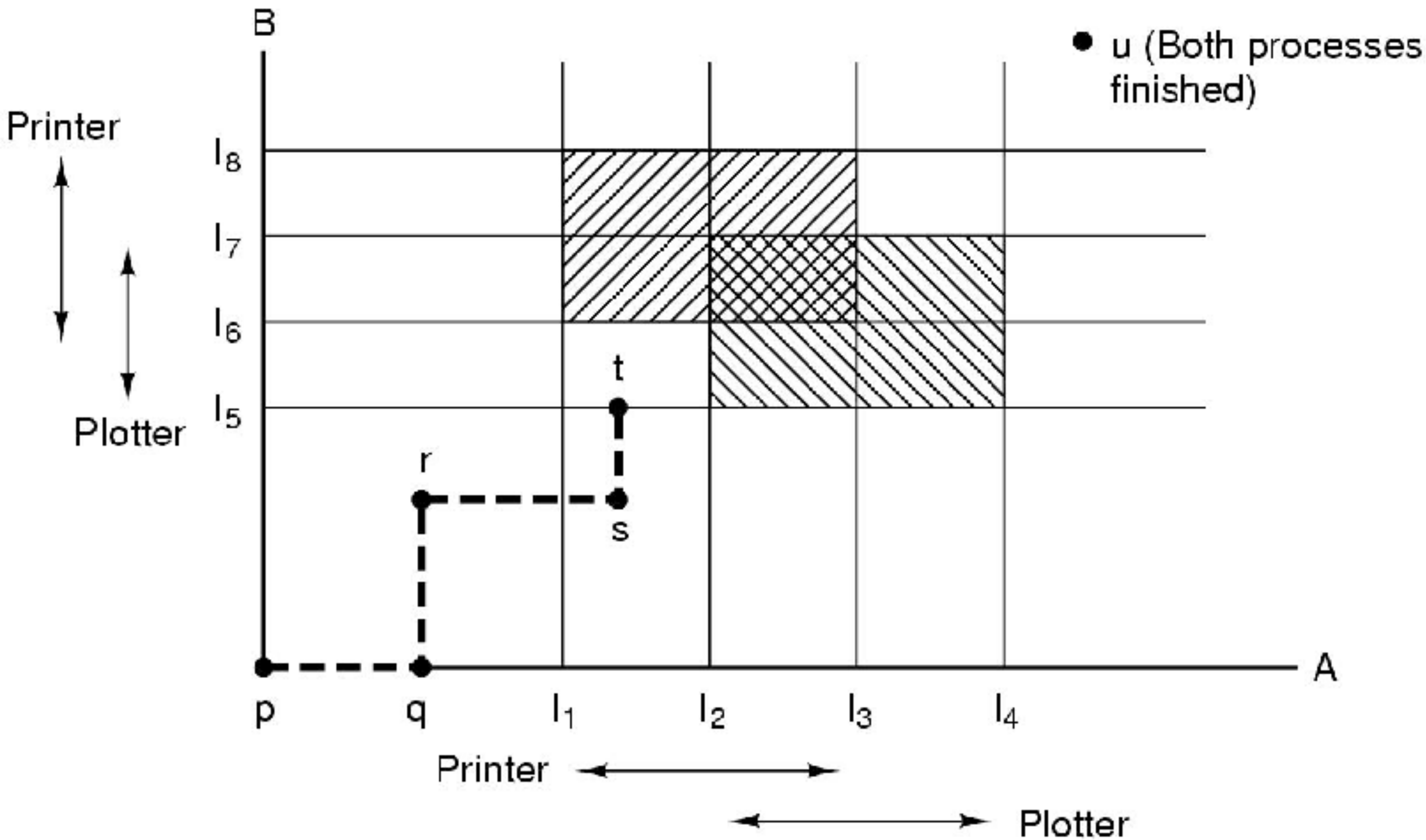
Condition	Prevented by
Mutual exclusion	Spool everything
Hold and wait	Request all resources initially
No preemption	Take resources away if there's not a complete set
Circular wait	Order resources numerically

Example: two-phase locking

- Phase One
  - Process tries to lock all data it needs, one at a time
  - If needed data found locked, start over
    (no real work done in phase one)
- Phase Two
  - Perform updates
  - Release locks
- Note similarity to requesting all resources at once
- This is often used in databases

- What condition does this avoid?

Resource trajectories



Two process resource trajectories

Handling resources with multiple instances

- Previous algorithm only works if there's one instance of each resource
- If there are multiple instances of each resource, we need a different method
  - Track current usage and requests for each process
  - To detect deadlock, try to find a scenario where all processes can finish
  - If no such scenario exists, we have deadlock

Deadlock detection algorithm

	A	B	C	D
Avail	2	3	0	1

Hold

Process	A	B	C	D
1	0	3	0	0
2	1	0	1	1
3	0	2	1	0
4	2	2	3	0

Want

Process	A	B	C	D
1	3	2	1	0
2	2	2	0	0
3	3	5	3	1
4	0	4	1	1

Note: want[j],hold[j],current,avail are arrays!

```
current = avail;
for (j = 0; j < N; j++) {
    for (k=0; k<N; k++) {
        if (finished[k])
            continue;
        if (want[k] < current) {
            finished[k] = 1;
            current += hold[k];
            break;
        }
    }
    if (k==N) {
        printf "Deadlock!\n";
        // finished[k]==0 means process
        // is in the deadlock
        break;
    }
}
}
```

Safe and unsafe states

	Has	Max
A	3	9
B	2	4
C	2	7
Free: 3		

	Has	Max
A	3	9
B	4	4
C	2	7
Free: 1		

	Has	Max
A	3	9
B	0	-
C	2	7
Free: 5		

	Has	Max
A	3	9
B	0	-
C	7	7
Free: 0		

	Has	Max
A	3	9
B	0	-
C	0	-
Free: 7		

Demonstration that the first state is safe

	Has	Max
A	3	9
B	2	4
C	2	7
Free: 3		

	Has	Max
A	4	9
B	2	4
C	2	7
Free: 2		

	Has	Max
A	4	9
B	4	4
C	2	7
Free: 0		

	Has	Max
A	4	9
B	0	-
C	2	7
Free: 4		

Demonstration that the second state is unsafe

Banker's Algorithm for a single resource

	Has	Max
A	0	6
B	0	5
C	0	4
D	0	7
Free: 10		

Any sequence finishes

	Has	Max
A	1	6
B	1	5
C	2	4
D	4	7
Free: 2		

C,B,A,D finishes

	Has	Max
A	1	6
B	2	5
C	2	4
D	4	7
Free: 1		

Deadlock (unsafe state)

- Bankers' algorithm: before granting a request, ensure that a sequence exists that will allow all processes to complete
  - Use previous methods to find such a sequence
  - If a sequence exists, allow the requests
  - If there's no such sequence, deny the request
- Can be slow: must be done on each request!

Banker's Algorithm with multiple resources

Process	Tape drives	Plotters	Scanners	DVD-ROMs
A	3	0	1	1
B	0	1	0	0
C	1	1	1	0
D	1	1	0	1
E	0	0	0	0

Resources assigned

Process	Tape drives	Plotters	Scanners	DVD-ROMs
A	1	1	0	0
B	0	1	1	2
C	3	1	0	0
D	0	0	1	0
E	2	1	1	0

Resources still needed

Total resources:	6 3 4 2
Already claimed:	5 3 2 2
Available:	1 0 2 0

Starvation

- Algorithm to allocate a resource
  - Give the resource to the shortest job first
- Works great for multiple short jobs in a system
- May cause long jobs to be postponed indefinitely
  - Even though not blocked
- Solution
  - First-come, first-serve policy
- Starvation can lead to deadlock
  - Process starved for resources can be holding resources
  - If those resources aren't used and released in a timely fashion, shortage could lead to deadlock

Livelock

- Sometimes, processes can still run, but not make progress
- Example: two processes want to use resources A and B
  - P0 gets A, P1 gets B
  - Each realizes that a deadlock will occur if they proceed as planned!
  - P0 drops A, P1 drops B
  - P0 gets B, P1 gets A
  - Same problem as before
  - This can go on for a very long time...
- Real-world example: Ethernet transmission collisions
  - If there's a "collision" on the wire, wait and try again
  - Multiple processes waited the exact same amount of time...