Chapter 7: Deadlock

CSCI 3753 Operating Systems

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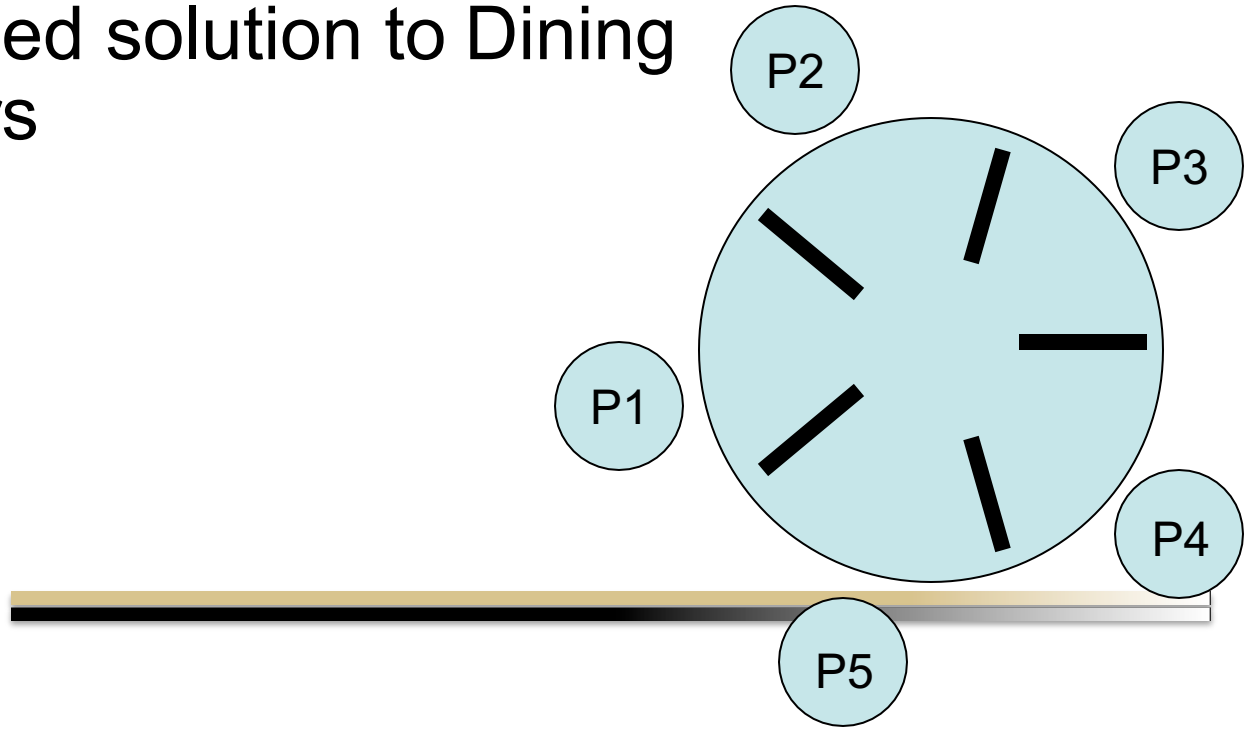
Announcements

- PA2 & PS2 next Monday, June 26th
  - Add a device driver to Linux using kernel modules

- Reading: Chapter 7
  - Next week
    - Ch. 7 - Deadlock
    - Ch. 6 - Scheduling

Recap

- Monitors for implicit mutual exclusion
- Condition variables for ordering
  - x.wait()
  - x.signal() differs from semaphore's signal()
- Monitor-based solution to Dining Philosophers



Complete Monitor-based Solution to Dining Philosophers

```
monitor DP {
   status state[5];
   condition self[5];

   Pickup(int i) {
      state[i] = hungry;
      test(i);
      if(state[i]!=eating)
         self[i].wait;
   }

   test(int i) {
      if (state[(i+1)%5] != eating &&
         state[(i-1)%5] != eating &&
         state[i] == hungry) {

         state[i] = eating;
         self[i].signal();
      }
   }
```

```
   Putdown(int i) {
         state[i] = thinking;
         test((i+1)%5);
         test((i-1)%5);
      }


      init() {
         for i = 0 to 4
            state[i] = thinking;
      }

   }  // end of monitor
```

- Pickup(), Putdown() and test() are all mutually exclusive, i.e. only one at a time can be executing
- Verify that this monitor-based solution is
  - deadlock-free
  - mutually exclusive in that no 2 neighbors can eat simultaneously

Deadlock Can Easily Occur

- Carefully engineered synchronization solutions to avoid deadlock
  - The 3 classic synchronization problems like Dining Philosophers, Readers/Writers, and Bounded Buffer P/C
- saw earlier that semaphores provide mutual exclusion, but can introduce deadlock
  - 2 tasks, each desires a resource locked by the other process
  - Circular dependency
  - can occur easily due to programming errors, e.g. by switching order of P and V, etc.

Deadlock Is Hard To Anticipate

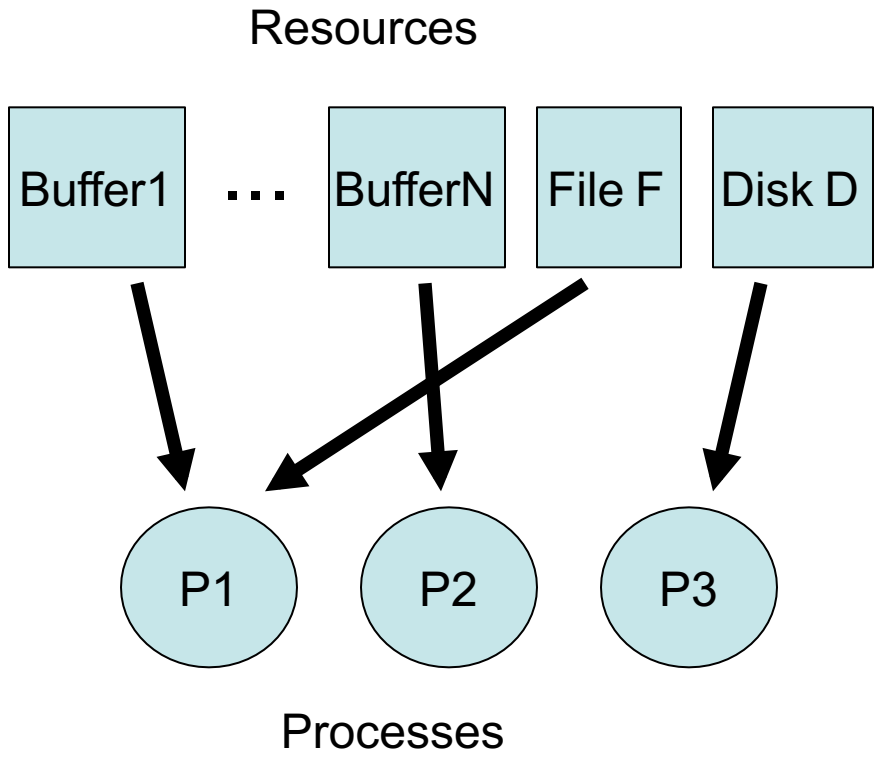
- Difficult to anticipate by looking at code of a single process or thread
  - deadlock is a higher-level concept that involves the distributed behavior of multiple processes/threads, e.g. a lengthy circular dependency across many Dining Philosophers
- Example:
  - a Web server talks with a MySQL database which talks with a data mining process which communicates back to the Web server
  - Each task is written by a different programmer with no advanced knowledge how it might be used with other tasks
- deadlock is difficult to anticipate, detect, reproduce, prevent, avoid, and recover from

Deadlock: General Solution?

- Want a general solution to deadlock that is not restricted to the solutions for the 3 classic problems of DP, R/W, and BB P/C
- A set of processes is in a deadlock state when every process in the set is waiting for an event (e.g. release of a resource) that can only be caused by another process in the set
  - You have a circular dependency
- multithreaded and multi-process applications are good candidates for deadlock
  - thread-thread deadlock within a process
  - process-process deadlock

Modeling Deadlock

- Develop a model so we can see circular dependency
  - to use a resource, a process must
    1. request() a resource -- must *wait* until it's available
    2. use() or hold() a resource
    3. release() a resource
  - thus, we have resources and processes
  - Most of the following discussion will focus on reusable resources



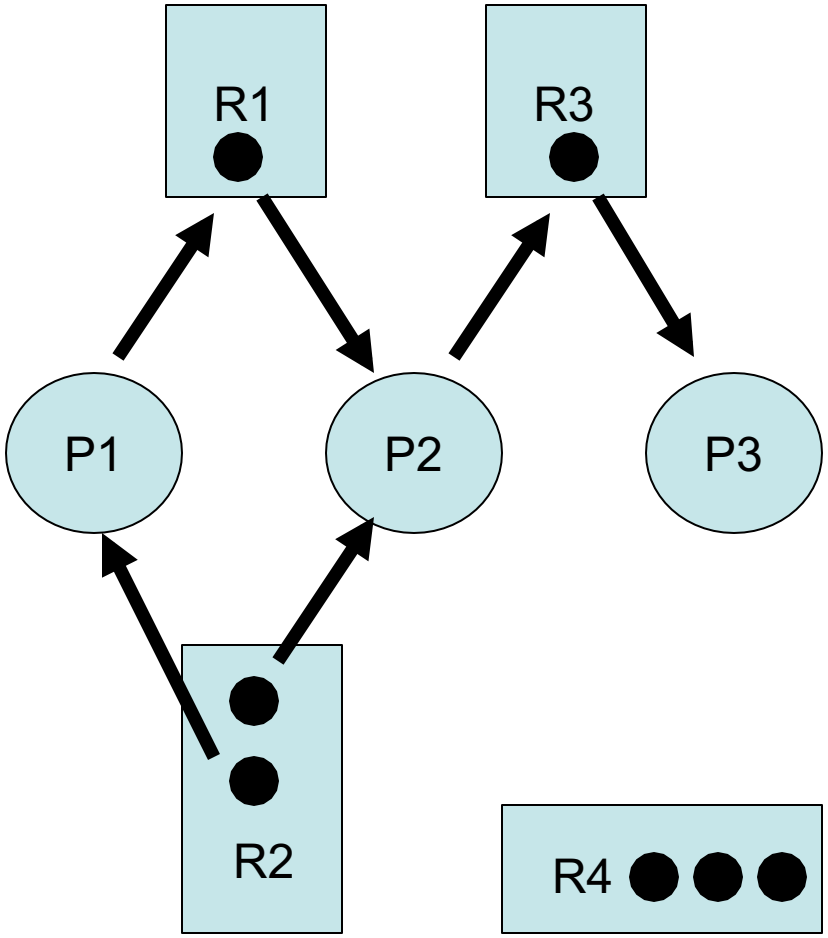
P1 holds Buffer 1 and File F
P2 holds Buffer N
P3 holds Disk D

Modeling Deadlock

- a *resource allocation graph* can be used to model deadlock
  - try to represent deadlock by a *directed graph* D(V,E), consisting of
    - vertices V: namely processes and resources
    - and edges E:
      - a request() for a resource R_j by a process P_i is signified by a directed arrow from process $P_i \rightarrow R_j$
      - a process P_i will hold() a resource R_j via a directed arrow $R_j \rightarrow P_i$

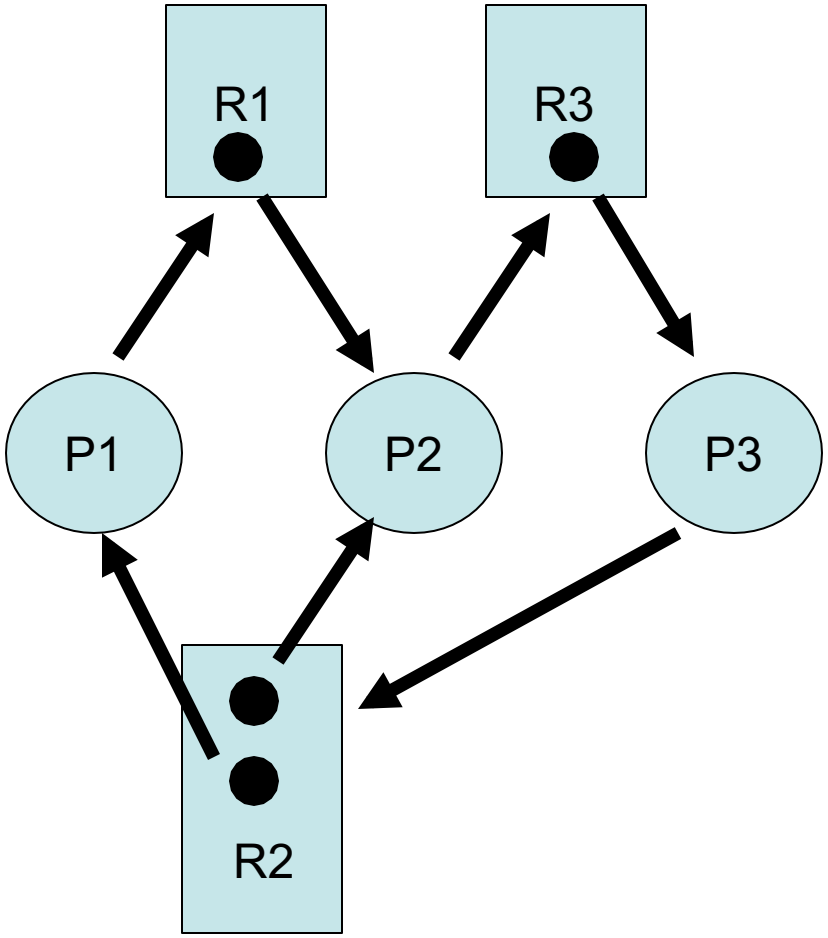
Modeling Deadlock

- Example 1:
  - P1 wants resource R1 but that is held by P2
  - P2 wants resource R3 but that is held by P3
  - Also, P1 holds an *instance* of resource R2, and
  - P2 holds an instance of R2
  - There is no deadlock
    - if the graph contains no cycles or loops, then there is no deadlock



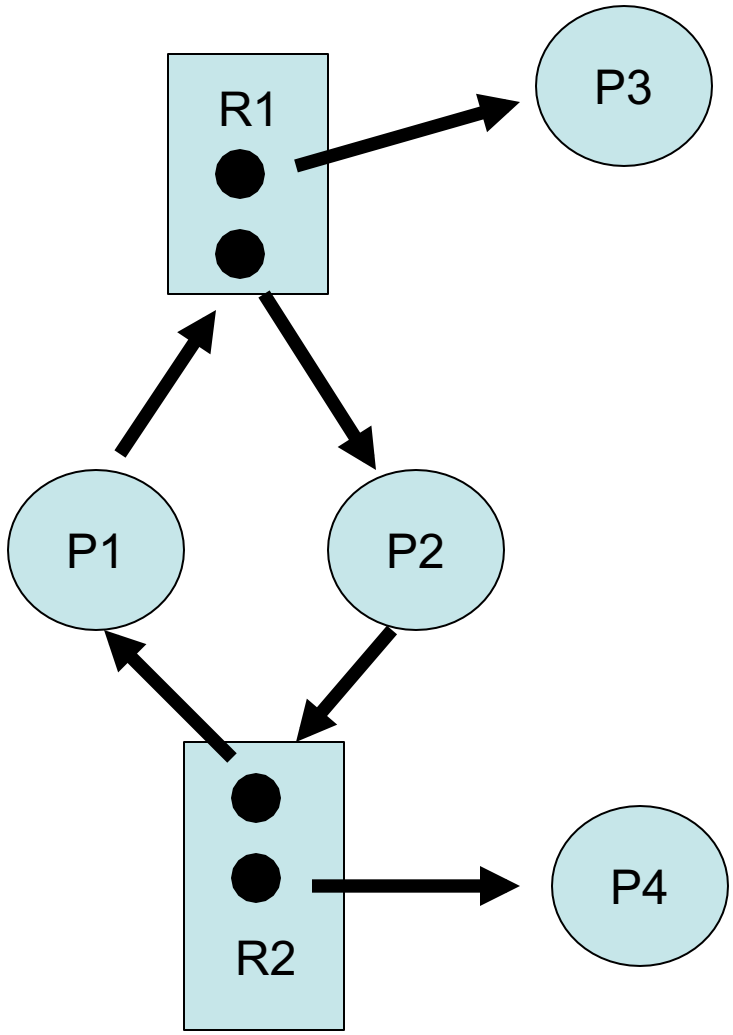
Modeling Deadlock

- Example 2:
  - same graph as before, except now P3 requests instance of R2
  - Deadlock occurs!
    - P3 requests R2, which is held by P2, which requests R3, which is held by P3 - this is a loop
      - $P_3 \rightarrow R_2 \rightarrow P_2 \rightarrow R_3 \rightarrow P_3$
      - If P1 could somehow release an instance of R2, then we could break the deadlock
    - But P1 is part of a second loop:
      - $P_3 \rightarrow R_2 \rightarrow P_1 \rightarrow R_1 \rightarrow P_2 \rightarrow R_3 \rightarrow P_3$
      - So P1 can't release its instance of R2
  - if the graph contains cycles or loops, then there *may be the possibility* of deadlock
    - but does a loop guarantee that there is deadlock?



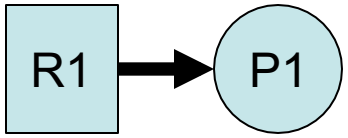
Modeling Deadlock

- Example 3:
  - there is a loop:
    - $P_1 \rightarrow R_1 \rightarrow P_2 \rightarrow R_2 \rightarrow P_1$
  - In this case, there is no deadlock
    - either P3 can release an instance of R1, or P4 can release an instance of R2
      - this breaks any possible deadlock cycle
  - if the graph contains cycles or loops, then there *may be the possibility* of deadlock, but this is not a guarantee of deadlock

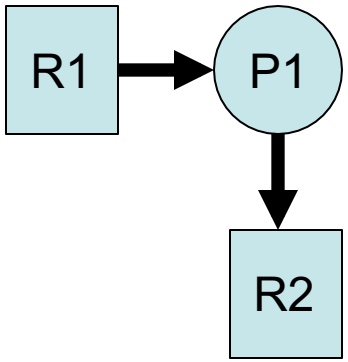


Necessary Conditions for Deadlock

- The following 4 conditions must hold simultaneously for deadlock to arise:
  1. Mutual exclusion
     - at least 1 resource is held in a non-sharable mode. Other requesting processes must wait until the resource is released



  2. Hold and wait
     - a process holds a resource while requesting (and waiting for) another one

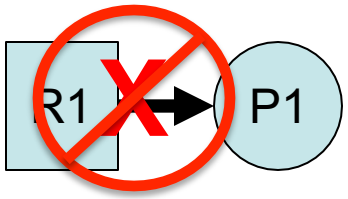


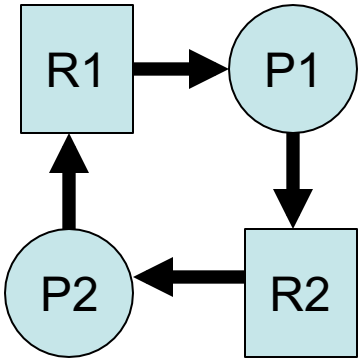
Necessary Conditions for Deadlock

- The following 4 conditions must hold simultaneously for deadlock to arise: (continued)

  3. No preemption:
     - resources cannot be preempted and can only be released voluntarily by the process holding them, after the process is finished. No OS intervention is allowed. A process cannot withdraw its request.

  4. Circular wait
     - A set of n waiting processes {P_0, ..., P_{n-1}} must exist such that Pi waits for a resource held by $P_{(i+1)\%n}$





Solutions to Handling Deadlocks

1. Prevention by OS
   - provide methods to guarantee that at least 1 of the 4 necessary conditions for deadlock does not hold
2. Avoidance by OS
   - the OS is given advanced information about process requests for various resources
   - this is used to determine whether there is a way for the OS to satisfy the resource requests and avoid deadlock

Solutions to Handling Deadlocks

3. Detection and Recovery by OS
   - Analyze existing system resource allocation, and see if there is a sequence of releases that satisifies every process' needs.
   - If not, then deadlock is detected, so must recover – drastic action needed, like killing the affected processes!

Solutions to Handling Deadlocks

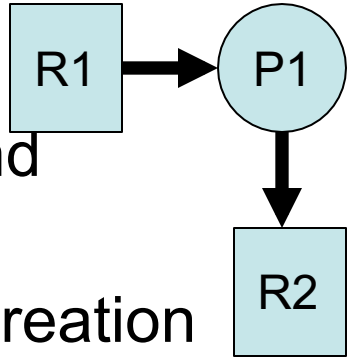
4. Application-level solutions (OS Ignores and Pretends)
   - the most common approach, e.g. UNIX and Windows, based on the assumption that deadlock is relatively infrequent
   - it's up to the application programmer to implement mechanisms that prevent, avoid, detect and deal with application-level deadlock
   - Map your problem to known deadlock-free solutions: e.g. Bounded Buffer P/C, Readers/ Writers problems, Dining Philosophers, …

Deadlock Prevention: Mutual Exclusion

- Prevent the *mutual exclusion* condition #1 from coming true
  - This is opposite of our original goal, which was to provide mutual exclusion.
  - Also, many resources are non-sharable and must be accessed in a mutually exclusive way
    - example: a printer should print a file X to completion before printing a file Y. a printer should not print half of file X, and then print the first half of file Y on the same paper
  - thus, it is unrealistic to prevent mutual exclusion

Deadlock Prevention: Hold and Wait

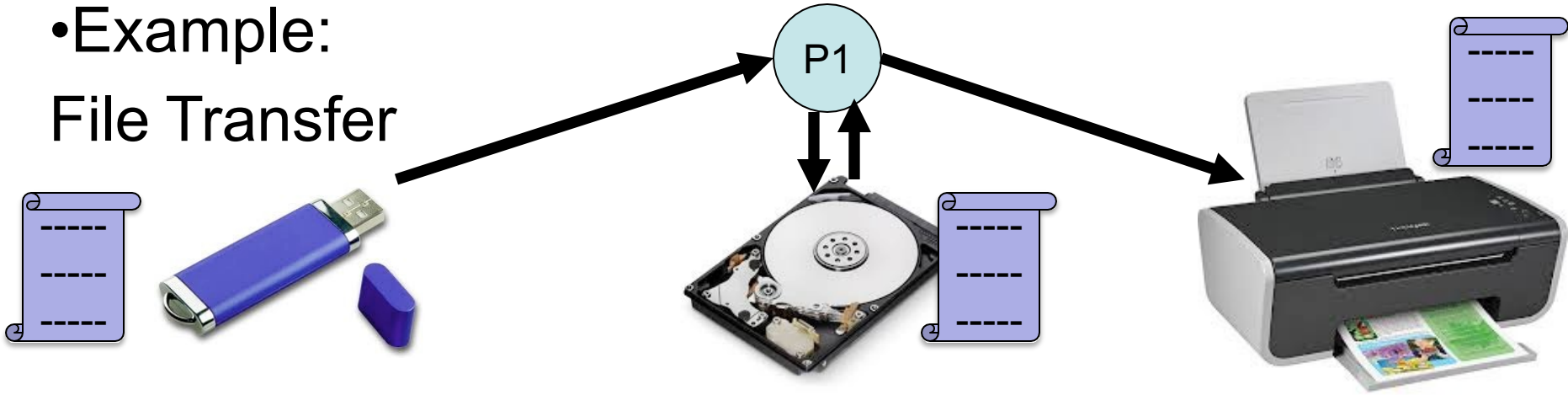
- Prevent the hold and wait condition #2 from coming true
  - prevent a process from holding resources and requesting others
  - Solution I: request all resources at process creation
  - Solution II: release all held resources before requesting a set of new ones simultaneously
  - Solution III: only allow a process to hold one resource at a time



Deadlock Prevention: Hold and Wait

•Example:

File Transfer

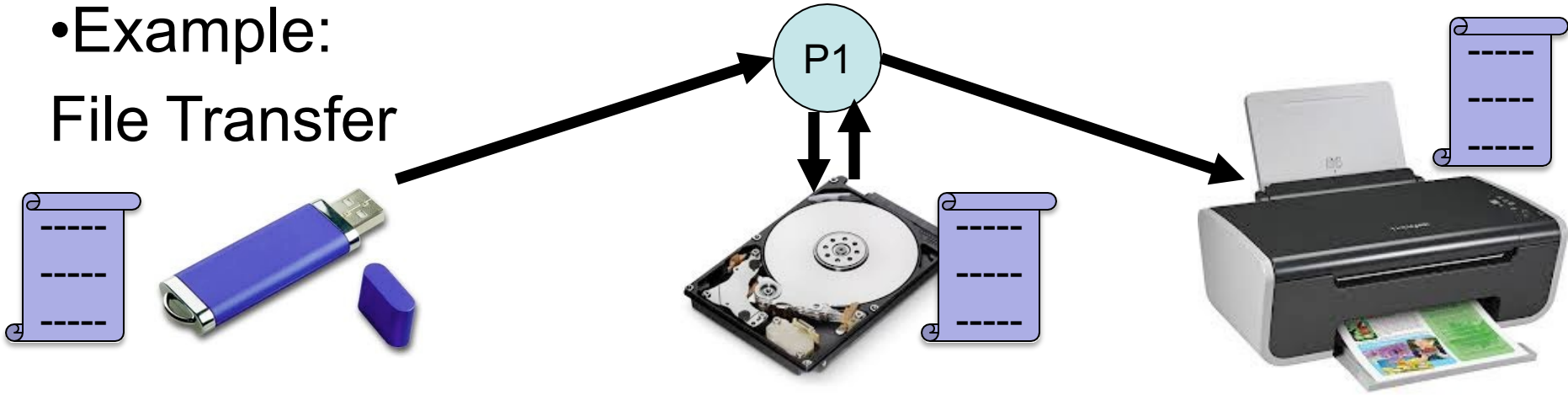


- a process reads file from USB drive and writes it to hard drive, retrieves the file, then sends the file to the printer
  - Solution I: request the USB drive, hard drive, and printer at process creation

Deadlock Prevention: Hold and Wait

•Example:

File Transfer

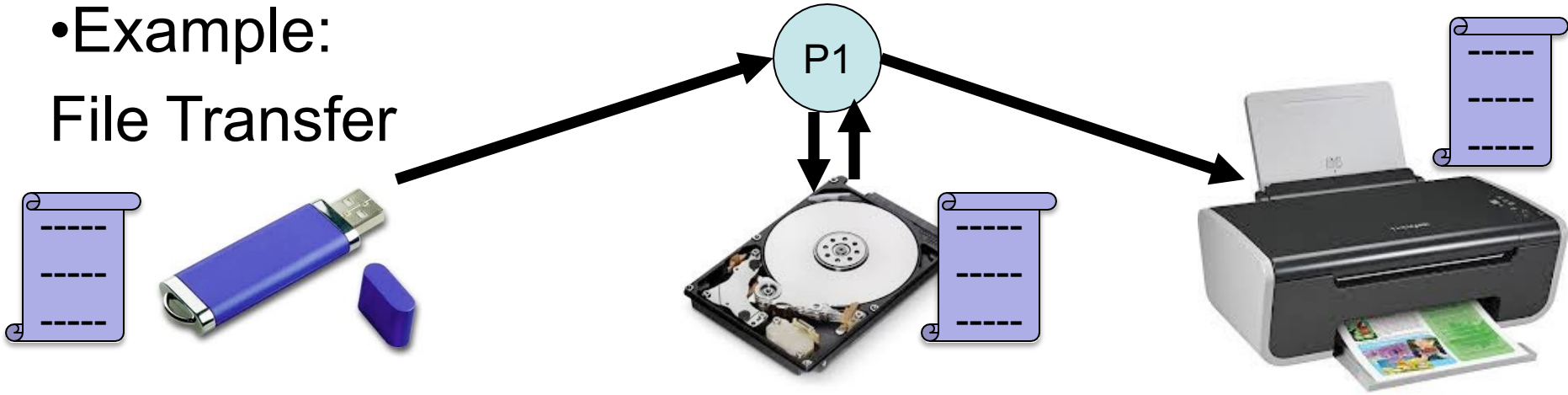


– Solution II: divide task into self-contained stages that release all & then request all resources
  - obtain the USB and hard drive together for the file transfer, then release both together
  - next obtain the hard drive and printer together for the printing operation, then release both together

Deadlock Prevention: Hold and Wait

•Example:

File Transfer



– Solution III:

- Request the USB drive then release
- Request the hard drive then release
- Request the hard drive again then release
- Request the printer then release

Deadlock Prevention: Hold and Wait

- Disadvantages of Hold-and-wait solutions
  - Solution I: don't know in advance all resources needed
  - Solutions I & II: poor resource utilization
    - a process that is holding multiple resources for a long time may only need each resource for a short time during execution
  - Solution II: possible starvation
    - a process that needs several popular resources simultaneously may have to wait a very long time

Deadlock Prevention: Hold and Wait

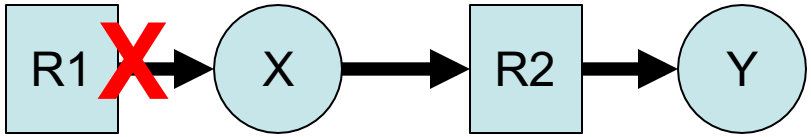
- Disadvantages of Hold-and-wait solutions
  - Solution III: Some processing may require holding more than one resource at a time
    - e.g. writing a file to a printer may require locking both the file and the printer
    - Reading a file from a drive may require locking both the file and the drive

Deadlock Prevention: Hold and Wait

- Example: Dining Philosophers Problem prevented hold-and-wait – How?
  - Enforced a rule that either a philosopher picked up both chopsticks or none at all, i.e. all-or-nothing
  - Hence no holding one chopstick while waiting on the other chopstick

Deadlock Prevention: No Preemption

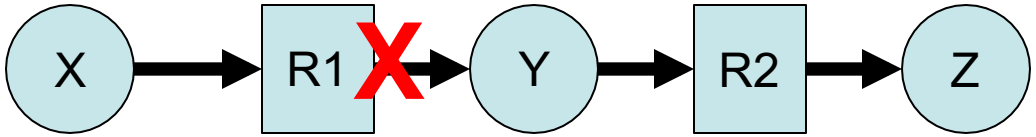
- Prevent the “No Preemption” condition #3 from coming true
  - allow resources to be preempted
  - Policy I:



    - If a Process X requests a held resource, then all resources currently held by X are released.
    - X is restarted only when it can regain all needed resources

Deadlock Prevention: No Preemption

– Policy II:



- If a process X requests a resource held by process Y, then preempt the resource from process Y, but only if Y is waiting on another resource
- Otherwise, X must wait.
- the idea is if Y is holding some resources but is waiting on another resource, then Y has no need to keep holding its resources since Y is suspended

Deadlock Prevention: No Preemption

- Disadvantages:
  - these policies don't apply to all resources, e.g. printers should not be prempted while in the middle of printing, disks should not be preempted while in the middle of writing a block of data
  - can result in unexpected behavior of processes, since an application developer may not know a priori which policy is being used

Deadlock Prevention: Circular Wait

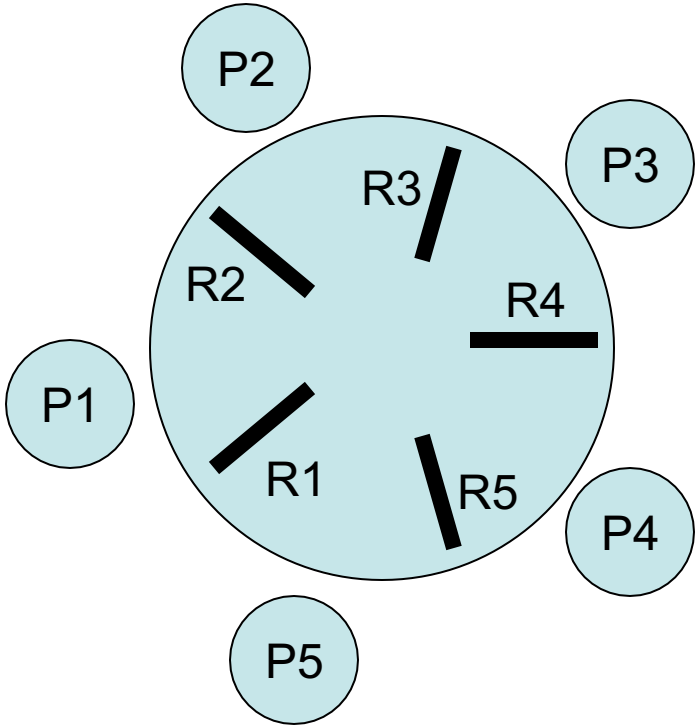
- Prevent the *circular wait* condition #4 from coming true
  - Solution I: a process can only hold 1 resource at a time
    - disadvantage: in some cases, a process needs to hold multiple resources to accomplish a task
  - Solution II: impose a total ordering of all resource types and require each process to request resources in increasing order
    - this prevents a circular wait - see next slide

Deadlock Prevention: Circular Wait

- Solution II example:
  - Order all resources into a list: R1, R2, ..., Rm, where R1 < R2 < ... < Rm
    - tape drive = R1, disk drive = R2, printer = R10, temporary buffer = R22
  - Impose the rule that a process holding R_i can only request R_j if $R_j > R_i$
  - If a process P holds some R_k and requests R_j such that $R_j < R_k$, then the process must release all such R_k, acquire R_j, then reacquire R_k

Deadlock Prevention: Circular Wait

- Applying ordering of resources to break circular waiting in the Dining Philosophers Problem
  - R1 < R2 < R3 < R4 < R5
  - Deadlock happened when all processes first requested their right chopsticks, then requested their left chopsticks
  - Here, P1 to P4 can all request their right then left chopsticks
  - *But Process P5 requests its left (R1) then right (R5) chopstick due to ordering*
    - thus, P5 blocks on R1, not R5, which breaks any possibility of a circular deadlock - why?



Deadlock Prevention: Circular Wait

- Disadvantages of ordering resources:
  - can lead to poor performance, due to releasing and then reacquiring resources
  - Difficult to implement in a dynamic resource environment
    - Coming up with a global scheme for numbering resources

Deadlock Avoidance

- Goal: analyze the system state to see if there is a way to avoid deadlock.
- At startup, each process provides OS with information about all of its requests and releases for resources R_i
  - e.g. batch jobs know a priori which resources they'll request, when, and in which order
- OS decides whether deadlock will occur at run time

Deadlock Avoidance

- Disadvantage: need a priori info
- Simple strategy:
  - each process specifies a maximum claim
  - knowing all individual future requests and releases is difficult
  - Having each process estimate its maximum demand for resources is easier and not completely unreasonable
- A *resource allocation state* is defined by
  - # of available resources
  - # of allocated resources to each process
  - maximum demands by each process

Deadlock Avoidance

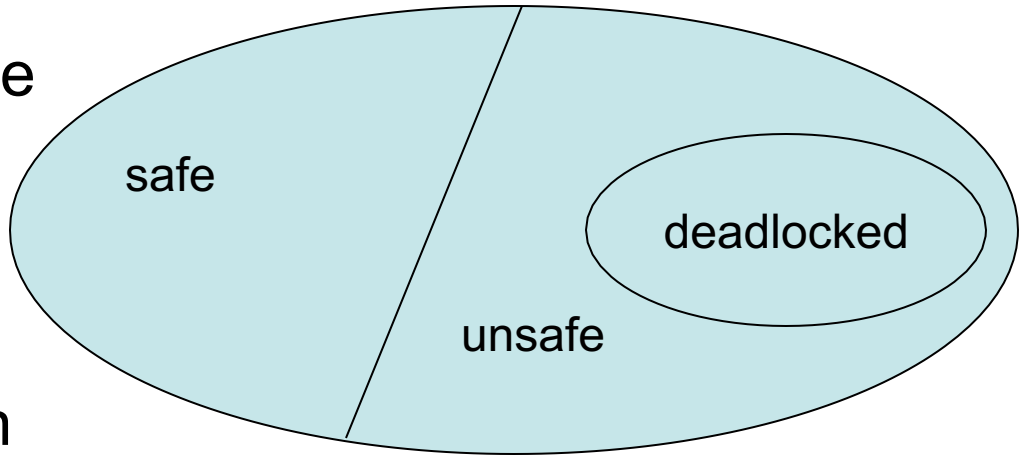
- A system is in a *safe* state if there exists a *safe sequence* of processes <P1, ..., Pn> for the current resource allocation state
  - A sequence of processes is safe if for each P_i in the sequence, the resource requests that P_i can still make can be satisfied by:
    - currently available resources + all resources held by all previous processes in the sequence P_j, $j<i$
  - If resources needed by P_i are not available, P_i waits for all P_j to release their resources

Deadlock Avoidance

- Intuition for a safe state: given that the system is in a certain state, we want to find at least one "way out of trouble"
  - i.e. find a sequence of processes that, even when they demand their maximum resources, won't deadlock the system
  - this is a worst-case analysis
    - it may be that during the normal execution of processes, none ever demands its maximum in a way that causes deadlock
  - to perform a more optimal (less than worst-case) analysis is more complex, and also requires a record of future accesses

Deadlock Avoidance

- A safe state provides a safe “escape” sequence
- A deadlocked state is unsafe
- An unsafe state is not necessarily deadlocked
- A system may transition from a safe to an unsafe state if a request for resources is granted
  - ideally, check with each request for resources whether the system is still safe



Deadlock Avoidance

- Example 1:
  - 12 instances of a resource
  - At time t0, P0 holds 5, P1 holds 2, P2 holds 2
  - Available = 3 free instances

processes	max needs	allocated
P0	10	5
P1	4	2
P2	9	2

Deadlock Avoidance

- Example 1 (cont):
  - Is the system in a safe state? Can I find a safe sequence?
  - Yes, I claim the sequence <P1, P0, P2> is safe.
    - P1 requests its maximum (currently has 2, so needs 2 more) and holds 4, then there is only 1 free resource
    - Then P1 releases all of its resources, so 5 free
    - Next, P0 requests its max (currently has 5, so needs 5 more) and holds 10, so that now 0 free
    - Then P0 releases all its held resources, so 10 free
    - Next P2 requests its max of 9, leaving 3 free and then releases them all

Deadlock Avoidance

- Example 1 (cont):
  - Is the system in a safe state? Can I find a safe sequence?
  - Yes the sequence <P1, P0, P2> is safe, and is able in the worst-case to request maximum resources for each process in the sequence, and release all such resources for the next process in the sequence
  - Can this system avoid deadlock? Yes, we can find a safe sequence.