Chapter 6

Deadlocks

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Learning Outcomes

- Understand what deadlock is and how it can occur when giving mutually exclusive access to multiple resources.
- Understand several approaches to mitigating the issue of deadlock in operating systems.
  - Including deadlock *prevention, detection and recovery*, and deadlock *avoidance.*

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Resources

- Examples of computer resources
  - printers
  - tape drives
  - Tables in a database
- Processes need access to resources in reasonable order
- Preemptable resources
  - can be taken away from a process with no ill effects
- Nonpreemptable resources
  - will cause the process to fail if taken away

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Resources & Deadlocks

- Suppose a process holds resource A and requests resource B
  - at same time another process holds B and requests A
  - both are blocked and remain so - *Deadlocked*
- Deadlocks occur when …
  - processes are granted exclusive access to devices, locks, tables, etc..
  - we refer to these entities generally as resources

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Resource Access

- Sequence of events required to use a resource
  1. request the resource
  2. use the resource
  3. release the resource
- Must wait if request is denied
  - requesting process may be blocked
  - may fail with error code

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Two example resource usage patterns

```
semaphore res_1, res_2;
void proc_A() {
  down(&res_1);
  down(&res_2);
  use_both_res();
  up(&res_2);
  up(&res_1);
}
void proc_B() {
  down(&res_1);
  down(&res_2);
  use_both_res();
  up(&res_2);
  up(&res_1);
}
```

```
semaphore res_1, res_2;
void proc_A() {
  down(&res_1);
  down(&res_2);
  use_both_res();
  up(&res_2);
  up(&res_1);
}
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  down(&res_2);
  down(&res_1);
  use_both_res();
  up(&res_1);
  up(&res_2);
}
```


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Introduction to Deadlocks

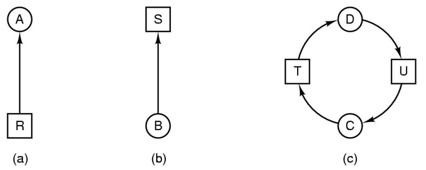
- Formal definition :
  A set of processes is deadlocked if each process in the set is waiting for an event that only another process in the set can cause
- Usually the event is release of a currently held resource
- None of the processes can …
  - run
  - release resources
  - be awakened

Four Conditions for Deadlock

1. Mutual exclusion condition
   - each resource assigned to 1 process or is available
2. Hold and wait condition
   - process holding resources can request additional
3. No preemption condition
   - previously granted resources cannot be forcibly taken away
4. Circular wait condition
   - must be a circular chain of 2 or more processes
   - each is waiting for resource held by next member of the chain

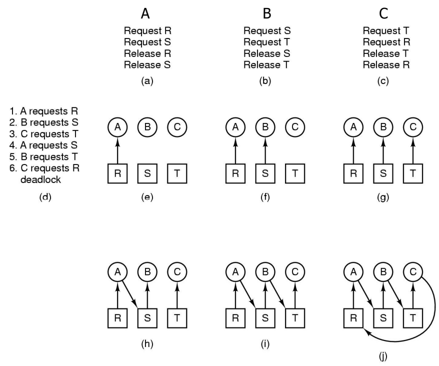
Deadlock Modeling

- Modeled with directed graphs



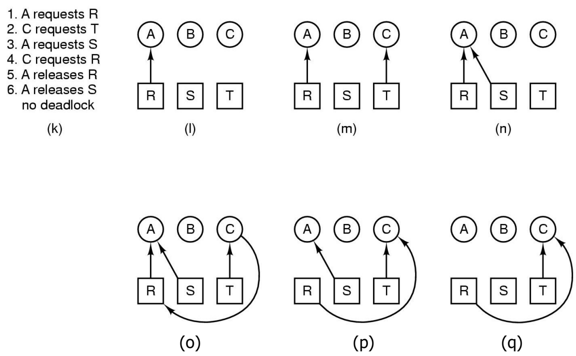
- resource R assigned to process A
- process B is requesting/waiting for resource S
- process C and D are in deadlock over resources T and U

Deadlock Modeling



How deadlock occurs

Deadlock Modeling



How deadlock can be avoided

Deadlock

Strategies for dealing with Deadlocks

1. just ignore the problem altogether
2. prevention
   - negating one of the four necessary conditions
3. detection and recovery
4. dynamic avoidance
   - careful resource allocation

Approach 1: The Ostrich Algorithm

- Pretend there is no problem
- Reasonable if
  - deadlocks occur very rarely
  - cost of prevention is high
    - Example of "cost", only one process runs at a time
- UNIX and Windows takes this approach for some of the more complex resource relationships they manage
- It's a trade off between
  - Convenience (engineering approach)
  - Correctness (mathematical approach)

Approach 2: Deadlock Prevention

- Resource allocation rules prevent deadlock by prevent one of the four conditions required for deadlock from occurring
  - Mutual exclusion
  - Hold and wait
  - No preemption
  - Circular Wait

Approach 2
Deadlock Prevention
Attacking the Mutual Exclusion Condition

- Not feasible in general
  - Some devices/resource are intrinsically not shareable.

Attacking the Hold and Wait Condition

- Require processes to request resources before starting
  - a process never has to wait for what it needs
- Issues
  - may not know required resources at start of run
    - ⇒ not always possible
  - also ties up resources other processes could be using
- Variations:
  - process must give up all resources if it would block holding a resource
  - then request all immediately needed
  - prone to livelock

Livelock

- Livelocked processes are not blocked, change state regularly, but never make progress.
- Example: Two people passing each other in a corridor that attempt to step out of each other's way in the same direction, indefinitely.
  - Both are actively changing state
  - Both never pass each other.

Deadlock example

```
void proc_A() {
  lock_acquire(&res_1);
  lock_acquire(&res_2);
  use_both_res();
  lock_release(&res_2);
  lock_release(&res_1);
}
```

```
void proc_B() {
  lock_acquire(&res_2);
  lock_acquire(&res_1);
  use_both_res();
  lock_release(&res_1);
  lock_release(&res_2);
}
```

Livelock example

```
void proc_A() {
 lock_acquire(&res_1);
 while(try_lock(&res_2) == FAIL) {
  lock_release(&res_1);
  wait_fixed_time();
  lock_acquire(&res_1);
 }
 use_both_res();
 lock_release(&res_2);
 lock_release(&res_1);
}
```

```
void proc_B() {
 lock_acquire(&res_2);
 while(try_lock(&res_1) == FAIL) {
  lock_release(&res_2);
  wait_fixed_time();
  lock_acquire(&res_2);
 }
 use_both_res();
 lock_release(&res_1);
 lock_release(&res_2);
}
```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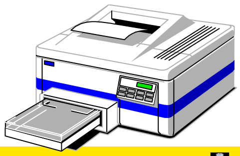
Attacking the No Preemption Condition

- This is not a viable option
- Consider a process given the printer
  - halfway through its job
  - now forcibly take away printer
  - !!??



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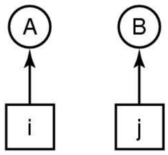
Attacking the Circular Wait Condition

1. Imagesetter
2. Scanner
3. Plotter
4. Tape drive
5. CD Rom drive

(a)



(b)

- Numerically ordered resources

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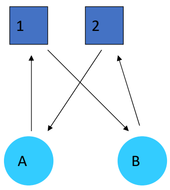
Attacking the Circular Wait Condition

- The displayed deadlock cannot happen
  - If A requires ***1***, it must acquire it before acquiring ***2***
  - Note: If B has ***1***, all higher numbered resources must be free or held by processes who doesn't need ***1***
- Resources ordering is a common technique in practice!!!!!



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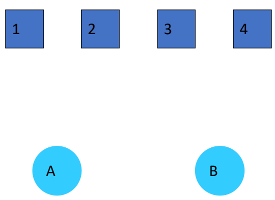
Example



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Summary of approaches to deadlock prevention

Condition	Approach
• Mutual Exclusion	• Not feasible
• Hold and Wait	• Request resources initially
	• Take resources away
• No Preemption	• Order resources
• Circular Wait	

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Approach 3: Detection and Recovery

- Need a method to determine if a system is deadlocked.
- Assuming deadlocked is detected, we need a method of recovery to restore progress to the system.

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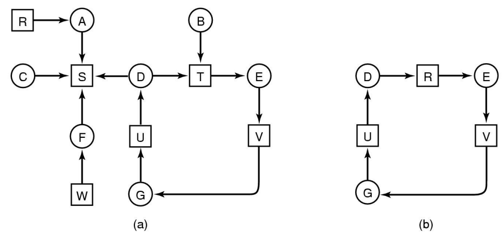
Approach 3
Detection with One Resource of Each Type



- Note the resource ownership and requests
- A cycle can be found within the graph, denoting deadlock

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What about resources with multiple units?

- Some examples of multi-unit resources
  - RAM
  - Blocks on a hard disk drive
  - Slots in a buffer
- We need an approach for dealing with resources that consist of more than a single unit.

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Detection with Multiple Resources of Each Type

Resources in existence
$(E_1, E_2, E_3, \ldots, E_m)$

Resources available
$(A_1, A_2, A_3, \ldots, A_m)$

Current allocation matrix

$$\begin{bmatrix} C_{11} & C_{12} & C_{13} & \cdots & C_{1m} \\ C_{21} & C_{22} & C_{23} & \cdots & C_{2m} \\ \vdots & \vdots & \vdots & & \vdots \\ C_{n1} & C_{n2} & C_{n3} & \cdots & C_{nm} \end{bmatrix}$$

Row n is current allocation to process n

Request matrix

$$\begin{bmatrix} R_{11} & R_{12} & R_{13} & \cdots & R_{1m} \\ R_{21} & R_{22} & R_{23} & \cdots & R_{2m} \\ \vdots & \vdots & \vdots & & \vdots \\ R_{n1} & R_{n2} & R_{n3} & \cdots & R_{nm} \end{bmatrix}$$

Row 2 is what process 2 needs

Data structures needed by deadlock detection algorithm

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Note the following invariant

Sum of current resource allocation + resources available = resources that exist

$$\sum_{i=1}^{n} C_{ij} + A_j = E_j$$

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Detection with Multiple Resources of Each Type

Tape drives, Plotters, Scanners, CD Roms

$E = (4 \quad 2 \quad 3 \quad 1)$

Tape drives, Plotters, Scanners, CD Roms

$A = (2 \quad 1 \quad 0 \quad 0)$

Current allocation matrix

$$C = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 2 & 0 & 0 & 1 \\ 0 & 1 & 2 & 0 \end{bmatrix}$$

Request matrix

$$R = \begin{bmatrix} 2 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 2 & 1 & 0 & 0 \end{bmatrix}$$

An example for the deadlock detection algorithm

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Detection Algorithm

1. Look for an unmarked process *Pi,* for which the *i*-th row of R is less than or equal to A
2. If found, add the *i*-th row of C to A, and mark *Pi*. Go to step 1
3. If no such process exists, terminate.

Remaining processes are deadlocked

31 UNSW

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Example Deadlock Detection

$$E = (4 \quad 2 \quad 3 \quad 1) \qquad A = (2 \quad 1 \quad 0 \quad 0)$$

$$C = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 2 & 0 & 0 & 1 \\ 0 & 1 & 2 & 0 \end{pmatrix} \qquad R = \begin{pmatrix} 2 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 2 & 1 & 0 & 0 \end{pmatrix}$$

32 UNSW

32

Example Deadlock Detection

$$E = (4 \quad 2 \quad 3 \quad 1) \qquad A = (2 \quad 1 \quad 0 \quad 0)$$

$$C = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 2 & 0 & 0 & 1 \\ 0 & 1 & 2 & 0 \end{pmatrix} \qquad R = \begin{pmatrix} 2 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 2 & 1 & 0 & 0 \end{pmatrix}$$

33 UNSW

33

Example Deadlock Detection

$$E = (4 \quad 2 \quad 3 \quad 1) \qquad A = (2 \quad 1 \quad 0 \quad 0)$$

$$C = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 2 & 0 & 0 & 1 \\ 0 & 1 & 2 & 0 \end{pmatrix} \qquad R = \begin{pmatrix} 2 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 2 & 1 & 0 & 0 \end{pmatrix}$$

34 UNSW

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Example Deadlock Detection

$$E = (4 \quad 2 \quad 3 \quad 1) \qquad A = (2 \quad 2 \quad 2 \quad 0)$$

$$C = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 2 & 0 & 0 & 1 \\ 0 & 1 & 2 & 0 \end{pmatrix} \qquad R = \begin{pmatrix} 2 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 2 & 1 & 0 & 0 \end{pmatrix}$$

35 UNSW

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Example Deadlock Detection

$$E = (4 \quad 2 \quad 3 \quad 1) \qquad A = (2 \quad 2 \quad 2 \quad 0)$$

$$C = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 2 & 0 & 0 & 1 \\ 0 & 1 & 2 & 0 \end{pmatrix} \qquad R = \begin{pmatrix} 2 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 2 & 1 & 0 & 0 \end{pmatrix}$$

36 UNSW

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Example Deadlock Detection

$$E = (4 \quad 2 \quad 3 \quad 1) \qquad A = (4 \quad 2 \quad 2 \quad 1)$$

$$C = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 2 & 0 & 0 & 1 \\ 0 & 1 & 2 & 0 \end{pmatrix} \qquad \begin{pmatrix} 2 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 2 & 1 & 0 & 0 \end{pmatrix}$$

Example Deadlock Detection

$$E = (4 \quad 2 \quad 3 \quad 1) \qquad A = (4 \quad 2 \quad 2 \quad 1)$$

$$C = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 2 & 0 & 0 & 1 \\ 0 & 1 & 2 & 0 \end{pmatrix} \qquad R = \begin{pmatrix} 2 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 2 & 1 & 0 & 0 \end{pmatrix}$$

Example Deadlock Detection

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Example Deadlock Detection

$$E = (4 \quad 2 \quad 3 \quad 1) \qquad A = (4 \quad 2 \quad 3 \quad 1)$$

$$C = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 2 & 0 & 0 & 1 \\ 0 & 1 & 2 & 0 \end{pmatrix} \qquad R = \begin{pmatrix} 2 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 2 & 1 & 0 & 0 \end{pmatrix}$$

Example Deadlock Detection

- Algorithm terminates with no unmarked processes
  - We have no dead lock

Example 2: Deadlock Detection

- Suppose, *P3* needs a CD-ROM as well as 2 Tapes and a Plotter

$$E = (4 \quad 2 \quad 3 \quad 1) \qquad A = (2 \quad 1 \quad 0 \quad 0)$$

$$C = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 2 & 0 & 0 & 1 \\ 0 & 1 & 2 & 0 \end{pmatrix} \qquad R = \begin{pmatrix} 2 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 2 & 1 & 0 & 1 \end{pmatrix}$$

Recovery from Deadlock

- Recovery through preemption
  - take a resource from some other process
  - depends on nature of the resource
- Recovery through rollback
  - checkpoint a process periodically
  - use this saved state
  - restart the process if it is found deadlocked
    - No guarantee is won't deadlock again

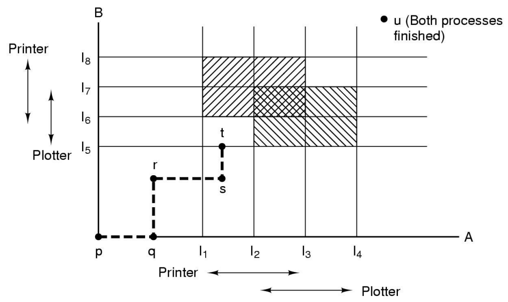
Recovery from Deadlock

- Recovery through killing processes
  - crudest but simplest way to break a deadlock
  - kill one of the processes in the deadlock cycle
  - the other processes get its resources
  - choose process that can be rerun from the beginning

Approach 4
Deadlock Avoidance

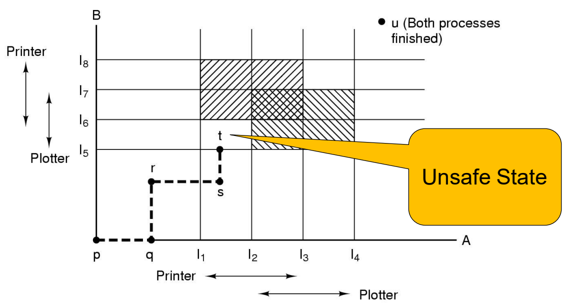
- Instead of detecting deadlock, can we simply avoid it?
  - YES, but only if enough information is available in advance.
    - Maximum number of each resource required

Deadlock Avoidance
Resource Trajectories



Two process resource trajectories

Deadlock Avoidance
Resource Trajectories



Two process resource trajectories

Safe and Unsafe States

- A state is *safe* if
  - The system is not deadlocked
  - There exists a scheduling order that results in every process running to completion, *even if they all request their maximum resources immediately*

Safe and Unsafe States

Note: We have 10 units of the resource

(a)

	Has	Max
A	3	9
B	2	4
C	2	7

Free: 3

(b)

	Has	Max
A	3	9
B	4	4
C	2	7

Free: 1

(c)

	Has	Max
A	3	9
B	0	–
C	2	7

Free: 5

(d)

	Has	Max
A	3	9
B	0	–
C	7	7

Free: 0

(e)

	Has	Max
A	3	9
B	0	–
C	0	–

Free: 7

Demonstration that the state in (a) is safe

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Safe and Unsafe States

A requests one extra unit resulting in (b)

(a)

	Has	Max
A	3	9
B	2	4
C	2	7

Free: 3

(b)

	Has	Max
A	4	9
B	2	4
C	2	7

Free: 2

(c)

	Has	Max
A	4	9
B	4	4
C	2	7

Free: 0

(d)

	Has	Max
A	4	9
B	—	—
C	2	7

Free: 4

Demonstration that the state in b is not safe

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Safe and Unsafe State

- Unsafe states are not necessarily deadlocked
  - With a lucky sequence, all processes may complete
  - However, we *cannot guarantee* that they will complete (not deadlock)
- Safe states guarantee we will eventually complete all processes
- Deadlock avoidance algorithm
  - Only grant requests that result in safe states

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Bankers Algorithm

- Modelled on a Banker with Customers
  - The banker has a limited amount of money to loan customers
    - Limited number of resources
  - Each customer can borrow money up to the customer's credit limit
    - Maximum number of resources required
- Basic Idea
  - Keep the bank in a *safe* state
    - So all customers are happy even if they all request to borrow up to their credit limit at the same time.
  - Customers wishing to borrow such that the bank would enter an unsafe state must wait until somebody else repays their loan such that the the transaction becomes safe.

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The Banker's Algorithm for a Single Resource

(a)

	Has	Max
A	0	6
B	0	5
C	0	4
D	0	7

Free: 10

(b)

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

Free: 2

(c)

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

Free: 1

- Three resource allocation states
  - safe
  - safe
  - unsafe

B requests one more, should we grant it?

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Banker's Algorithm for Multiple Resources

Resources assigned

Process	Tape drives	Plotters	Scanners	CD 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 still needed

Process	Tape drives	Plotters	Scanners	CD 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

E = (6342)
P = (5322)
A = (1020)

- Example of banker's algorithm with multiple resources
- Problem is structured similar to deadlock detection with multiple resources.
- Example in tutorial

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Bankers Algorithm is not commonly used in practice

- It is difficult (sometimes impossible) to know in advance
  - the resources a process will require
  - the number of processes in a dynamic system

Starvation

- A process never receives the resource it is waiting for, despite the resource (repeatedly) becoming free, the resource is always allocated to another waiting process.
  - Example: An algorithm to allocate a resource may be to give the resource to the shortest job first
  - Works great for multiple short jobs in a system
  - May cause a long job to wait indefinitely, even though not blocked.
- One solution:
  - First-come, first-serve policy