Chapter 6

Deadlocks

6.1. Resources
6.2. Introduction to deadlocks
6.3. The ostrich algorithm
6.4. Deadlock detection and recovery
6.5. Deadlock avoidance
6.6. Deadlock prevention
6.7. Other issues

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 *detection and recovery*, deadlock *avoidance*, and deadlock *prevention*.

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

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 <u>resources</u>

A B

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

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);
}
void proc_B() {
   down(&res_2); ✓
   down(&res_1); ✓+
   use_both_res();
   up(&res_1);
   up(&res_2);
}
```

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 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

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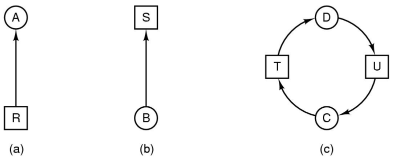
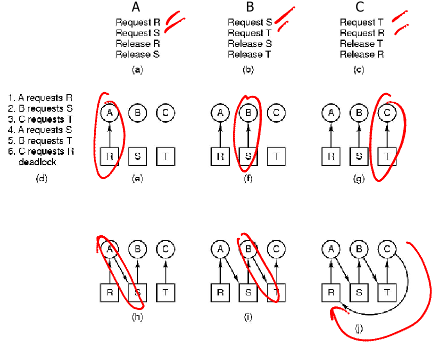
Deadlock Modeling

- 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


A
Request R
Request S
Release R
Release S
(a)

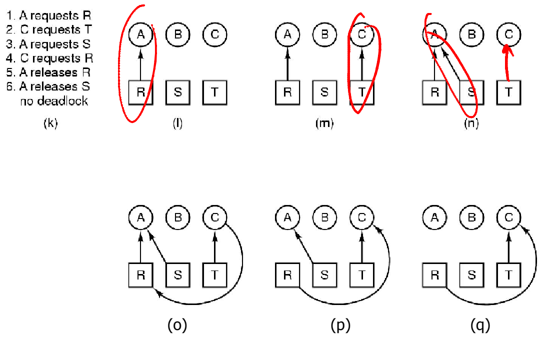
B
Request S
Request T
Release S
Release T
(b)

C
Request T
Request R
Release T
Release R
(c)

1. A requests R
2. B requests S
3. C requests T
4. A requests S
5. B requests T
6. C requests R
deadlock
(d)

How deadlock occurs

Deadlock Modeling


1. A requests R
2. C requests T
3. A requests S
4. C requests R
5. A releases R
6. A releases S
no deadlock
(k)

How deadlock can be avoided

Deadlock

Strategies for dealing with Deadlocks

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

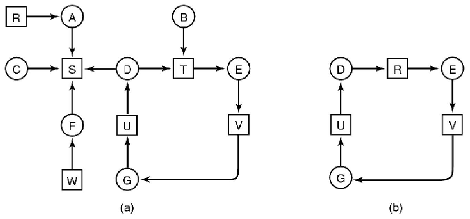
Approach 1: The Ostrich Algorithm

- 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 to manage
- It’s a trade off between
  - Convenience (engineering approach)
  - Correctness (mathematical approach)

Approach 2: 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.

Approach 2
Detection with One Resource of Each Type

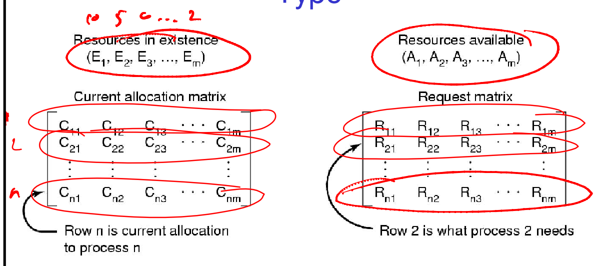


- Note the resource ownership and requests
- A cycle can be found within the graph, denoting deadlock

What about resources with multiple units?

- We need an approach for dealing with resources that consist of more than a single unit.

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

Note the following invariant

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

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

Detection with Multiple Resources of Each Type

$$\begin{array}{lcccc} & \text{Tape drives} & \text{Plotters} & \text{Scanners} & \text{CD Roms} \\ E = (& 4 & 2 & 3 & 1\ ) \end{array} \qquad \begin{array}{lcccc} & \text{Tape drives} & \text{Plotters} & \text{Scanners} & \text{CD Roms} \\ A = (& 2 & 1 & 0 & 0\ ) \end{array}$$

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

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

Example Deadlock Detection

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

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

Example Deadlock Detection

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

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

Example Deadlock Detection

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

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

Example Deadlock Detection

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

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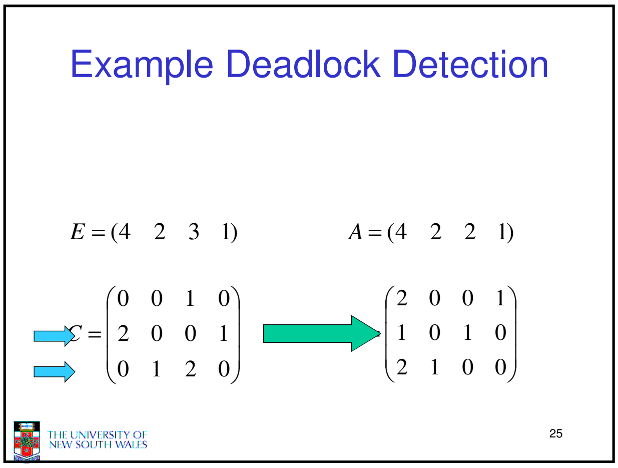
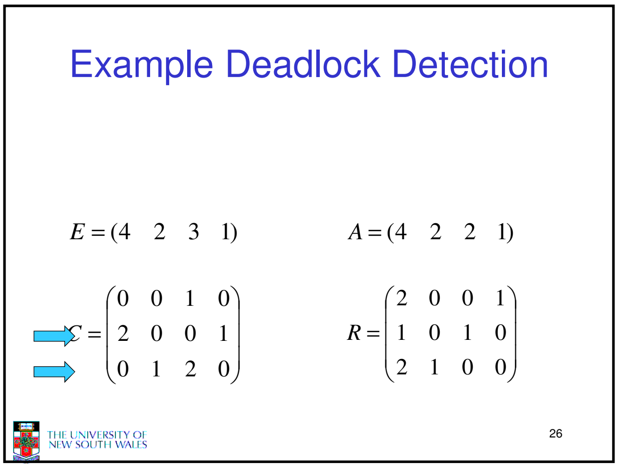


Example Deadlock Detection

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

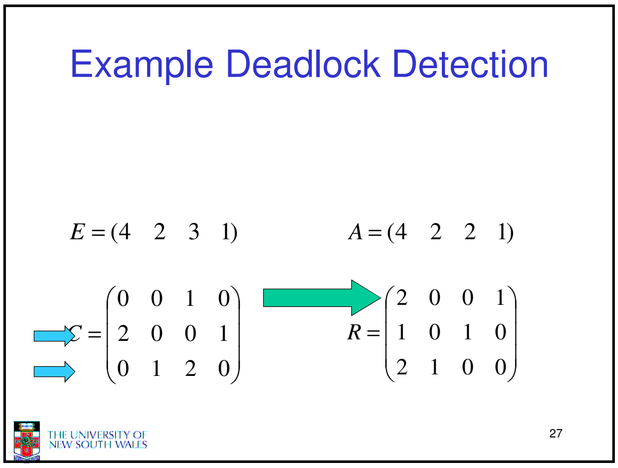
$$C = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 2 & 0 & 0 & 1 \\ 0 & 1 & 2 & 0 \end{pmatrix} \qquad \begin{pmatrix} 2 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 2 & 1 & 0 & 0 \end{pmatrix}$$



Example Deadlock Detection

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

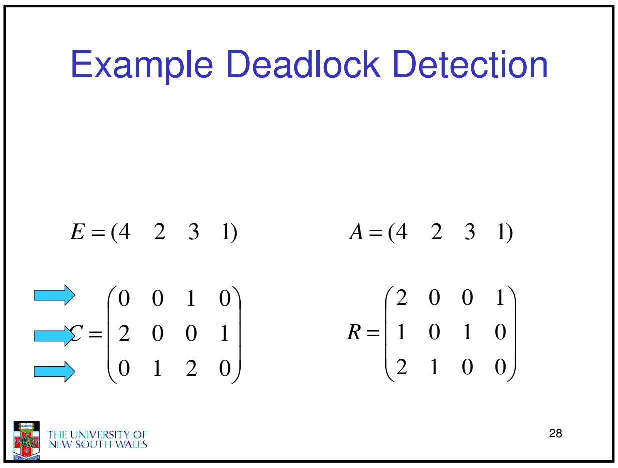
$$C = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 2 & 0 & 0 & 1 \\ 0 & 1 & 2 & 0 \end{pmatrix} \qquad R = \begin{pmatrix} 2 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 2 & 1 & 0 & 0 \end{pmatrix}$$



Example Deadlock Detection

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

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



Example Deadlock Detection

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

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

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

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

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

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

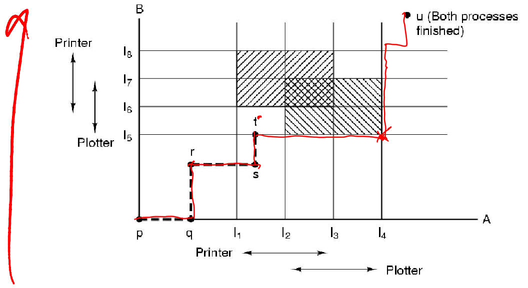
Recovery from Deadlock

- 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 3
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

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

	Has	Max
A	3	9
B	2	4
C	2	7

Free: 3
(a)

	Has	Max
A	3	9
B	4	4
C	2	7

Free: 1
(b)

	Has	Max
A	3	9
B	0	–
C	2	7

Free: 5
(c)

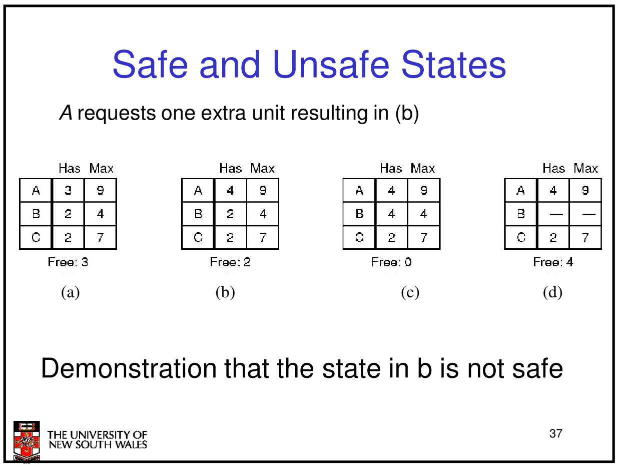
	Has	Max
A	3	9
B	0	–
C	7	7

Free: 0
(d)

	Has	Max
A	3	9
B	0	–
C	0	–

Free: 7
(e)

Demonstration that the state in (a) is safe



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

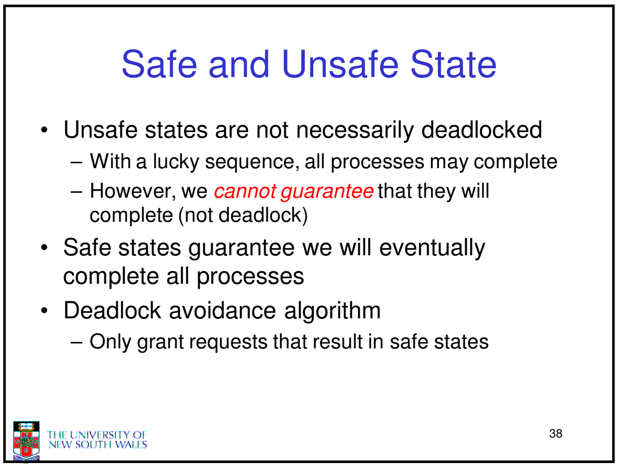
Free: 0

(d)

	Has	Max
A	4	9
B	—	—
C	2	7

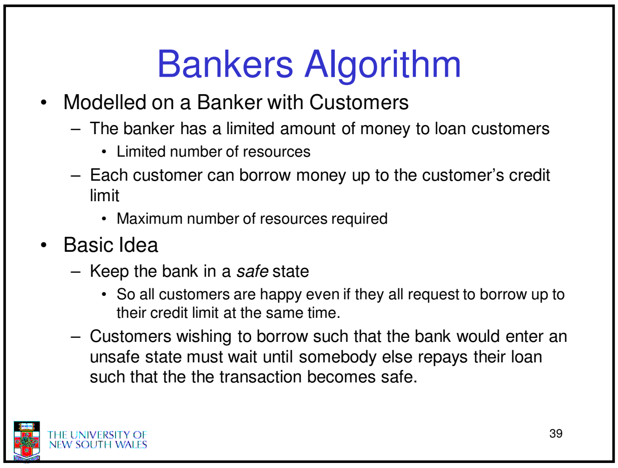
Free: 4

Demonstration that the state in b is not safe



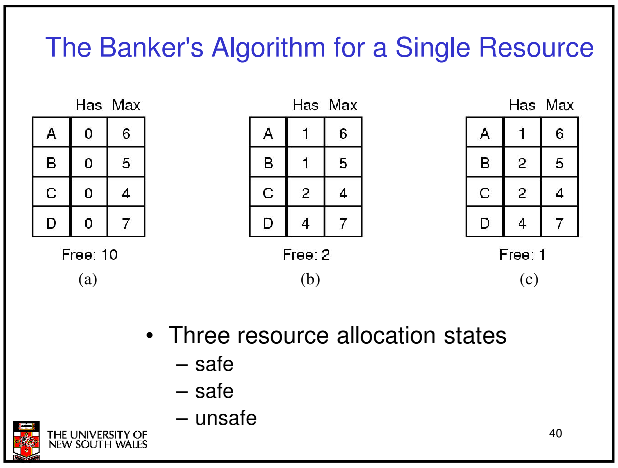
Safe and Unsafe State

- 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



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.



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

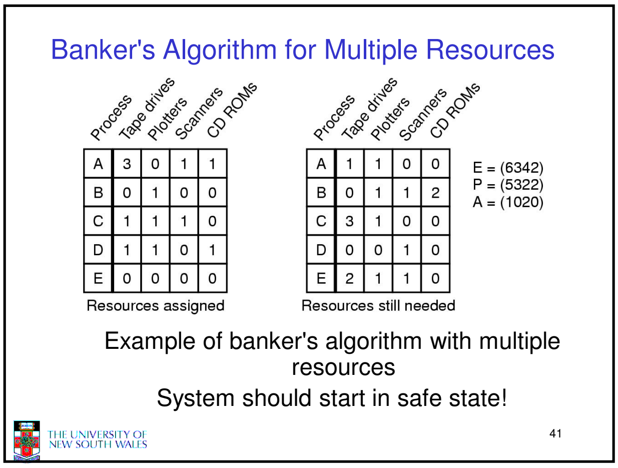
Free: 2

(c)

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

Free: 1

- Three resource allocation states
  - safe
  - safe
  - unsafe



Banker's Algorithm for Multiple Resources

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 assigned

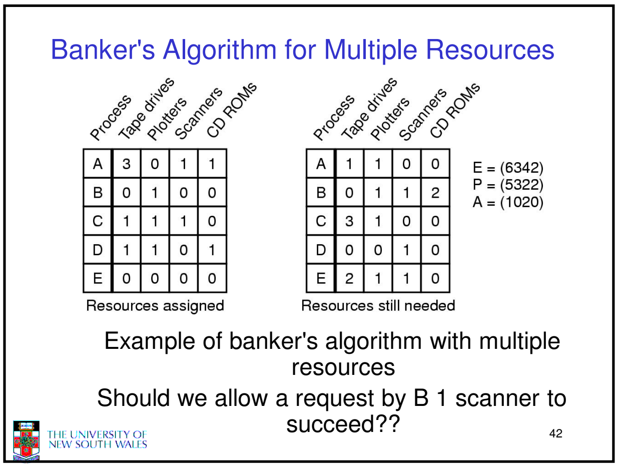
Process	Tape drives	Plotters	Scanners	CD ROMs
A	1	1	0	0
B	0	1	1	2
C	3	1	0	0
D	0	0	1	0
E	2	1	1	0

Resources still needed

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

Example of banker's algorithm with multiple resources

System should start in safe state!



Banker's Algorithm for Multiple Resources

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 assigned

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

Resources still needed

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

Example of banker's algorithm with multiple resources

Should we allow a request by B 1 scanner to succeed??

Banker's Algorithm for Multiple Resources

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 assigned

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

Resources still needed

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

Example of banker's algorithm with multiple resources

Should we allow a request by B and E for 1 scanner to succeed??

Bankers Algorithm is not commonly used in practice

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

Approach 4: 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 4
Deadlock Prevention
Attacking the Mutual Exclusion Condition

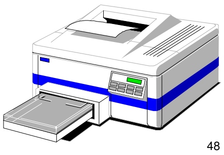
- Not feasible in general
  - Some devices/resource are intrinsically not shareable.

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 hold a resource
  - then request all immediately needed
  - prone to starvation

Attacking the No Preemption Condition

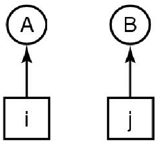
- This is not a viable option
- Consider a process given the printer
  - halfway through its job
  - now forcibly take away printer
  - !!??



Attacking the Circular Wait Condition

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

(a)

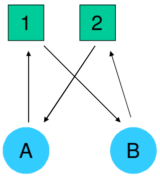


(b)

- Numerically ordered resources

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!!!!!



Summary of approaches to deadlock prevention

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

Starvation

- Starvation is where the overall system makes progress, but one or more processes never make progress.
  - Example: An algorithm to allocate a resource may be to give to shortest job first
  - Works great for multiple short jobs in a system
  - May cause long job to be postponed indefinitely, even though ready and not waiting for a resource.
- One solution:
  - First-come, first-serve policy