Chapter 6

Deadlock

(Part 1)

Resources and Deadlocks

Processes need access to resources in order to make progress.

Examples of Resources:

- **Kernel Data Structures**
  (ProcessControlBlocks, Threads, OpenFile…)
- **Locks/semaphores to protect critical sections**
- **Memory (page frames, buffers, etc.)**
- **Files**
- **I/O Devices**
  (printers, ports, tape drives, speaker, etc.)

Resources and Deadlocks

<u>Scenario:</u>

Process P1...
is holding resource A, and
is requesting resource B

Process P2...
is holding resource B, and
is requesting resource A

Both are blocked and remain so …

This is deadlock

Resource Usage Model

Sequence of events required to use a resource:

- request the resource (e.g., acquire a mutex lock)
- use the resource
- release the resource (e.g., release a mutex lock)

Must wait if request is denied

- block
- busy wait
- fail with error code

Preemptable vs Nonpreemptable Resources

Preemptable resources

Can be taken away from a process with no ill effects

Nonpreemptable resources

Once given to the process, can't be taken back

Will cause the process to fail if taken away

"Deadlocks occur when processes are granted exclusive access to non-preemptable resources and wait when the resource is not available."

Definition of Deadlock

"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:

The release of a currently held resource

All processes in the set are waiting

... for a resource request to be granted.

None of the processes can proceed

... so no process can release the resources it holds.

Starvation vs. Deadlock

Starvation **and** ***Deadlock*** **are two different things!**

Deadlock:

- **No work is being accomplished for the processes that are deadlocked, because processes are waiting for each other. Once present, will not go away!**

Starvation:

- **Work (progress) is occurring. However, a particular set of processes may not be getting any work done because they cannot obtain the resources they need.**
- **May only last a short time; may go away.**

Both are probabilistic events & may occur only rarely.

Deadlock Conditions

A deadlock situation can occur *if and only if* the following conditions hold simultaneously...

Mutual Exclusion Condition

A resource can be assigned to only one process at a time

Hold And Wait Condition

Processes can get more than one resource

No Preemption Condition

Circular Wait Condition

A cyclic chain of two or more processes (must be waiting for resource from next one in chain)

Resource acquisition scenarios

Thread A:

```
acquire (resource_1)
use resource_1
release (resource_1)
```

Example:

```
var r1_mutex: Mutex
...
r1_mutex.Lock()
Use resource_1
r1_mutex.Unlock()
```

Resource acquisition scenarios

Thread A:

```
acquire (resource_1)
use resource_1
release (resource_1)
```

Another Example:

```
var r1_sem: Semaphore
r1_sem.Up()
...
r1_sem.Down()
Use resource_1
r1_sem.Up()
```

Resource acquisition scenarios

Thread A:

```
acquire (resource_1)
use resource_1
release (resource_1)
```

Thread B:

```
acquire (resource_2)
use resource_2
release (resource_2)
```

Resource acquisition scenarios

Thread A:

```
acquire (resource_1)
use resource_1
release (resource_1)
```

Thread B:

```
acquire (resource_2)
use resource_2
release (resource_2)
```

No deadlock can occur here!

Resource Acquisition Scenarios: 2 Resources

Thread A:

```
acquire (resource_1)
acquire (resource_2)
use resources 1 & 2
release (resource_2)
release (resource_1)
```

Thread B:

```
acquire (resource_1)
acquire (resource_2)
use resources 1 & 2
release (resource_2)
release (resource_1)
```

Resource Acquisition Scenarios: 2 Resources

Thread A:

```
acquire (resource_1)
acquire (resource_2)
use resources 1 & 2
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```

Thread B:

```
acquire (resource_1)
acquire (resource_2)
use resources 1 & 2
release (resource_2)
release (resource_1)
```

No deadlock can occur here!

Resource Acquisition Scenarios: 2 Resources

Thread A:

```
acquire (resource_1)
use resources 1
release (resource_1)
acquire (resource_2)
use resources 2
release (resource_2)
```

Thread B:

```
acquire (resource_2)
use resources 2
release (resource_2)
acquire (resource_1)
use resources 1
release (resource_1)
```

Resource Acquisition Scenarios: 2 Resources

Thread A:

```
acquire (resource_1)
use resources 1
release (resource_1)
acquire (resource_2)
use resources 2
release (resource_2)
```

Thread B:

```
acquire (resource_2)
use resources 2
release (resource_2)
acquire (resource_1)
use resources 1
release (resource_1)
```

No deadlock can occur here!

Resource Acquisition Scenarios: 2 Resources

Thread A:

```
acquire (resource_1)
acquire (resource_2)
use resources 1 & 2
release (resource_2)
release (resource_1)
```

Thread B:

```
acquire (resource_2)
acquire (resource_1)
use resources 1 & 2
release (resource_1)
release (resource_2)
```

Resource Acquisition Scenarios: 2 Resources

Thread A:

```
acquire (resource_1)
acquire (resource_2)
use resources 1 & 2
release (resource_2)
release (resource_1)
```

Thread B:

```
acquire (resource_2)
acquire (resource_1)
use resources 1 & 2
release (resource_1)
release (resource_2)
```

Deadlock is possible!

Examples of Deadlock

- Deadlock occurs within a single application

  ...Not so bad

  Programmer created a situation that deadlocks

  Kill the program and move on

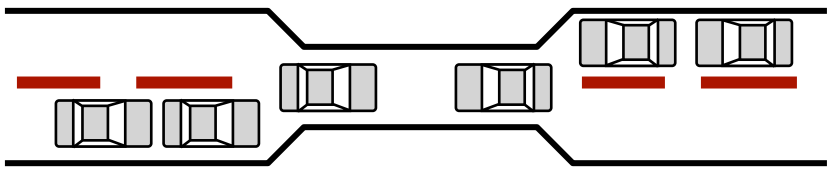
- Deadlock occurs within the OS

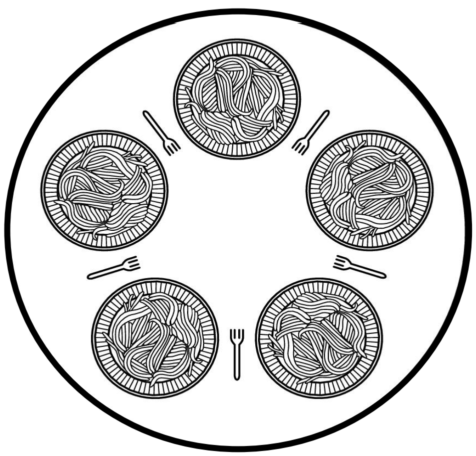
  ...More of a problem

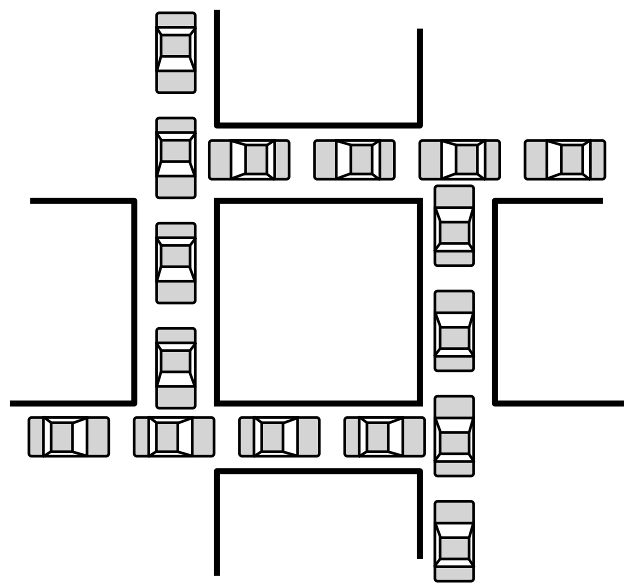
  System crashes, or some threads become frozen

  Must restart system (i.e., kill every thread)

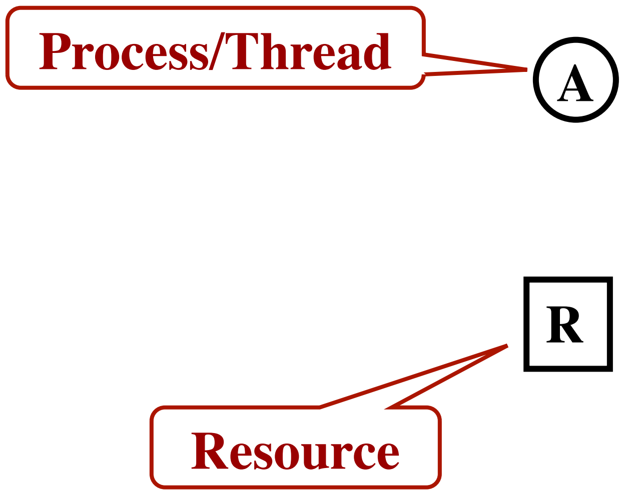
Other examples of deadlock



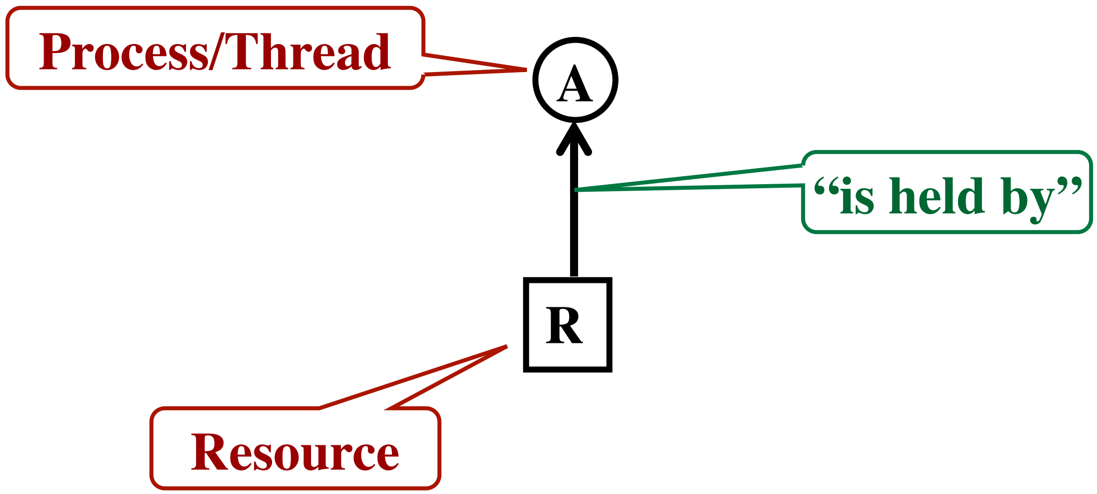




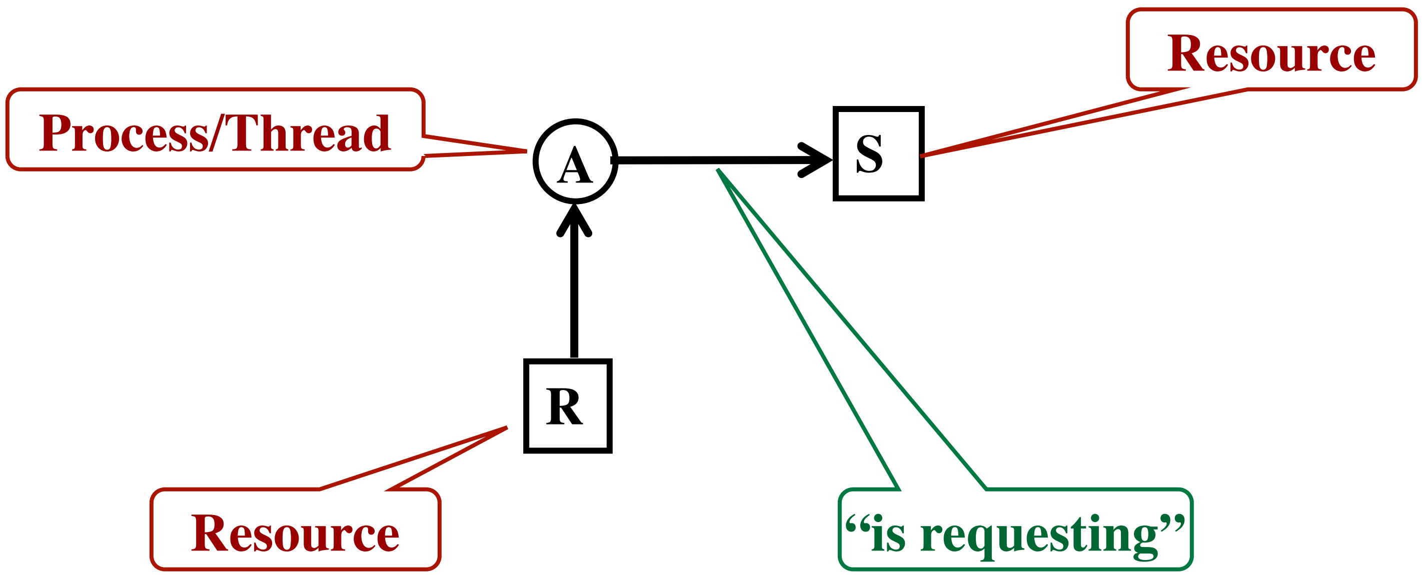
Resource Allocation Graphs



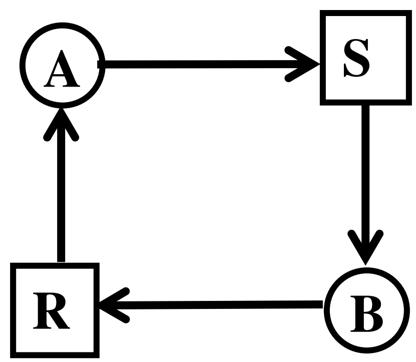
Resource Allocation Graphs



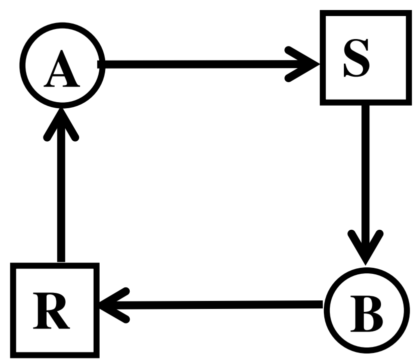
Resource Allocation Graphs



Resource Allocation Graphs

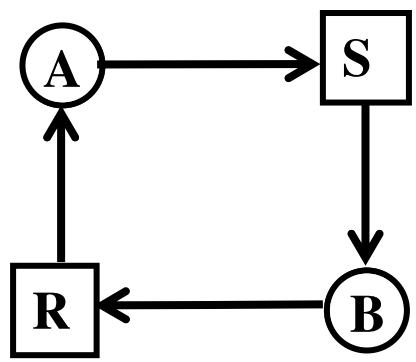


Resource Allocation Graphs



Deadlock

Resource Allocation Graphs



Deadlock = a cycle in the graph

Mulitple Units of a Resource

Some resources have only one “unit”.
Only one thread at a time may hold the resource.

- **Printer**
- **Lock on ProcessTable**

Some resources have several units.
All units are considered equal; any one will do.

- **Page Frames**
- **Dice**

A thread requests “k” units of the resource.
Several requests may be satisfied simultaneously.

Dealing with deadlock

General strategies

Ignore the Problem

Hmm… advantages, disadvantages?

Detection and Recovery

Avoidance

through careful resource allocation

Prevention

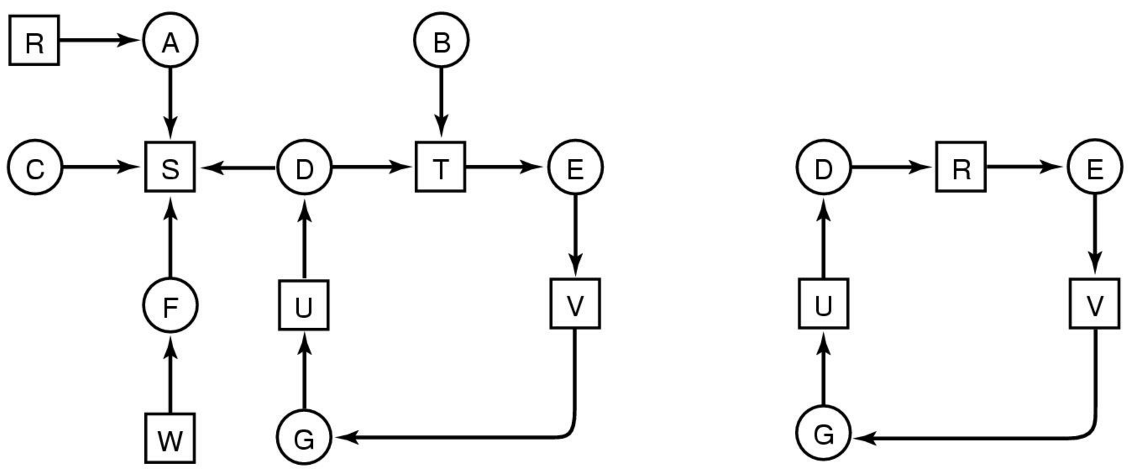
by structurally negating one of the four conditions

Deadlock detection (1 unit of each)

Let the problem happen, then recover

How do you know it happened?

Do a depth-first-search on the resource allocation graph



(a) (b)

Deadlock detection (1 unit of each)

Let the problem happen, then recover

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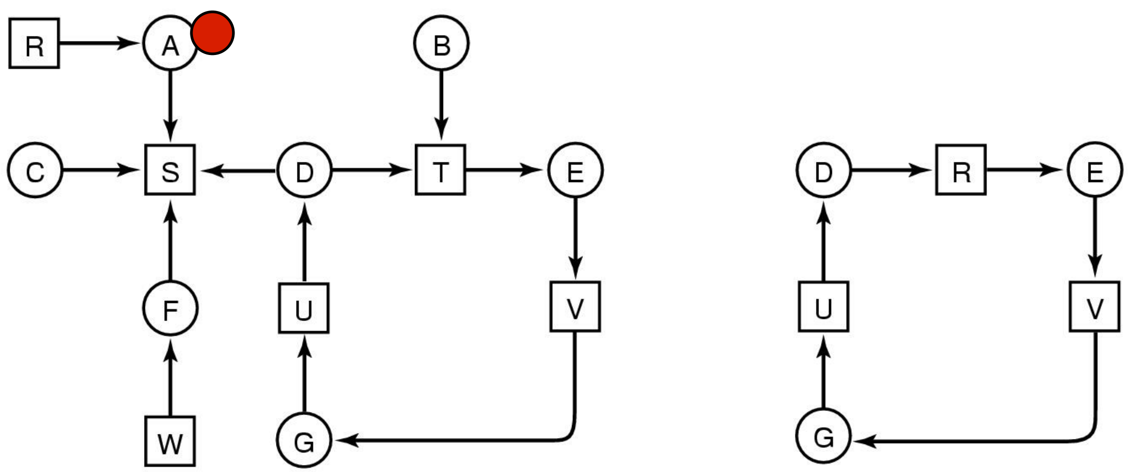
Do a depth-first-search on the resource allocation graph



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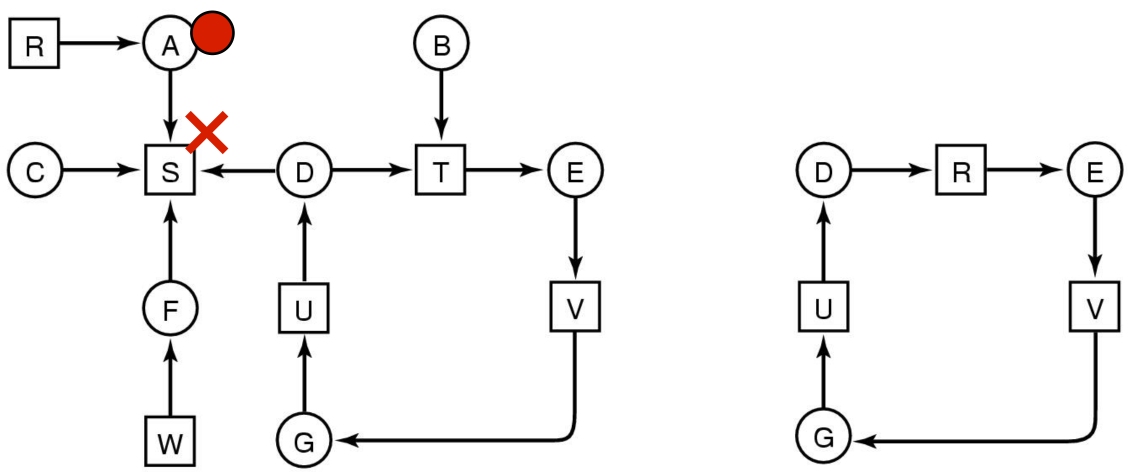

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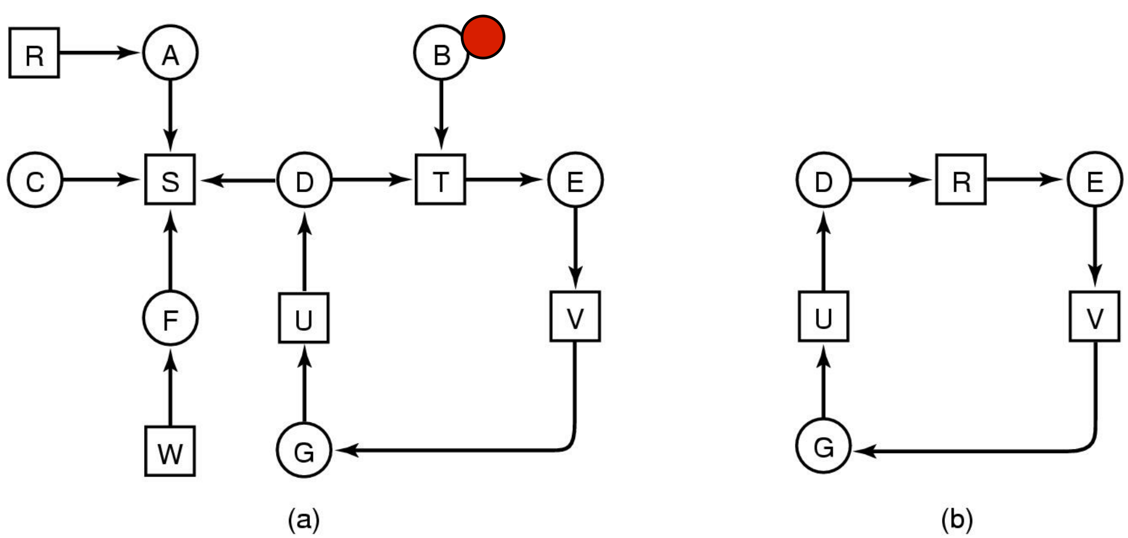
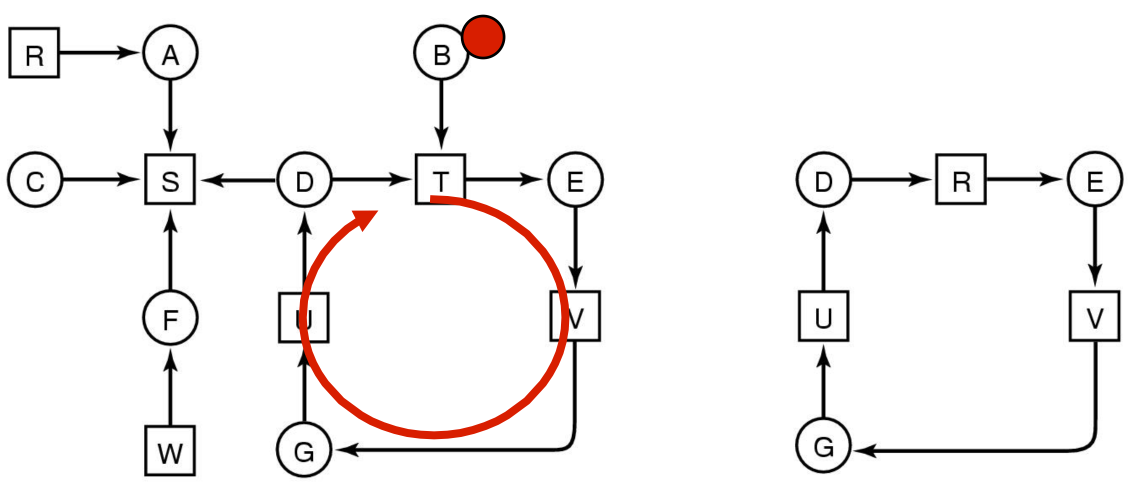


Deadlock detection (1 unit of each)

Let the problem happen, then recover

How do you know it happened?

Do a depth-first-search on the resource allocation graph



(a) (b)

Deadlock modeling with multiple resources

Theorem: ***If a graph does not contain a cycle then no processes are deadlocked***

A cycle in a RAG is a *necessary* condition for deadlock.

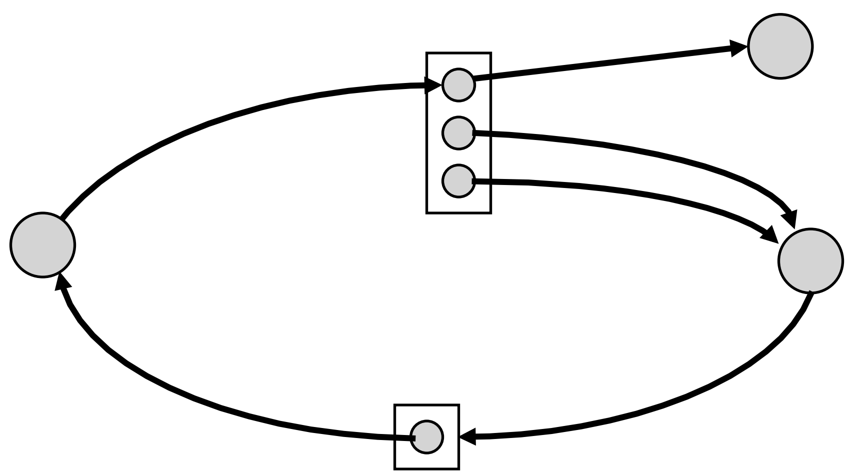
Is the existence of a cycle a *sufficient* condition?

Deadlock modeling with multiple resources

<u>Theorem</u>: ***If a graph does not contain a cycle then no processes are deadlocked***

A cycle in a RAG is a <u>*necessary*</u> condition for deadlock.

Is the existence of a cycle a <u>*sufficient*</u> condition?



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Deadlock Detection (multiple resources)

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

skip

Example

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

$$\begin{array}{ccccc} & \text{Tape drives} & \text{Plotters} & \text{Scanners} & \text{CD Roms} \\ A = (& 2 & 1 & 0 & 0\ ) \end{array}$$

Current allocation matrix

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

Request matrix

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

Deadlock Detection Algorithm

Is there a sequence of running the processes such that all the resources will be returned?

1. **Look for an unmarked process P_i, for which the *i*th row of R is less than or equal to A**

2. **If such a process is found, add the i-th row of C to A, mark the process and go back to step 1**

3. **If no such process exists the algorithm terminates**

If all marked, no deadlock!

skip

Deadlock Detection Algorithm - Example

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

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Request matrix

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skip

Deadlock Detection Algorithm - Example

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

Current allocation matrix

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

Request matrix

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

skip

Deadlock Detection Algorithm - Example

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

Current allocation matrix

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

Request matrix

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

skip

Deadlock Detection Algorithm - Example

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$$A = \begin{array}{cccc} \text{Tape drives} & \text{Plotters} & \text{Scanners} & \text{CD Roms} \\ 2 & 1 & 0 & 0 \end{array}$$

2 2 2 0

Current allocation matrix

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

Request matrix

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

skip

Deadlock Detection Algorithm - Example

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

Current allocation matrix

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

Request matrix

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

skip

Deadlock Detection Algorithm - Example

$$
\begin{array}{cccc}
\text{Tape drives} & \text{Plotters} & \text{Scanners} & \text{CD Roms}
\end{array}
$$

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

$$
\begin{array}{cccc}
\text{Tape drives} & \text{Plotters} & \text{Scanners} & \text{CD Roms}
\end{array}
$$

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

2 2 2 0

4 2 2 1

Current allocation matrix

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

Request matrix

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

skip

Deadlock Detection Algorithm - Example

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$$
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 & \text{Tape drives} & \text{Plotters} & \text{Scanners} & \text{CD Roms} & \\
A = (& 2 & 1 & 0 & 0 &) \\
 & \mathbf{2} & \mathbf{2} & \mathbf{2} & \mathbf{0} & \\
 & \mathbf{4} & \mathbf{2} & \mathbf{2} & \mathbf{1} &
\end{array}
$$

Current allocation matrix

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

Request matrix

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

No deadlock!

Deadlock Detection Issues

How often should the algorithm run?

- **After every resource request?**
- **Periodically?**
- **When CPU utilization is low?**
- **When we suspect deadlock?**
- **When some process/thread has been asleep for a long time?**

Recovery from Deadlock

What should be done to recover?

- **Abort deadlocked processes and reclaim resources**
- **Temporarily reclaim resource, if possible**
- **Abort one process at a time until deadlock cycle is eliminated**

Where to start?

Low priority processes
How long process has been executing
How many resources a process holds
Batch or interactive
Number of processes that must be terminated

Other Deadlock Recovery Techniques

Recovery through rollback

- **Save state periodically**
  (Take a "checkpoint")

- **Need to kill a process?**
  Start computation again from checkpoint

- **Done for large computation tasks**