Deadlocks

Concurrency Issues

- Past lectures:
  - Problem: Safely coordinate access to shared resource
  - Solutions:
    - Use semaphores, monitors, locks, condition variables
    - Coordinate access *within* shared objects
- What about coordinated access *across* multiple objects?
  - If you are not careful, it can lead to *deadlocks*
- Today's lecture:
  - What is a deadlock?
  - How can we address deadlocks?

Deadlocks
Motivating Examples

- Two *producer* processes share a buffer but use a different protocol for accessing the buffers

```
Producer1() {
  P(emptyBuffer)
  P(producerMutexLock)
    :
}
```

```
Producer2(){
  P(producerMutexLock)
  P(emptyBuffer)
    :
}
```

- A postscript interpreter and a visualization program compete for memory frames

```
PS_Interpreter() {
  request(memory_frames, 10)
  <process file>
  request(frame_buffer, 1)
  <draw file on screen>
}
```

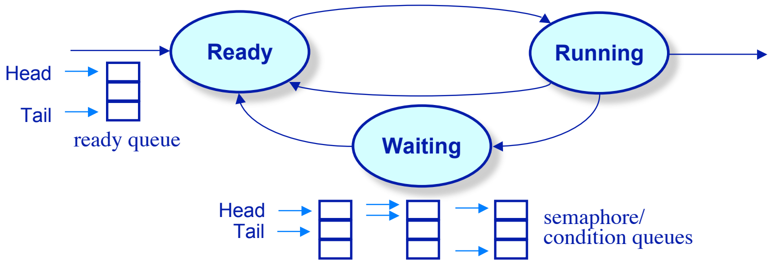
```
Visualize() {
  request(frame_buffer, 1)
  <display data>
  request(memory_frames,
20)
  <update display>
}
```


The TENEX Case

- If a process requests all systems buffers, operator console tries to print an error message
- To do so
  - lock the console
  - request a buffer

DUH!

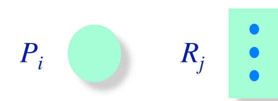
Deadlock
Definition



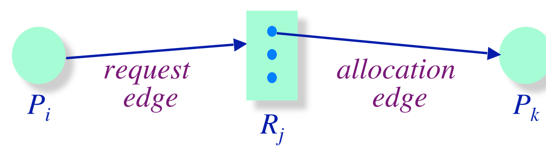
- A set of processes is deadlocked when every process in the set is waiting for an event that can only be generated by some process in the set
- Starvation vs. deadlock
  - Starvation: threads wait indefinitely (e.g., because some other thread is using a resource)
  - Deadlock: circular waiting for resources
  - Deadlock ➔ starvation, but not the other way

A Graph Theoretic Model of Deadlock
The resource allocation graph (RAG)

- Basic components of any resource allocation problem
  - Processes and resources
- Model the state of a computer system as a directed graph
  - $G = (V, E)$
  - V = the set of vertices = $\{P_1, ..., P_n\} \cup \{R_1, ..., R_m\}$



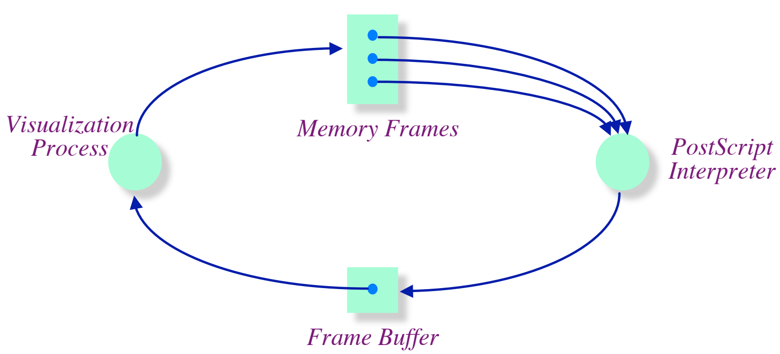
  - E = the set of edges =
    {*edges from a resource to a process*} ∪
    {*edges from a process to a resource*}



Resource Allocation Graphs
Examples

- A PostScript interpreter that is waiting for the frame buffer lock and a visualization process that is waiting for memory

V = {*PS interpret, visualization*} ∪ {*memory frames, frame buffer lock*}

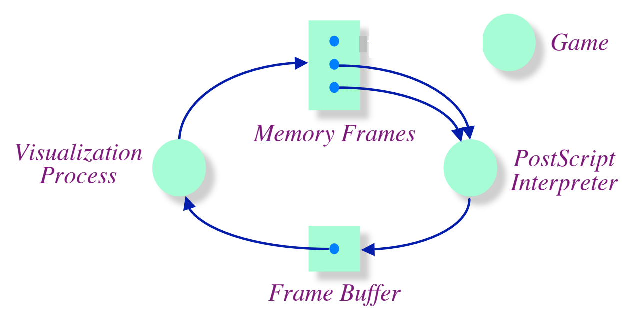


A Graph Theoretic Model of Deadlock
Resource allocation graphs & deadlock

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

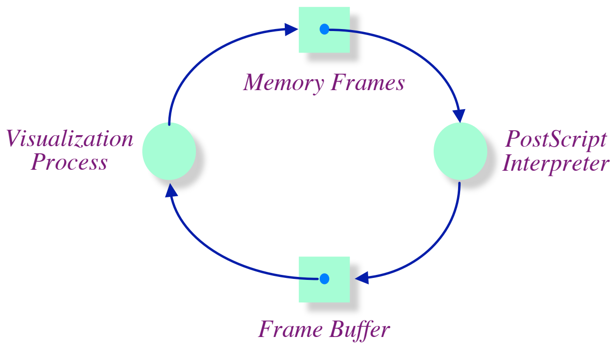
A cycle in a *RAG is* a necessary condition for deadlock

Is the existence of a cycle a sufficient condition?

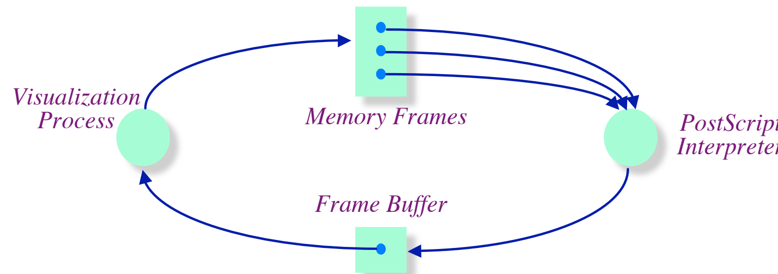


A Graph Theoretic Model of Deadlock
Resource allocation graphs & deadlock

- <u>Theorem</u>: *If there is only a single unit of all resources then a set of processes are deadlocked* iff *there is a cycle in the resource allocation graph*



Using the Theory
An operational definition of deadlock



- A set of processes are deadlocked *iff* the following conditions hold simultaneously
  1. Mutual exclusion is required for resource usage
  2. A process is in a "hold-and-wait" state
  3. Preemption of resource usage is not allowed
  4. Circular waiting exists (a cycle exists in the *RAG*)

Dealing With Deadlock
Deadlock prevention & avoidance

- Adopt some resource allocation protocol that ensures deadlock can never occur
  - Deadlock prevention/avoidance
    - Guarantee that deadlock will never occur
    - Generally breaks one of the following conditions:
      - Mutex: each resource is either assigned to exactly one process, or available
      - Hold-and-wait: processes holding resources and ask for new resources
      - No preemption:resources cannot be forcibly taken away from a process
      - Circular wait: a chain of 2 or more processes, each waiting for a resource held by the next in the chain
  - Deadlock detection and recovery
    - Admit the possibility of deadlock occurring and periodically check for it
    - On detecting deadlock, abort
      - Breaks the no-preemption condition

Dealing With Deadlock
Deadlock avoidance

- Examine each resource request and determine whether or not granting the request can lead to deadlock

Define a set of vectors and matrices that characterize the current state of all resources and processes

- *resource allocation state matrix*

  $Alloc_{ij}$ = the number of units of resource *j* held by process *i*

- *maximum claim matrix*

  Max_{ij} = the maximum number of units of resource *j* that the process *i* will ever require simultaneously

- *available vector*

  $Avail_j$ = the number of units of resource *j* that are unallocated

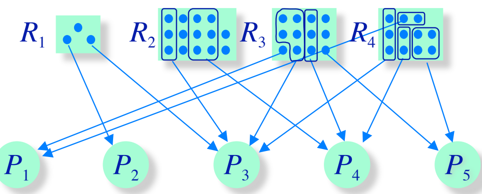
$$\begin{array}{c} \\ P_1 \\ P_2 \\ P_3 \\ \vdots \\ P_p \end{array} \begin{array}{c} \begin{array}{ccccc} R_1 & R_2 & R_3 & \dots & R_r \end{array} \\ \begin{pmatrix} n_{1,1} & n_{1,2} & n_{1,3} & \dots & n_{1,r} \\ n_{2,1} & n_{2,2} & & & \\ n_{3,1} & & \ddots & & \vdots \\ \vdots & & & & \\ n_{p,1} & & \dots & & n_{p,r} \end{pmatrix} \end{array}$$

$$\langle n_1, n_2, n_3, \dots, n_r \rangle$$

Deadlock Avoidance
State matrices example

- A computer system with 5 processes and 4 resources

	ALLOCATION R_1	R_2	R_3	R_4	MAX_CLAIM R_1	R_2	R_3	R_4	AVAILABLE R_1	R_2	R_3	R_4
P_1	0	0	1	2	0	0	1	2	1	5	2	0
P_2	1	0	0	0	1	7	5	0				
P_3	1	3	5	3	2	3	5	6				
P_4	0	6	3	2	0	6	5	2				
P_5	0	0	1	4	0	6	5	6				



Deadlock Avoidance
Concept

- The OS will examine each resource request and determine whether or not granting the request can lead to deadlock
  - If, after we grant this request, all processes simultaneously make their maximum claim, will the system deadlock?
  - Can we satisfy the maximum claims of processes in some order?

	ALLOCATION R_1	R_2	R_3	R_4	MAX_CLAIM R_1	R_2	R_3	R_4	AVAILABLE R_1	R_2	R_3	R_4
P_1	0	0	1	2	0	0	1	2	1	5	2	0
P_2	1	0	0	0	1	7	5	0				
P_3	1	3	5	3	2	3	5	6				
P_4	0	6	3	2	0	6	5	2				
P_5	0	0	1	4	0	6	5	6				

Deadlock Avoidance Algorithm
State definitions

- A *resource allocation state* is *safe* if the system can allocate resources to each process up to its maximum claim such that the system can not deadlock

  There must be an ordering of the processes P_1, P_2, ..., P_n, such that for all processes P_i,

$$\underbrace{MAX\_CLAIM_{P_i} - ALLOCATION_{P_i}}_{\text{The largest request for resources that process } P_i \text{ can make}} \le \underbrace{AVAIL + \sum_{Term.\,j} ALLOCATION_{P_j}}_{\text{The resources available to process } P_i \text{ after processes } P_1 \text{ through } P_{i-1} \text{ terminate}}$$

This ordering of processes is called a *safe sequence*

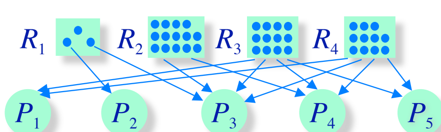
If a safe sequence exists then there exists a process (P_1) that can execute to completion in the current state, and

P_j can execute to completion at worst after processes P_1 - $P_{j\text{-}1}$ complete

Deadlock Avoidance Algorithm
Example

- A computer system with 5 processes and 4 resources

	ALLOCATION R_1	R_2	R_3	R_4	MAX_CLAIM R_1	R_2	R_3	R_4	AVAILABLE R_1	R_2	R_3	R_4
P_1	0	0	1	2	0	0	1	2	1	5	2	0
P_2	1	0	0	0	1	7	5	0				
P_3	1	3	5	3	2	3	5	6				
P_4	0	6	3	2	0	6	5	2				
P_5	0	0	1	4	0	6	5	6				



Is this system in a safe state?

Does there exist a safe sequence?

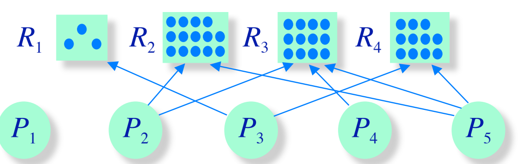
$$MAX\_CLAIM_{P_i} - ALLOCATION_{P_i} \le AVAIL + \sum_{j=1}^{i-1} ALLOCATION_{P_j}$$

Deadlock Avoidance Example
Safe sequence computation

1. Compute the largest possible resource request a process can make

$$
\begin{array}{c|cccc}
 & R_1 & R_2 & R_3 & R_4 \\
\hline
P_1 & 0 & 0 & 1 & 2 \\
P_2 & 1 & 7 & 5 & 0 \\
P_3 & 2 & 3 & 5 & 6 \\
P_4 & 0 & 6 & 5 & 2 \\
P_5 & 0 & 6 & 5 & 6
\end{array}
\;-\;
\begin{array}{cccc}
R_1 & R_2 & R_3 & R_4 \\
\hline
0 & 0 & 1 & 2 \\
1 & 0 & 0 & 0 \\
1 & 3 & 5 & 3 \\
0 & 6 & 3 & 2 \\
0 & 0 & 1 & 4
\end{array}
\;=\;
\begin{array}{cccc}
R_1 & R_2 & R_3 & R_4 \\
\hline
0 & 0 & 0 & 0 \\
0 & 7 & 5 & 0 \\
1 & 0 & 0 & 3 \\
0 & 0 & 2 & 0 \\
0 & 6 & 4 & 2
\end{array}
$$

MAX_CLAIM − ALLOCATION = MAX_REQUEST



2. Attempt to build a safe sequence

Deadlock Avoidance Example
Safe sequence computation

	ALLOCATION $R_1\ R_2\ R_3\ R_4$	MAX_CLAIM $R_1\ R_2\ R_3\ R_4$	AVAILABLE $R_1\ R_2\ R_3\ R_4$	MAX_REQUEST $R_1\ R_2\ R_3\ R_4$
P_1	0 0 1 2	0 0 1 2	1 5 2 0	0 0 0 0
P_2	1 0 0 0	1 7 5 0		0 7 5 0
P_3	1 3 5 3	2 3 5 6		1 0 0 3
P_4	0 6 3 2	0 6 5 2		0 0 2 0
P_5	0 0 1 4	0 6 5 6		0 6 4 2

- Does there exist a process P_i such that $MAX\_REQUEST_{P_i} \le AVAILABLE$?
- If no, then there is no safe sequence, the state is unsafe
- If yes, add P_i to the sequence
- Set $AVAILABLE = AVAILABLE + ALLOCATION_{P_i}$

Deadlock Avoidance Example
Safe sequence computation

	ALLOCATION $R_1\ R_2\ R_3\ R_4$	MAX_CLAIM $R_1\ R_2\ R_3\ R_4$	AVAILABLE $R_1\ R_2\ R_3\ R_4$	MAX_REQUEST $R_1\ R_2\ R_3\ R_4$
P_1	0 0 1 2	0 0 1 2	1 5 2 0	0 0 0 0
P_2	1 0 0 0	1 7 5 0		0 7 5 0
P_3	1 3 5 3	2 3 5 6		1 0 0 3
P_4	0 6 3 2	0 6 5 2		0 0 2 0
P_5	0 0 1 4	0 6 5 6		0 6 4 2

0 4 2 0

2 1 0 0

1 3 3 0

- What if P_2 wants to change its allocation to ‹0, 4, 2, 0›?
  - Is the resulting allocation state safe?

Deadlock Avoidance
Banker's algorithm (Dijkstra and Habermann)

- When a process makes a request for resources…
  - Simulate the effect of granting the process's request
  - Then check to see if a safe sequence exists

	ALLOCATION $R_1\ R_2\ R_3\ R_4$	MAX_CLAIM $R_1\ R_2\ R_3\ R_4$	AVAILABLE $R_1\ R_2\ R_3\ R_4$	MAX_REQUEST $R_1\ R_2\ R_3\ R_4$
P_1	0 0 1 2	0 0 1 2	1 5 2 0	0 0 0 0
P_2	1 0 0 0	1 7 5 0		0 7 5 0
P_3	1 3 5 3	2 3 5 6		1 0 0 3
P_4	0 6 3 2	0 6 5 2		0 0 2 0
P_5	0 0 1 4	0 6 5 6		0 6 4 2

Dealing With Deadlock
Deadlock detection & recovery

- Deadlock prevention and avoidance:
  - Develop and use resource allocation mechanisms and protocols that prohibit deadlock
- Deadlock detection and recovery:
  - Let the system deadlock and *then* deal with it
    - Detect that a set of processes are deadlocked
    - Recover from the deadlock

Deadlock Detection & Recovery
Detecting deadlock

- Run Banker's algorithm and see if a safe sequence exists
  - Replace *MAX_REQUEST* with a "*REQUEST*" matrix
  - If a safe sequence does not exist then the system is deadlocked

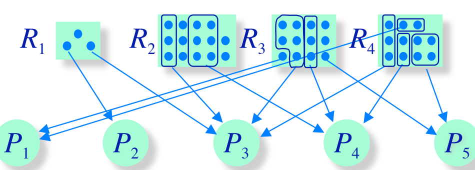
	ALLOCATION				MAX_CLAIM				AVAILABLE				REQUEST			
	R_1	R_2	R_3	R_4	R_1	R_2	R_3	R_4	R_1	R_2	R_3	R_4	R_1	R_2	R_3	R_4
P_1	0	0	1	2	0	0	1	2	1	5	2	0	0	0	0	0
P_2	1	0	0	0	1	7	5	0					0	2	1	0
P_3	1	3	5	3	2	3	5	6					1	0	0	0
P_4	0	6	3	2	0	6	5	2					0	0	2	0
P_5	0	0	1	4	0	6	5	6					0	2	2	2

Deadlock Detection & Recovery
Detecting deadlock

- How often should the OS check for deadlock?
  - After every resource request?
  - Only when we suspect deadlock has occurred?

	ALLOCATION				MAX_CLAIM				AVAILABLE				REQUEST			
	R_1	R_2	R_3	R_4	R_1	R_2	R_3	R_4	R_1	R_2	R_3	R_4	R_1	R_2	R_3	R_4
P_1	0	0	1	2	0	0	1	2	1	5	2	0	0	0	0	0
P_2	1	0	0	0	1	7	5	0					0	2	1	0
P_3	1	3	5	3	2	3	5	6					1	0	0	0
P_4	0	6	3	2	0	6	5	2					0	0	2	0
P_5	0	0	1	4	0	6	5	6					0	2	2	2

Deadlock Detection & Recovery
Recovering from deadlock



- Abort all deadlocked processes & reclaim their resources
- Abort one process at a time until all cycles in the *RAG* are eliminated
- Where to start?
  - Select low priority process
  - Processes with most allocation of resources
- Caveat: ensure that system is in consistent state (e.g., transactions)
- Optimization:
  - Checkpoint processes periodically; rollback processes to checkpointed state