CS162
Operating Systems and Systems Programming
Lecture 13

Deadlock

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https://cs162.org/

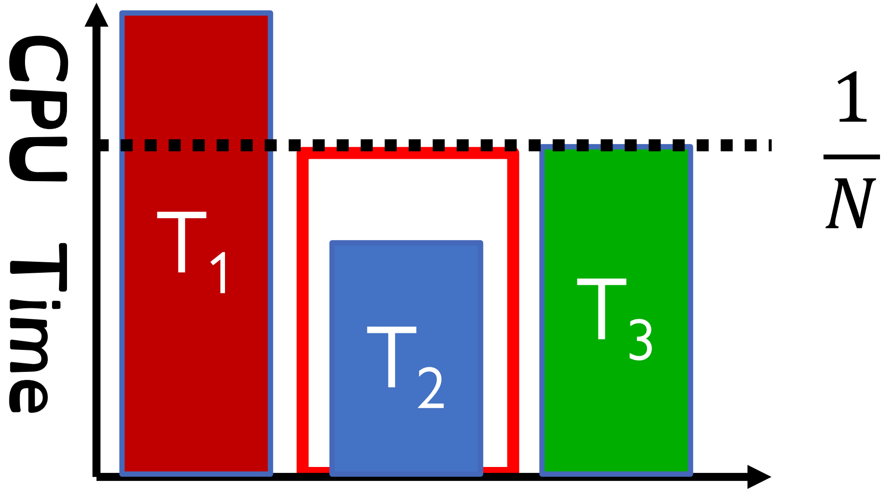
Slides based on prior slide decks from David Culler, Ion Stoica, John Kubiatowicz, Alison Norman and Lorenzo Alvisi

Linux Completely Fair Scheduler (CFS)

Basic Idea

Track CPU time per thread

CFS: Average rate of execution = $\frac{1}{N}$:



Scheduling Decision

"Repair" illusion of complete fairness

Choose thread with minimum CPU time

Linux Completely Fair Scheduler (CFS)

Fair by construction

Scheduling Cost is O(log n)
Threads are stored in a Red-Black tree.

Easy to capture interactivity
Sleeping threads don't advance their CPU time, so automatically get a boost when wake up again

Linux CFS: Responsiveness

Low response time & Starvation-freedom

Make sure that everyone gets to run in a given period of time

Constraint 1: *Target Latency*

Period of time over which every process gets service

Quanta = Target_Latency / n

Linux CFS: Latency

Constraint 1: *Target Latency*

Quanta = Target_Latency / n

Target Latency: 20 ms, 4 Processes

Each process gets 5ms time slice

Target Latency: 20 ms, 200 Processes

Each process gets 0.1ms time slice

Linux CFS: Throughput

Goal: Throughput
Avoid excessive overhead

Constraint 2: Minimum Granularity
Minimum length of any time slice

Target Latency 20 ms,
Minimum Granularity 1 ms, 200 processes
Each process gets 1 ms time slice

Linux CFS: Proportional Shares

Allow different threads to have different *rates of execution* (cycles/time)

Use weights!

Assign a weight w_i to each process I to compute the switching quanta Q_i

Basic equal share: $Q_i = \text{Target Latency} \cdot \frac{1}{N}$

Weighted Share: $Q_i = \left({}^{w_i}/_{\sum_p w_p}\right) \cdot \text{Target Latency}$

Linux CFS: Proportional Shares

Target Latency = 20ms
Minimum Granularity = 1ms

Two CPU-Bound Threads
- Thread A has weight 1
- Thread B has weight 4

What should the time slice of A and B be?

Weighted Share: $Q_i = \left({w_i}/{\sum_p w_p} \right) \cdot \text{Target Latency}$

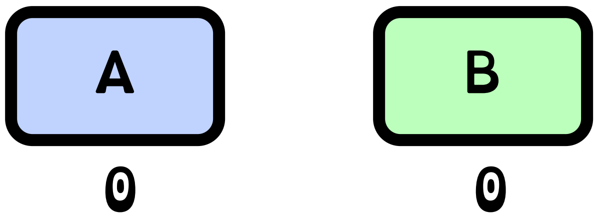
A = (1/5) * 20 = 4

B = (4/5) * 20 = 16

Linux CFS: Proportional Shares

Target Latency = 20ms
Minimum Granularity = 1ms
A timeslice = 4ms
B timeslice = 16 ms

Recall: Run the thread with the lowest amount of CPU use



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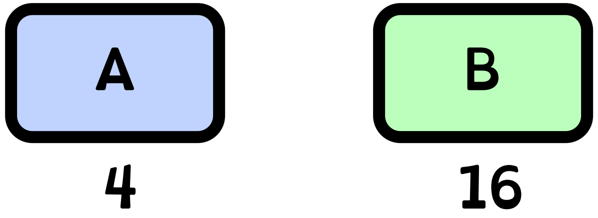

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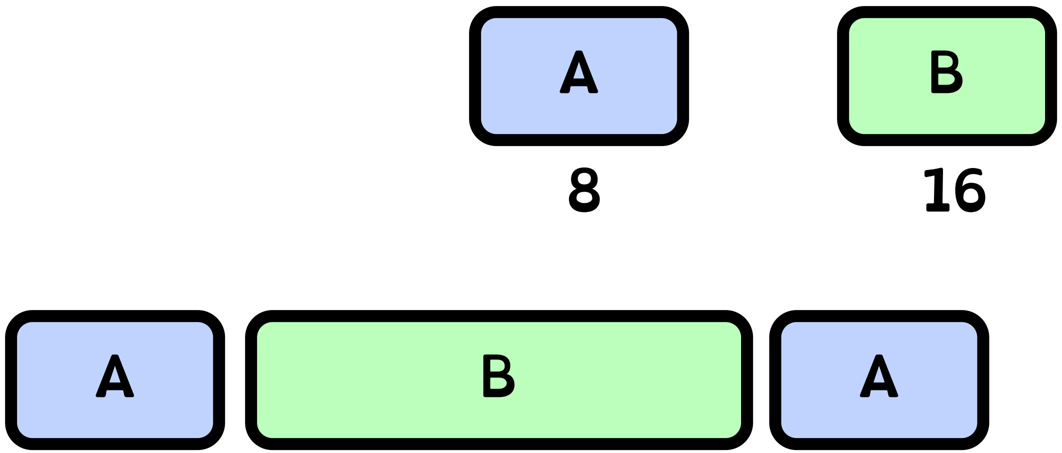

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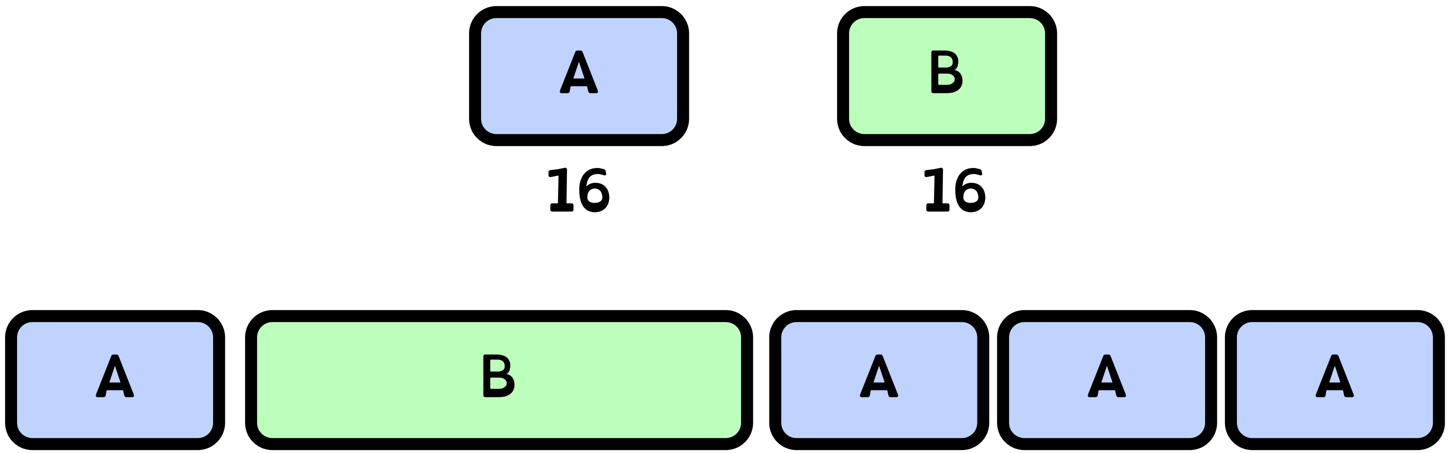
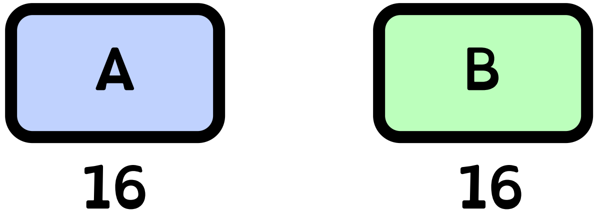
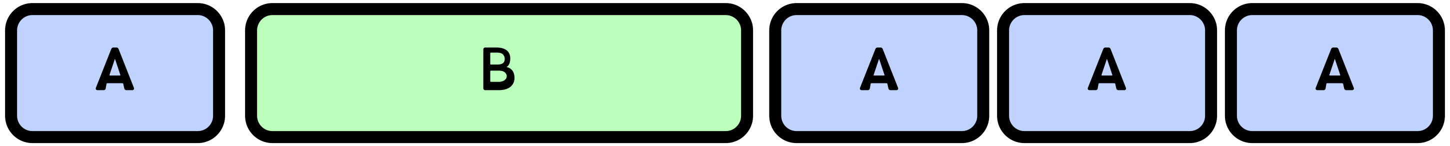


Linux CFS: Proportional Shares

A and B got 50% of the CPU. Something went wrong!

Recall: U use





Virtual Runtime

Must track a thread's virtual runtime rather than its true physical runtime

Higher weight: Virtual runtime increases more slowly

Lower weight: Virtual runtime increases more quickly

Virtual Runtime = Virtual Runtime + $\left({}^{1}/_{w_i}\right)$ Physical Runtime

Linux CFS: Proportional Shares

Target Latency = 20ms
Minimum Granularity = 1ms
A timeslice = 4ms
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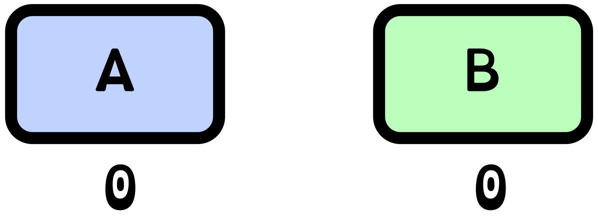
Recall: Run the thread with the lowest amount of CPU use



Linux CFS: Proportional Shares

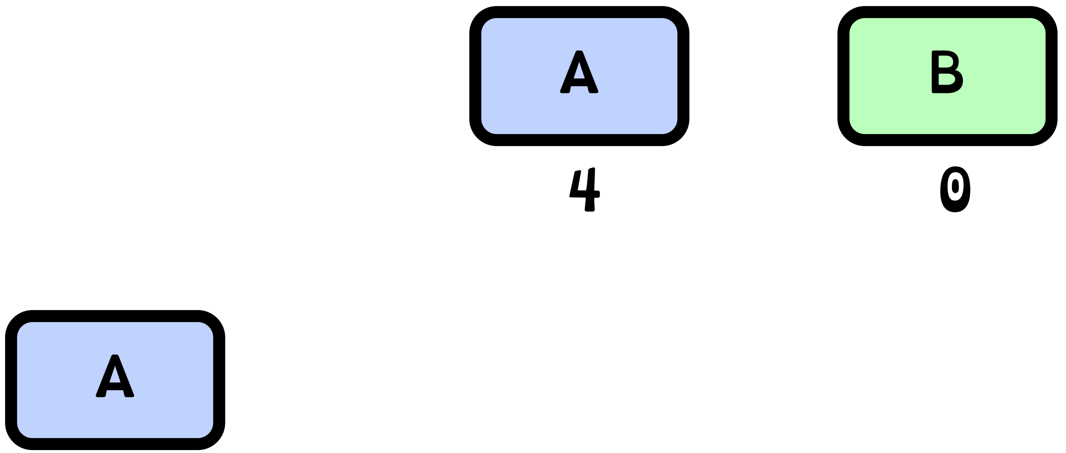
Target Latency = 20ms

Minimum Granularity = 1ms

A timeslice = 4ms

B timeslice = 16 ms

Virtual Runtime = 0 + Physical Runtime / Weight = 0 + 4/1



Linux CFS: Proportional Shares

Target Latency = 20ms
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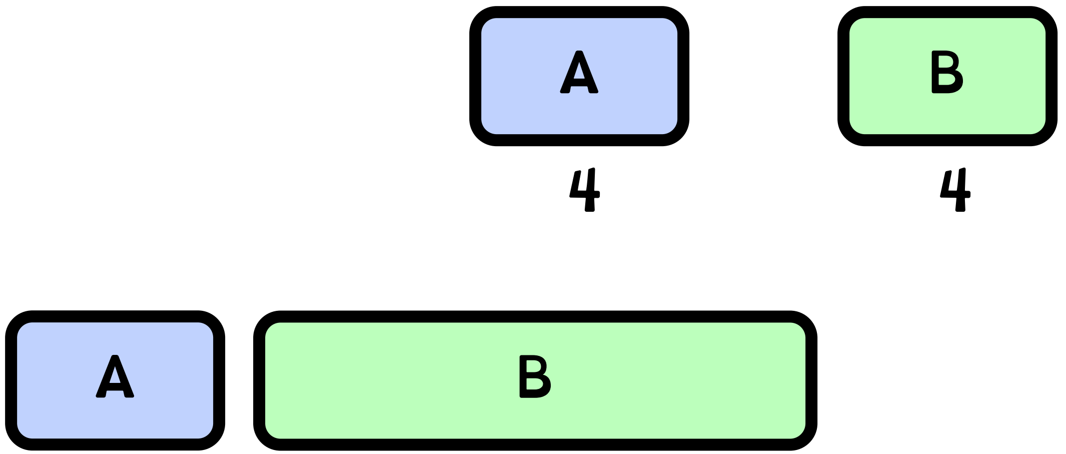
A timeslice = 4ms
B timeslice = 16 ms

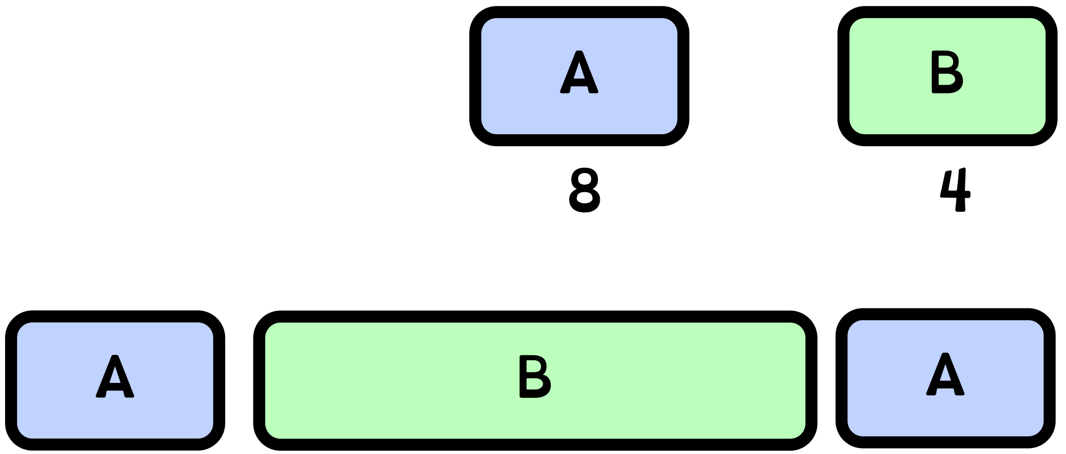
Virtual Runtime = 0 + Physical Runtime / Weight = 0 + 16/4 = 4



Linux CFS: Proportional Shares

Target Latency = 20ms
Minimum Granularity = 1ms
A timeslice = 4ms
B timeslice = 16 ms

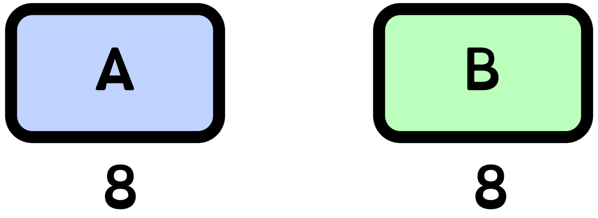
Virtual Runtime = 4 + Physical Runtime / Weight = 4 + 4/1 = 8

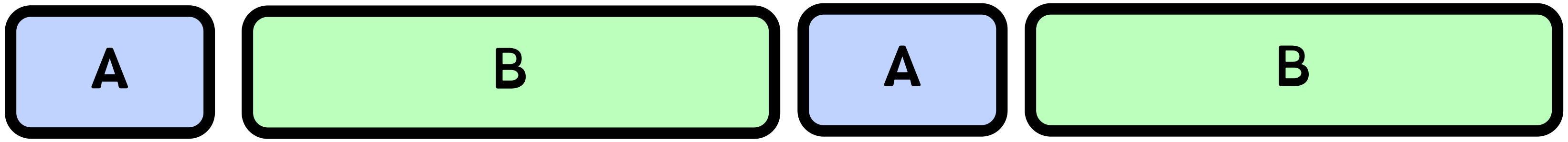


Linux CFS: Proportional Shares

Target Latency = 20ms
Minimum Granularity = 1ms
A timeslice = 4ms
B timeslice = 16 ms

Virtual Runtime = 4 + Physical Runtime / Weight = 4 + 16/4 = 8





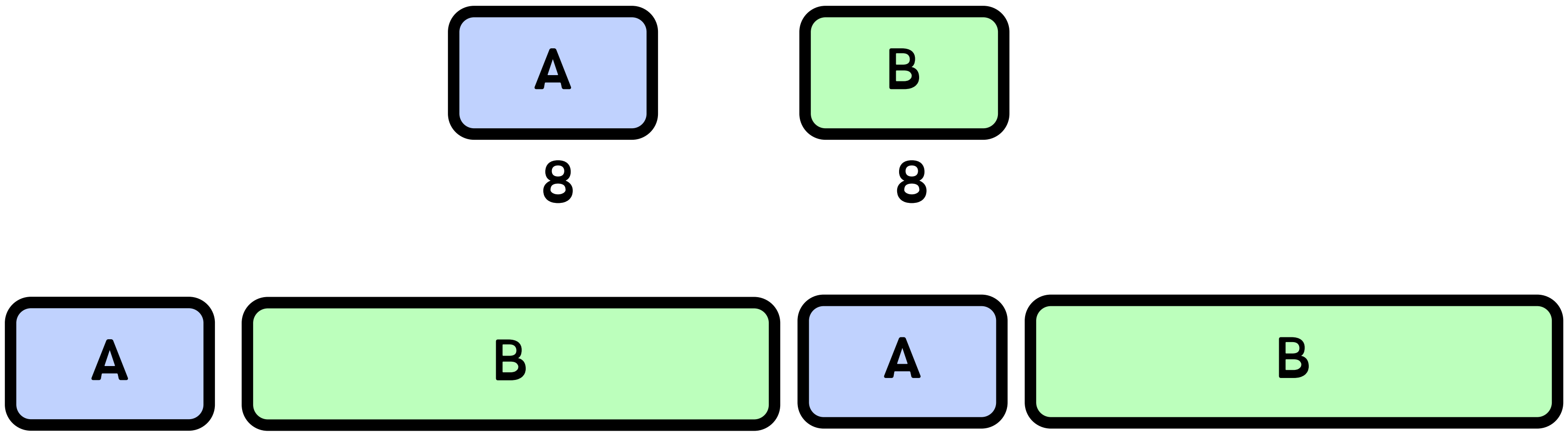
Linux CFS: Proportional Shares

A "Physical" CPU utilization: 4 + 4 = 8

B "Physical" CPU utilization: 16 + 16 = 32

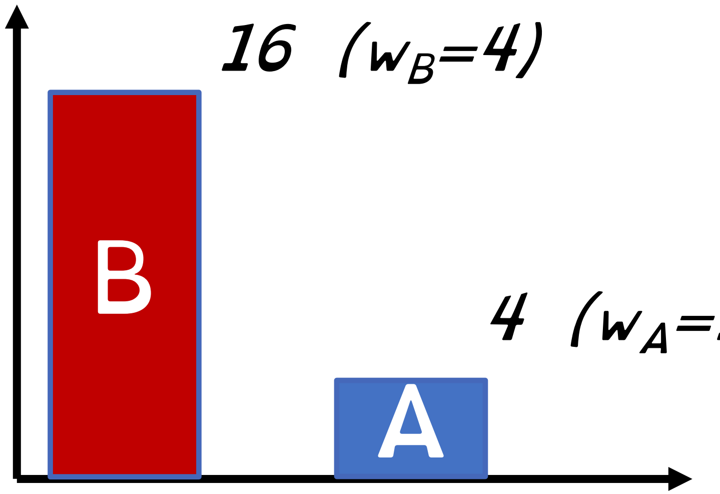
But equal virtual runtime!

CFS shares vruntime equally

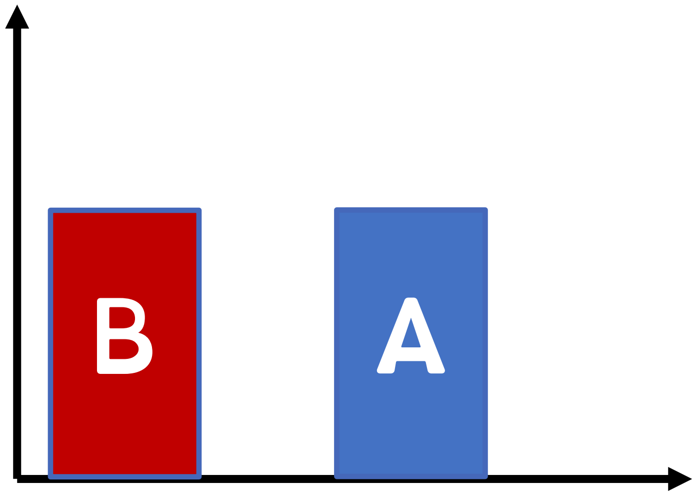


Linux CFS: Proportional Shares

Physical
CPU Time



Virtual
CPU Time



What about new jobs or very sleepy jobs?

Linux CFS: Proportional Shares

Reuse nice value to reflect share, rather than priority

CFS uses nice values to scale weights exponentially

$$Weight = 1024/(1.25)^{nice}$$

CFS & Priorities Cheat Sheet

Weight the real running time with priority of the task

Nice 0 is the reference: vruntime == real runtime ○

Nice < 0: vruntime increases slower than real time ○

Nice > 0: vruntime increases faster than real time

Summary: Schedulers in Linux

O(n) scheduler Linux 2.4 to Linux 2.6	Did not scale with large number of processes
O(1) scheduler Linux 2.6 to 2.6.22	Heuristics too complex
CFS scheduler Linux 2.6.23 onwards	Proportional Fair Sharing. Throughput and Latency constraints Gives all processes 1/N *virtual time * on CPU

Summary: Schedulers in Linux

O(n) scheduler
Linux 2.4 to Linux 2.6

Did not scale with large number of processes

O(1) scheduler
Linux 2.6 to 2.6.22

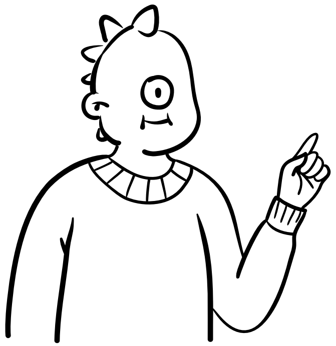
Heuristics too complex

CFS scheduler
Linux 2.6.23 onwards

Proportional Fair Sharing. Throughput and Latency constraints

Gives all processes 1/N *virtual time * on CPU

Understanding Deadlock

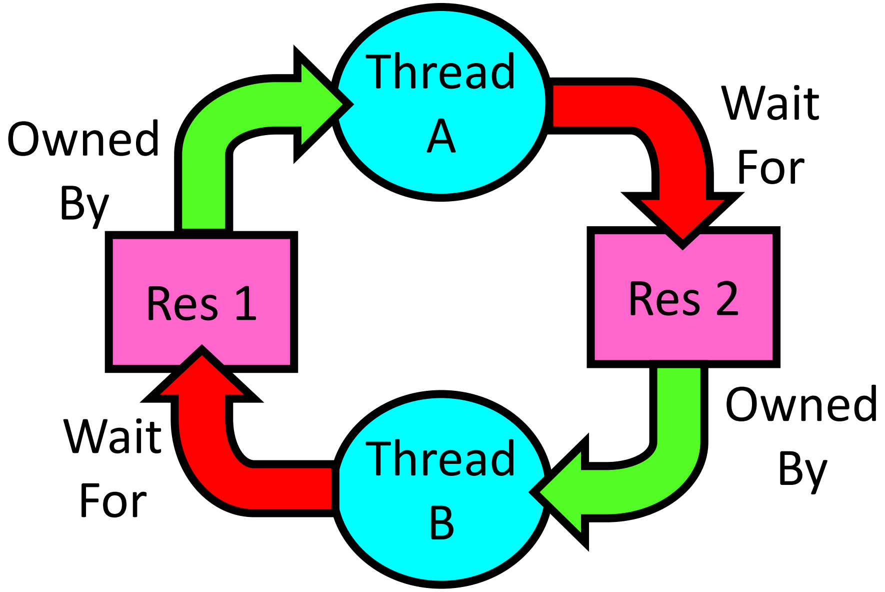


I will if you will

I will if you will

Deadlock: A Deadly type of Starvation

Deadlock: cyclic waiting for resources



Thread A owns Res 1 and is waiting for Res 2

Thread B owns Res 2 and is waiting for Res 1

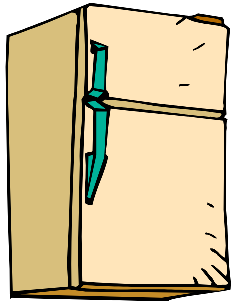
Deadlock: A Deadly type of Starvation

Starvation: thread waits indefinitely

Deadlock implies starvation
but starvation does not imply deadlock

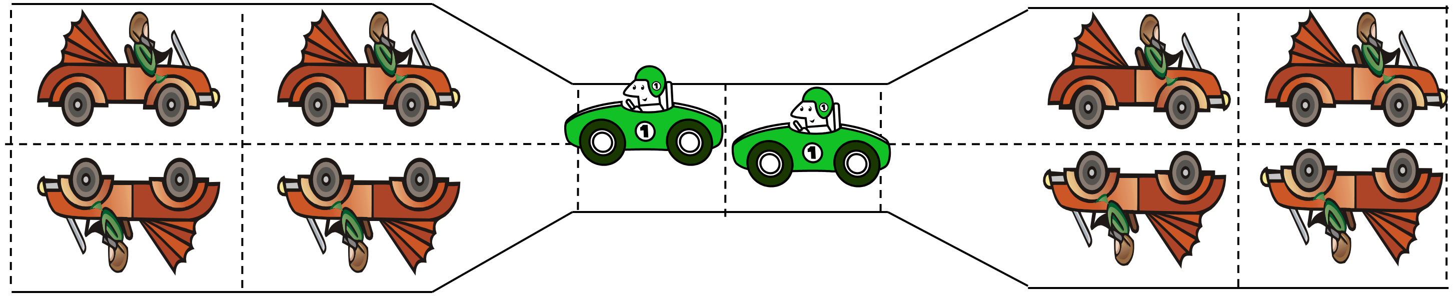
Starvation can end (but doesn't have to)
Deadlock can't end without external intervention

Example: Single-Lane Bridge Crossing



Bridge Crossing Example

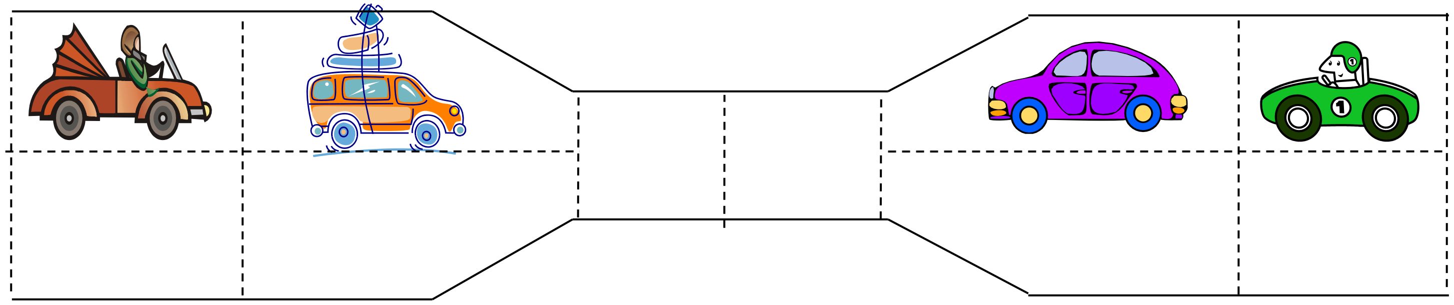
Each segment of road can be viewed as a resource



Rules:

- Car must own the segment under them
- Must acquire segment that they are moving into
- For bridge: traffic only in one direction at a time

Bridge Crossing Example

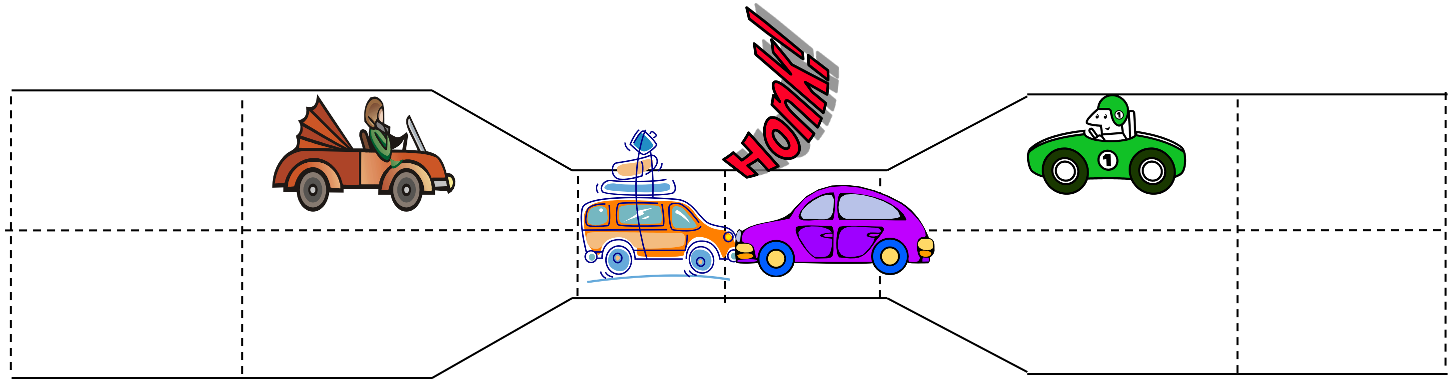


Car must own the segment under them

Must acquire segment that they are moving into

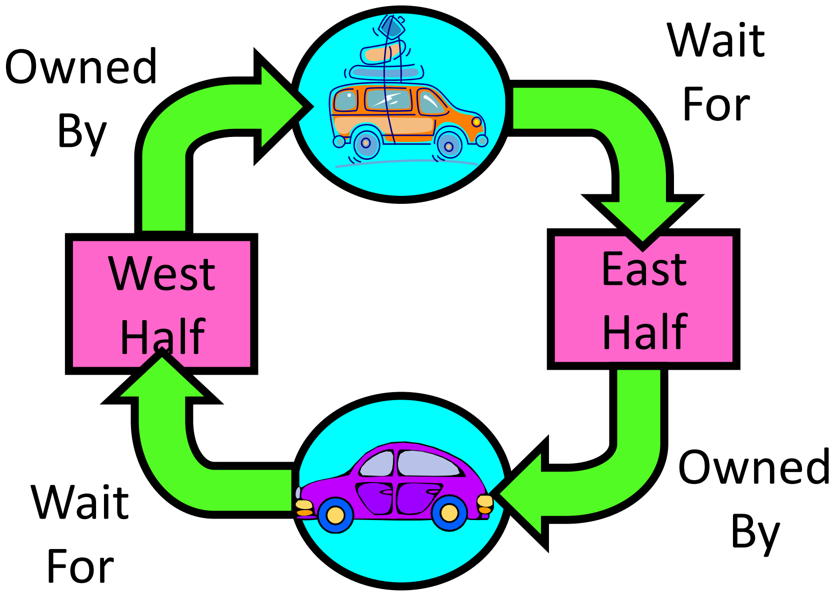
For bridge: traffic only in one direction at a time

Bridge Crossing Example

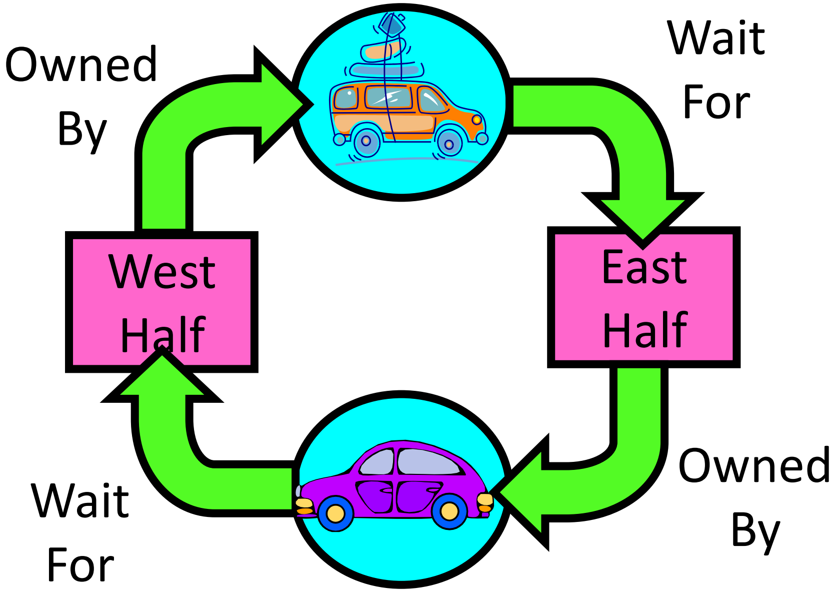


Deadlock:

Circular waiting for resources



Bridge Crossing Example



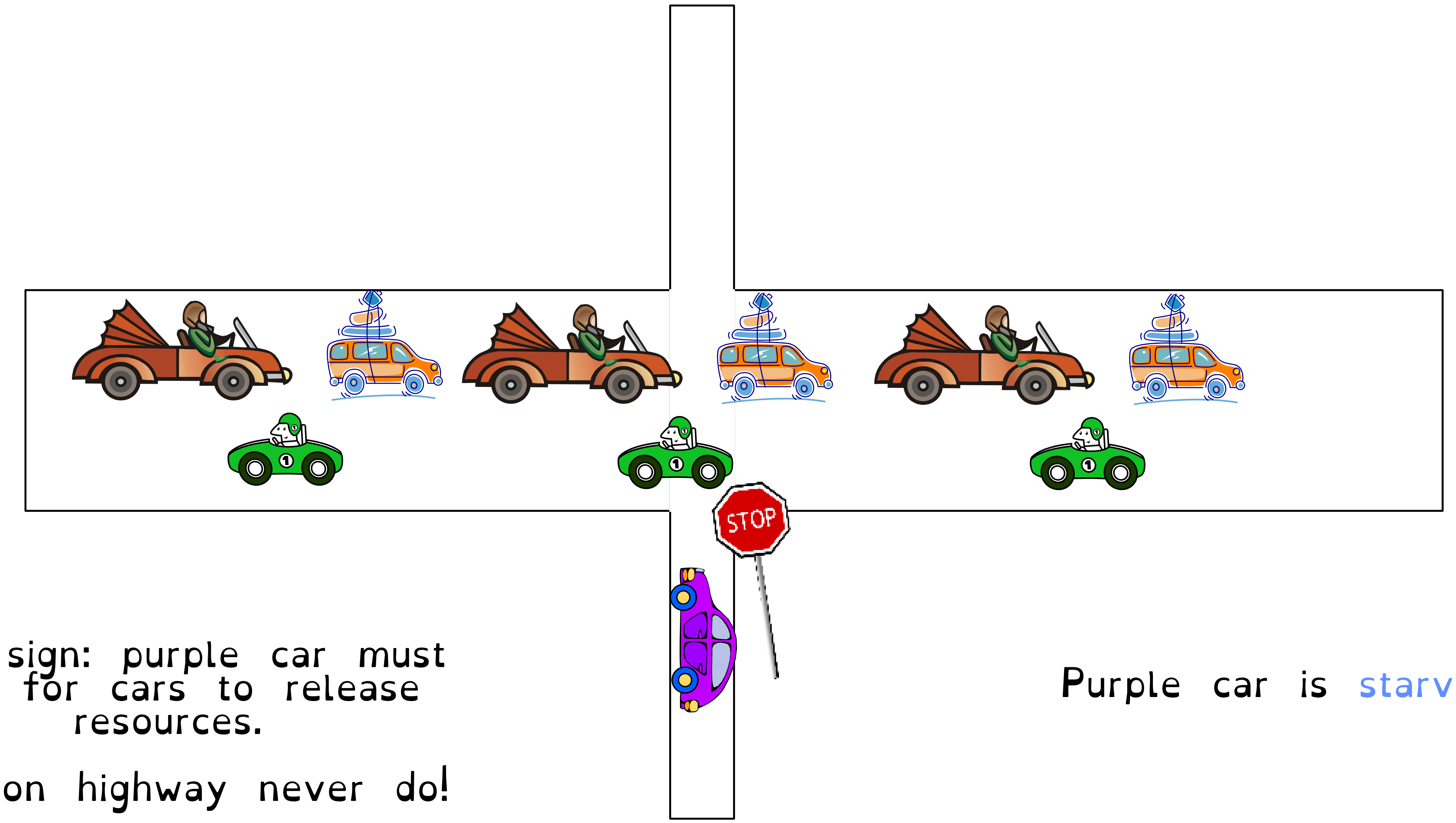
Deadlock:

Circular waiting for resources

Could be resolved by "external" intervention:

- fork-lifting a car of the bridge (equivalent to killing a thread)
- Asking cars to backup (equivalent to removing the resource from the thread)

Starvation does not mean deadlock!



Stop sign: purple car must wait for cars to release resources.

Cars on highway never do!

Purple car is starved

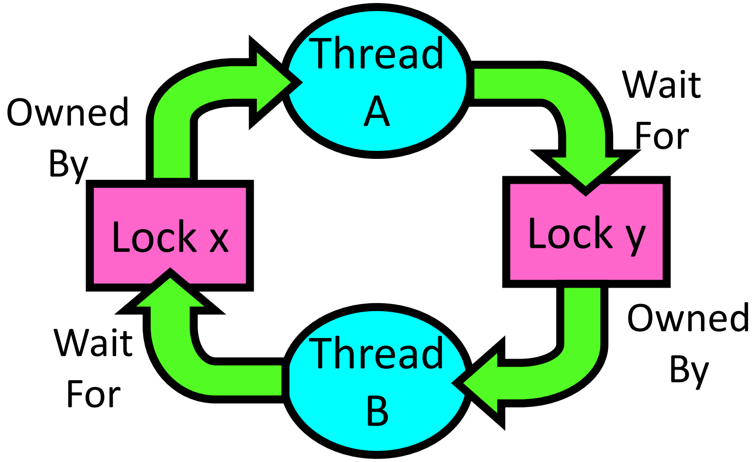
Deadlock with Locks

<u>Thread A:</u>

```
x.Acquire();
y.Acquire();
…
y.Release();
x.Release();
```

<u>Thread B:</u>

```
y.Acquire();
x.Acquire();
…
x.Release();
y.Release();
```



Will threads deadlock

a) Always b) Never c) Sometimes d) I'm still trying to cross the road

This lock pattern exhibits *non-deterministic deadlock*

A system is subject to deadlock if deadlock can happen in any execution

Deadlock with Locks: “Lucky” Case

Thread A:

```
x.Acquire();
y.Acquire();
…
y.Release();
x.Release();
```

Thread B:

```
y.Acquire();
x.Acquire();
…
x.Release();
y.Release();
```

Sometimes, schedule won’t trigger deadlock!

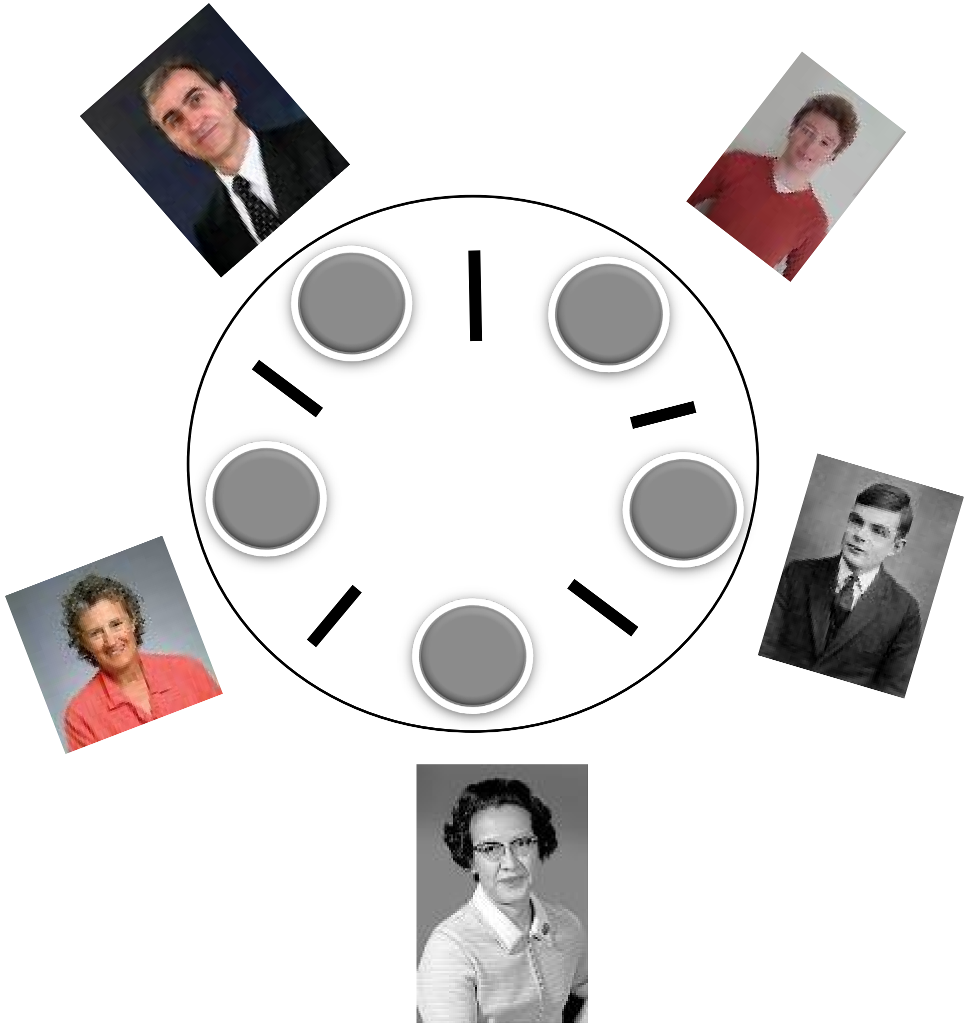
Other Types of Deadlock

Threads often block waiting for resources
- Locks
- Terminals
- Printers
- CD drives
- Memory

Threads often block waiting for other threads
- Pipes
- Sockets

You can deadlock on any of these!

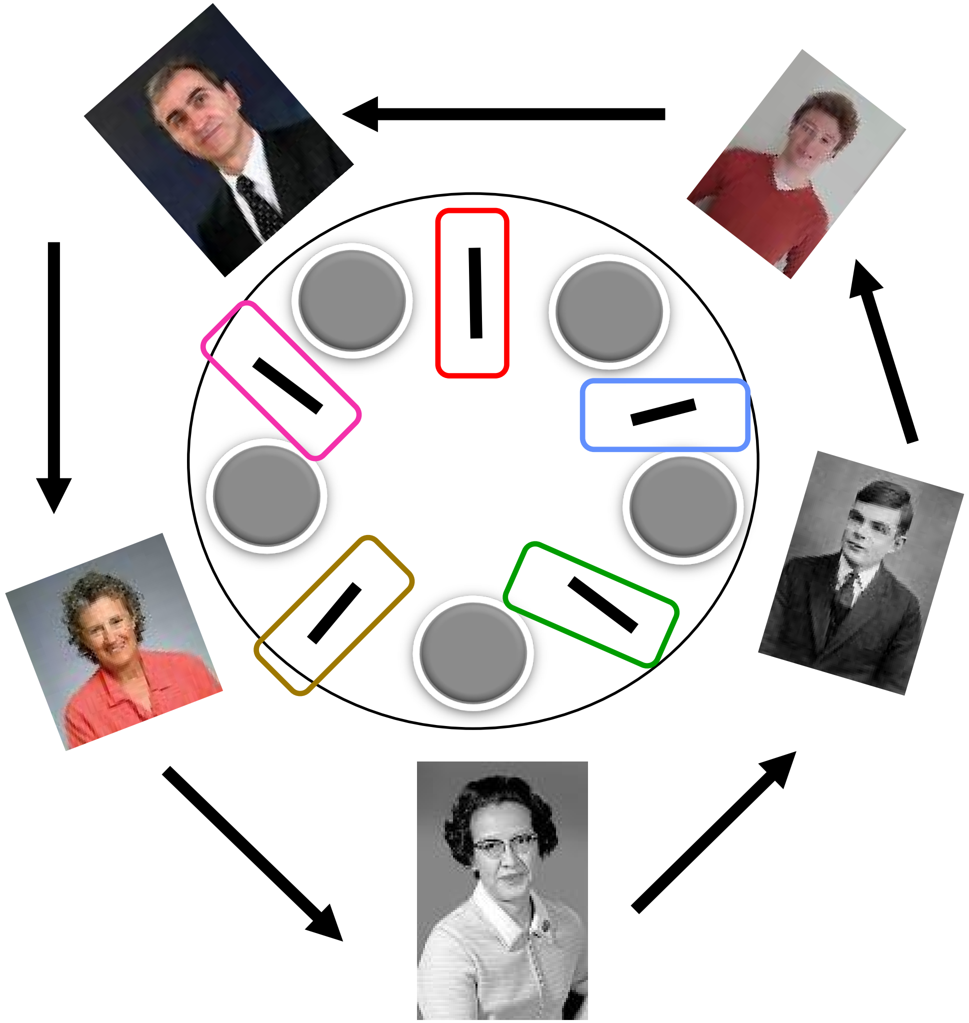
Dining Computer Scientists Problem



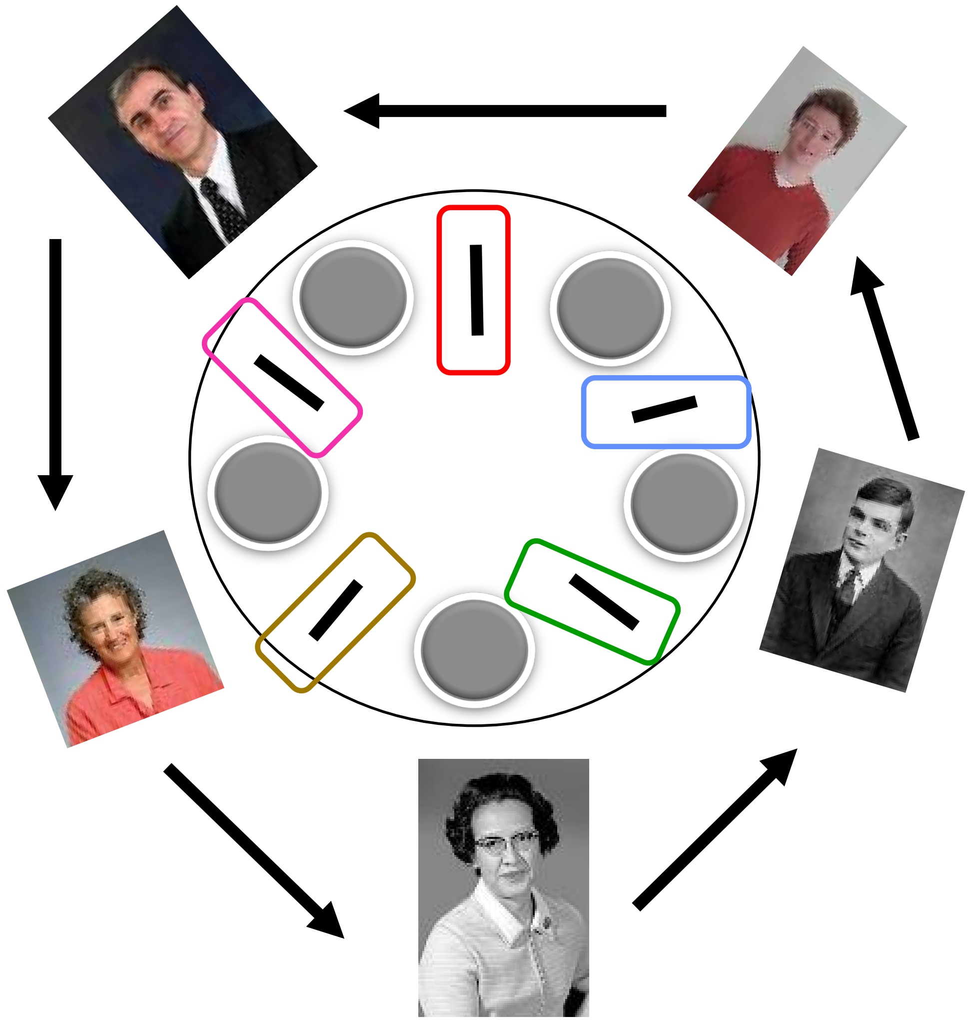
Five chopsticks/Five computer scientists

Need two chopsticks to eat

Free for all leads to deadlock



Intervention needed



Fixing deadlock needs external intervention!

How could we have prevented this?

- Give everyone two chopsticks
- Make everyone “give up” after a while
- Require everyone to pick up both chopsticks atomically

Four requirements for occurrence of deadlock

1) Mutual exclusion and bounded resources

Only one thread at a time can use a resource.

2) Hold and wait

Thread holding at least one resource is waiting to acquire additional resources held by other threads

Four requirements for occurrence of deadlock

3) No preemption

Resources are released only voluntarily by the thread holding the resource, after thread is finished with it

4) Circular wait

There exists a set $\{T_1, ..., T_n\}$ of waiting threads

- » T_1 is waiting for a resource that is held by T_2
- » T_2 is waiting for a resource that is held by T_3
- » …
- » T_n is waiting for a resource that is held by T_1

Detecting Deadlock: Resource-Allocation Graph

System Model

A set of Threads $T_1, T_2, \ldots, T_n$

Resource types $R_1, R_2, \ldots, R_m$

CPU cycles, memory space, I/O devices

Each resource type R_i has W_i instances

Each thread

`Request() / Use() / Release()` a resource:

Detecting Deadlock: Resource-Allocation Graph

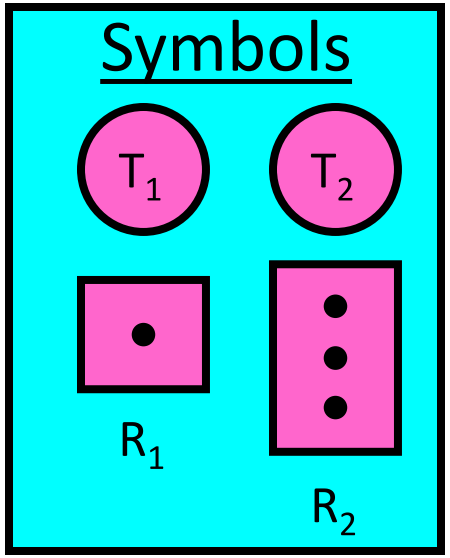
Resource-Allocation Graph

- V is partitioned into two types:

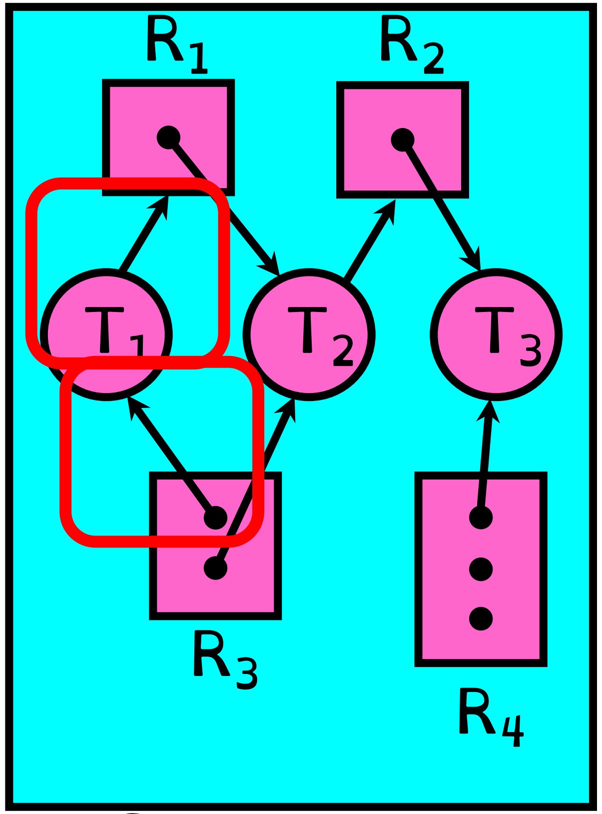
  $T = \{T_1, T_2, \ldots, T_n\}$, the set threads in the system.

  $R = \{R_1, R_2, \ldots, R_m\}$, the set of resource types in system

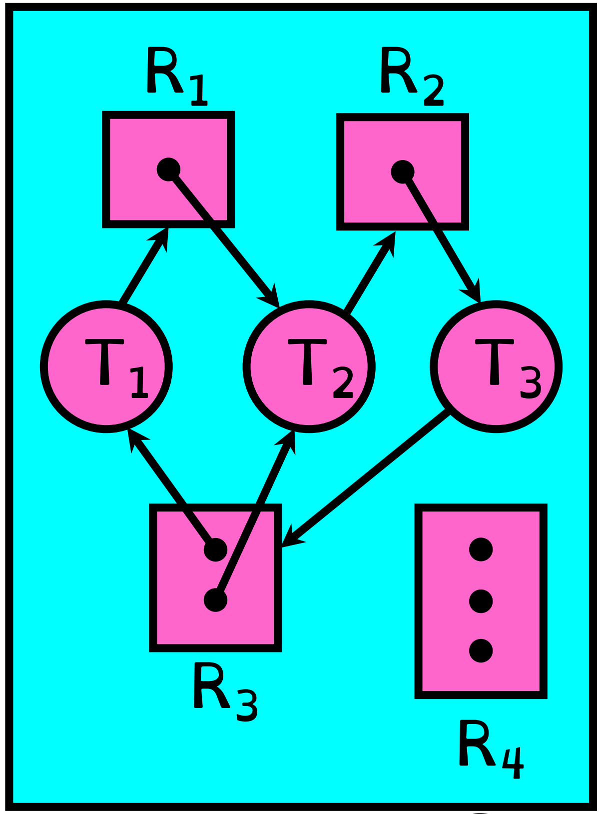
- request edge – directed edge $T_1 \rightarrow R_j$
- assignment edge – directed edge $R_j \rightarrow T_i$



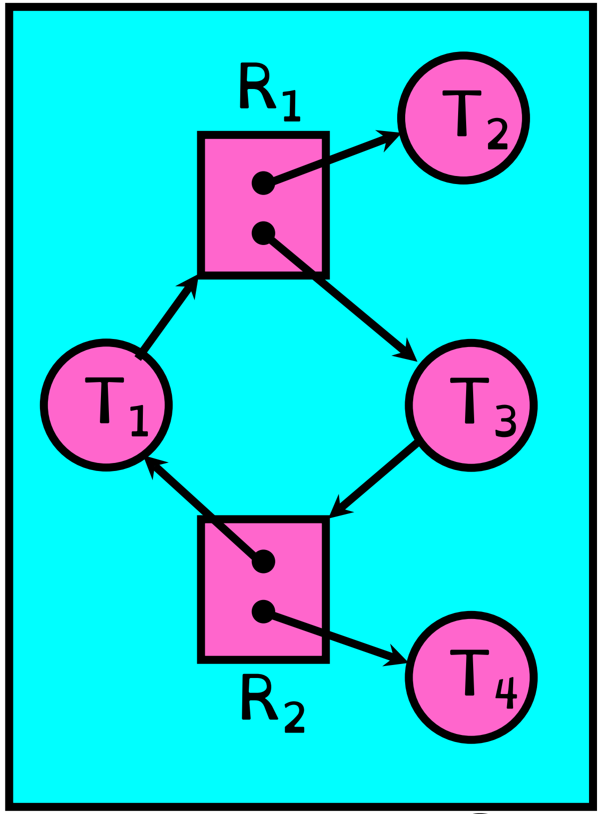
Resource-Allocation Graph Examples



Simple Resource Allocation Graph



Allocation Graph With Deadlock



Allocation Graph With Cycle, but No Deadlock

Deadlock Detection Algorithm

Let [X] represent an m-ary vector of non-negative integers (quantities of resources of each type)

`[FreeResources]:`	Current free resources each type
`[Request`$_X$`]:`	Current requests from thread X
`[Alloc`$_X$`]:`	Current resources held by thread X

Deadlock Detection Algorithm

See if tasks can eventually terminate on their own

```
[Avail] = [FreeResources]
Add all threads to UNFINISHED
do {
   done = true
   Foreach thread in UNFINISHED {
      if ([Request_node] <= [Avail]) {
         remove thread from UNFINISHED
         [Avail] = [Avail] + [Alloc_node]
         done = false
      }
   }
} until(done)
```

Threads left in UNFINISHED ⇒ deadlocked

Deadlock Detection Algorithm

```
[Avail] = [FreeResources]
        Add all threads to UNFINISHED
        do {
            done = true
            Foreach thread in UNFINISHED {
                if ([Request_node] <= [Avail]) {
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                }
            }
        } until(done)
```
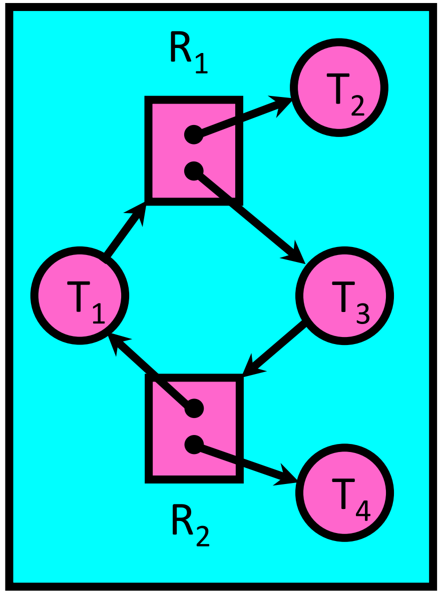

Threads left in UNFINISHED $\Rightarrow$ deadlocked




```
[Avail] = {0,0}
UNFINISHED = T1, T2, T3, T4

Looking at T1: [1,0] > [0,0]

Looking at T2: [0,0] <= [0,0]
Avail = [1,0]
UNFINISHED = T1,T3,T4

Looking at T3: [0,1] > [1,0]

Looking at T4
[0,0] <= [0,0]
Avail = [1,1]
UNFINISHED = T1, T3

Looking at T1: [1,0] <= [1,1]
Avail = [2,1]
UNFINISHED = T3

Looking at T3: [0,1] <= [2,1]
Avail = [2,2]
UNFINISHED = Empty!
```

How should a system deal with deadlock?

Deadlock prevention

Write your code in a way that it isn't prone to deadlock

Deadlock recovery

Let deadlock happen, and figure out how to recover from it

Deadlock avoidance

Dynamically delay resource requests so deadlock doesn't happen

Deadlock denial

Ignore the possibility of deadlock

Deadlock prevention

Condition 1: Mutual exclusion and bounded resources
=> Provide sufficient resources

Condition 2: Hold and wait
⇒Abort request or acquire requests atomically

Condition 3: No preemption
=> Preempt threads

Condition 4: Circular wait
=> Order resources and always acquire resources in the same way

Condition 1 Fix: (Virtually) Infinite Resources

```
Thread A                     Thread B
AllocateOrWait(1 MB)         AllocateOrWait(1 MB)
AllocateOrWait(1 MB)         AllocateOrWait(1 MB)
Free(1 MB)                   Free(1 MB)
Free(1 MB)                   Free(1 MB)
```

With virtual memory we have "infinite" space so everything will always succeed

Condition 2 Fix: Request Resources Atomically

Rather than:

```
Thread A:                Thread B:
x.Acquire();             y.Acquire();
y.Acquire();             x.Acquire();
…                        …
y.Release();             x.Release();
x.Release();             y.Release();
```

Consider instead:

```
Thread A:                Thread B:
Acquire_both(x, y);      Acquire_both(y, x);
…                        …
y.Release();             x.Release();
x.Release();             y.Release();
```

Condition 3 Fix: Preemption

Force thread to give up resource

Common technique in databases using database aborts
- A transaction is "aborted": all of its actions are undone, and the transaction must be retried

Common technique in wireless networks:
- Everyone speaks at once. When a resource collision is detected, retry at a new, random time

Condition 4 Fix: Circular Waiting

Force all threads to request resources in the same order

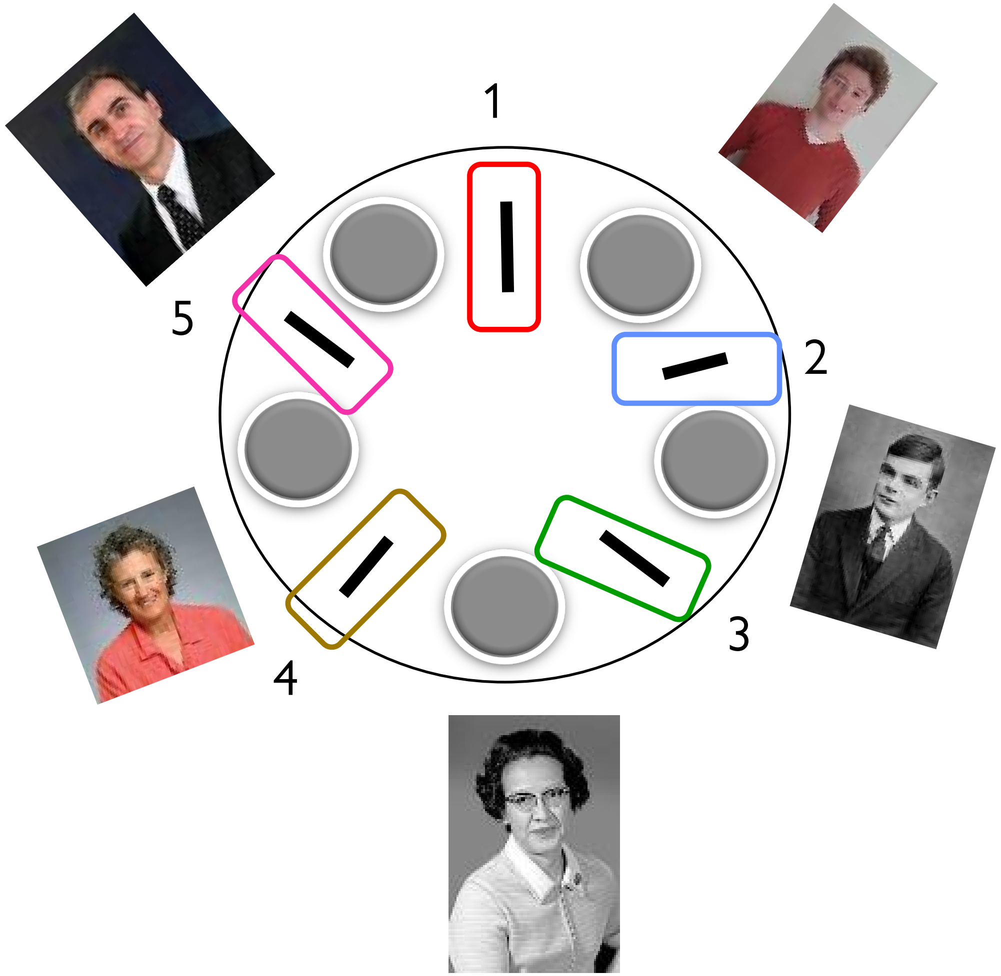
Thread A:
```
x.Acquire();
y.Acquire();
…
y.Release();
x.Release();
```

Thread B:
```
y.Acquire();
x.Acquire();
…
x.Release();
y.Release();
```

Thread A:
```
x.Acquire();
y.Acquire();
…
y.Release();
x.Release();
```

Thread B:
```
x.Acquire();
y.Acquire();
…
y.Release();
x.Release();
```

Condition 4 Fix: Circular Waiting



Garcia: first 1 then 5
Crooks: first 2 then 1
Turing: first 3 then 2
Johnson: first 4 than 3
Liskov: first 5 then 4

If ensure that Garcia graphs chopstick 5 followed by 1, no deadlock!

How should a system deal with deadlock?

Deadlock prevention

Write your code in a way that it isn't prone to deadlock

Deadlock recovery

Let deadlock happen, and figure out how to recover from it

Deadlock avoidance

Dynamically delay resource requests so deadlock doesn't happen

Deadlock denial

Ignore the possibility of deadlock

Techniques for Deadlock Avoidance

Attempt 1

When a thread requests a resource, OS checks if it would result in deadlock

If not, it grants the resource right away

If so, it waits for other threads to release resources

Techniques for Deadlock Avoidance

This does not work!

Thread A:

```
x.Acquire();
y.Acquire();   // Blocks…
…
y.Release();
x.Release();
```

Thread B:

```
y.Acquire();
x.Acquire();
…
x.Release();
y.Release();
```

Wait?

But it's already too late…

Deadlock Avoidance: Three States

Safe state

System can delay resource acquisition to prevent deadlock

Unsafe state

No deadlock yet...

But threads can request resources in a pattern that *unavoidably* leads to deadlock

Deadlocked state

There exists a deadlock in the system

Deadlock avoidance: prevent system from reaching an *unsafe* state

Deadlock Avoidance: Three States

Thread A:

```
x.Acquire();
y.Acquire();
…
y.Release();
x.Release();
```

Thread B:

```
y.Acquire();
x.Acquire();
…
x.Release();
y.Release();
```

A acquires x.
There exists a sequence A-A(y),A-R(y),A-R(x), B-A(y), B-A(x), B-R(x), B-R(y) => safe state

B acquires y.
No sequence that won't lead to deadlock. => unsafe state

Banker's Algorithm for Avoiding Deadlock

Banker's algorithm ensures never enter an unsafe state.

Evaluate each request and grant if some ordering of threads is still deadlock free afterward

Technique: pretend each request is granted, then run deadlock detection algorithm

Banker's Algorithm for Avoiding Deadlock

```
[Avail] = [FreeResources]
     Add all threads to UNFINISHED
     do {
        done = true
        Foreach thread in UNFINISHED {
           if ([Request_thread] <= [Avail]) {
              remove thread from UNFINISHED
              [Avail] = [Avail] + [Alloc_thread]
              done = false
           }
        }
     } until(done)
```

```
[Avail] = [FreeResources]
     Add all threads to UNFINISHED
     do {
        done = true
        Foreach threads in UNFINISHED {
           if ([Max_threads]-[Alloc_thread] <= [Avail]) {
              remove thread from UNFINISHED
              [Avail] = [Avail] + [Alloc_thread]
              done = false
           }
        }
     } until(done)
```

Banker's Algorithm for Avoiding Deadlock

```
[Avail] = [FreeResources]
      Add all threads to UNFINISHED
      do {
         done = true
         Foreach threads in UNFINISHED {
            if ([Max_threads]-[Alloc_thread] <= [Avail]) {
               remove thread from UNFINISHED
               [Avail] = [Avail] + [Alloc_thread]
               done = false
            }
         }
      } until(done)
```

Step 1: "Assume" request is made

Step 2: If request is made, is system still in SAFE state?
There exists a sequence $\{T_1, T_2, \ldots T_n\}$ such that all transactions finish

Step 3: If SAFE, grant resources. If UNSAFE, delay

Banker's Algorithm for Avoiding Deadlock

```
[Avail] = [FreeResources]
        Add all threads to UNFINISHED
        do {
            done = true
            Foreach threads in UNFINISHED {
                if ([Max_threads]-[Alloc_thread] <= [Avail]) {
                    remove thread from UNFINISHED
                    [Avail] = [Avail] + [Alloc_thread]
                    done = false
                }
            }
        } until(done)
```

Thread A:

```
x.Acquire();
y.Acquire();
…
y.Release();
x.Release();
```

Thread B:

```
y.Acquire();
x.Acquire();
…
x.Release();
y.Release();
```

When Thread A acquires x:

Avail = [0,1]
For A: [1,1] – [1,0] <= [0,1]
Update Avail to = 1,1.
Remove A from UNFINISHED
For B:
[1,1] – [0,0] <= [1,1]
Update Avail to = [1,1].
Remove B from UNFINISHED

Safe state!

When Thread B acquires y:

Avail = [0,0]
For A: [1,1] – [1,0] <= [0,0]
For B: [1,1] – [0,1] <= [0,0]

UNFINISHED not empty

Unsafe state! Must delay acquiring y!

Summary

Deadlock => Starvation, Starvation does not imply deadlock

Four conditions for deadlocks
Mutual exclusion
Hold and wait
No preemption
Circular wait

Techniques for addressing deadlock: prevention, recovery, avoidance, or denial

Banker's algorithm for avoiding deadlock