CSC 112: Computer Operating Systems
Lecture 12

Scheduling 3: Starvation (Finished), Deadlock

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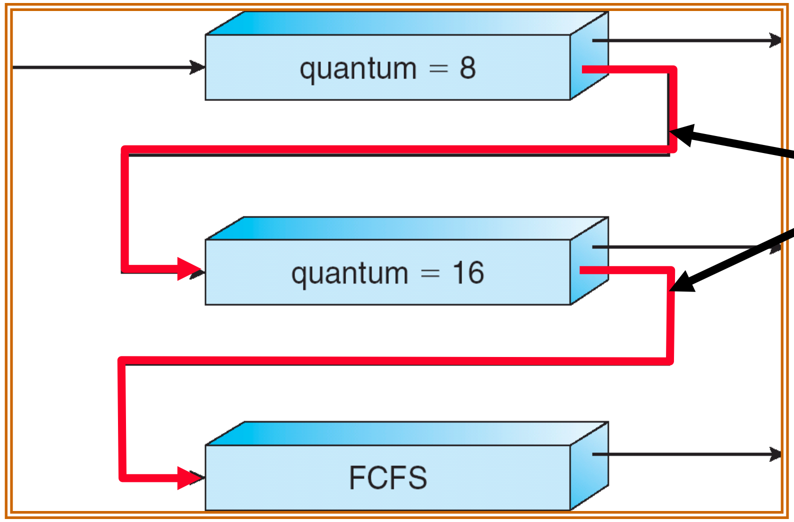
Acknowledgement: Lecture slides based on UC Berkeley CS 162: Operating Systems and System Programming

Recall: Real-Time Scheduling

- Goal: Predictability of Performance!
  - We need to predict with confidence worst case response times for systems!
  - In RTS, performance guarantees are:
    - » Task- and/or class centric and often ensured a priori
  - In conventional systems, performance is:
    - » System/throughput oriented with post-processing (… wait and see …)
  - Real-time is about enforcing predictability, and does not equal fast computing!!!
- Hard real-time: for time-critical safety-oriented systems
  - Meet all deadlines (if at all possible)
  - Ideally: determine in advance if this is possible
  - Earliest Deadline First (EDF), Least Laxity First (LLF), Rate-Monitonic Scheduling (RMS), Deadline Monotonic Scheduling (DM)
- Soft real-time: for multimedia
  - Attempt to meet deadlines with high probability
  - Constant Bandwidth Server (CBS)

Are SRTF and MLFQ Prone to Starvation?



Long-Running Compute Tasks Demoted to Low Priority

- In SRTF, long jobs are starved in favor of short ones
  - Same fundamental problem as priority scheduling
- MLFQ is an approximation of SRTF, so it suffers from the same problem

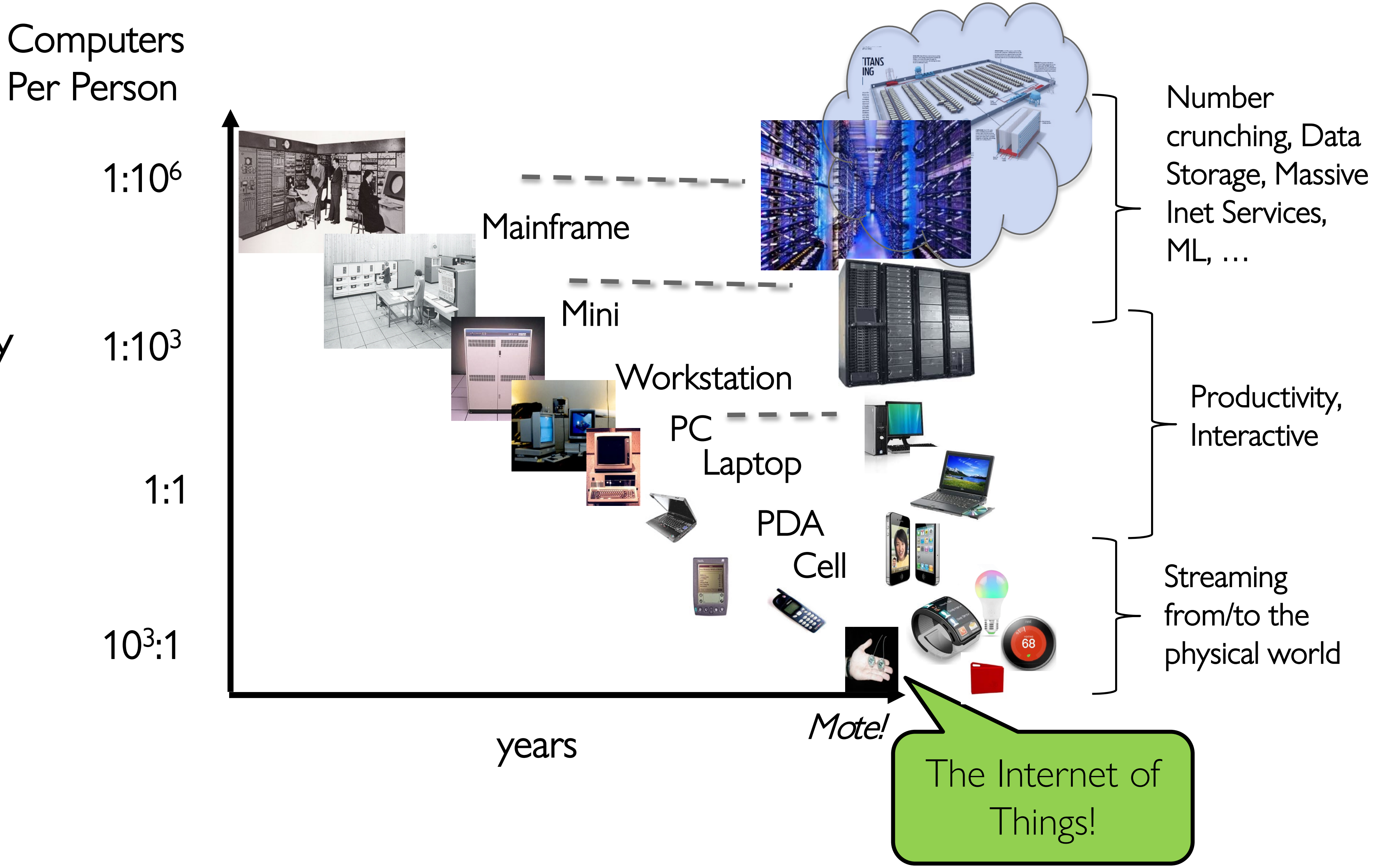
Cause for Starvation: Priorities?

- The policies we've studied so far:
  - Always prefer to give the CPU to a prioritized job
  - Non-prioritized jobs may never get to run

- But priorities were a means, not an end
- Our end goal was to serve a mix of CPU-bound, I/O bound, and Interactive jobs effectively on common hardware
  - Give the I/O bound ones enough CPU to issue their next file operation and wait (on those slow discs)
  - Give the interactive ones enough CPU to respond to an input and wait (on those slow humans)
  - Let the CPU bound ones grind away without too much disturbance

Recall: Changing Landscape…

Bell's Law: New computer class every 10 years



Changing Landscape of Scheduling

- Priority-based scheduling rooted in “time-sharing”
  – Allocating precious, limited resources across a diverse workload
    » CPU bound, vs interactive, vs I/O bound
- 80’s brought about personal computers, workstations, and servers on networks
  – Different machines of different types for different purposes
  – Shift to fairness and avoiding extremes (starvation)
- 90’s emergence of the web, rise of internet-based services, the data-center-is-the-computer
  – Server consolidation, massive clustered services, huge flashcrowds
  – It’s about predictability, 95^{th} percentile performance guarantees

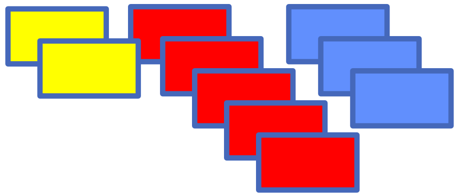
DOES PRIORITIZING SOME JOBS *NECESSARILY* STARVE THOSE THAT AREN'T PRIORITIZED?

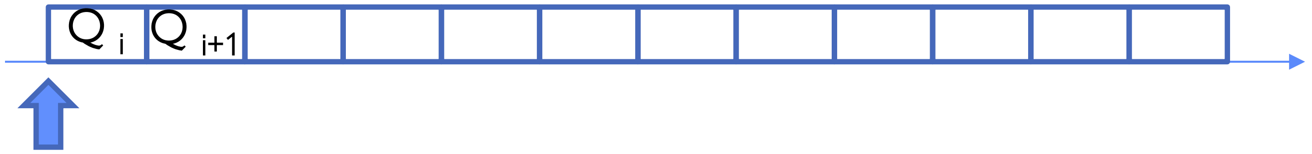
Key Idea: Proportional-Share Scheduling

- The policies we've studied so far:
  - Always prefer to give the CPU to a prioritized job
  - Non-prioritized jobs may never get to run

- Instead, we can share the CPU *proportionally*
  - Give each job a share of the CPU according to its priority
  - Low-priority jobs get to run less often
  - But all jobs can at least make progress (no starvation)

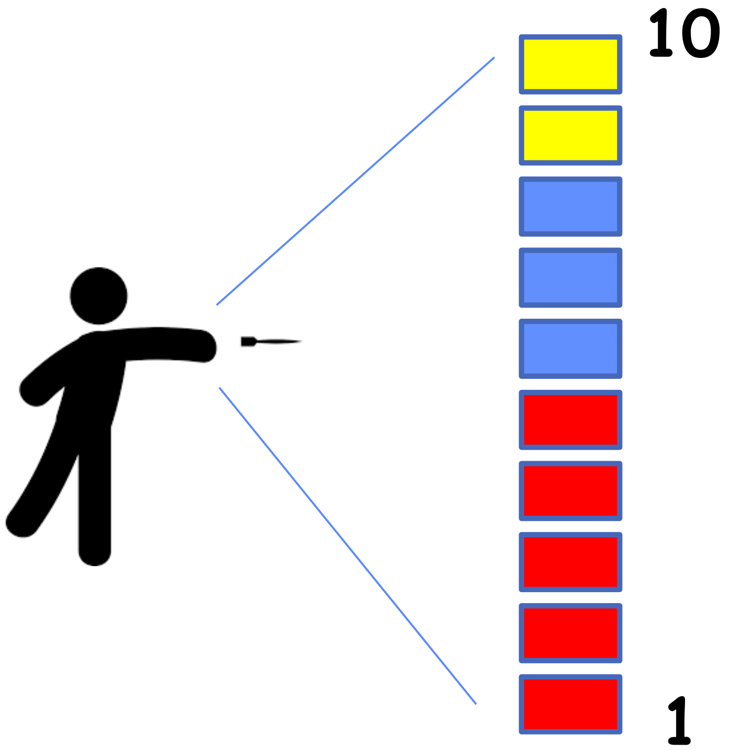
Recall: Lottery Scheduling





- Given a set of jobs (the mix), provide each with a share of a resource
  - e.g., 50% of the CPU for Job A, 30% for Job B, and 20% for Job C
- Idea: Give out tickets according to the proportion each should receive,
- Every quantum (tick): draw one at random, schedule that job (thread) to run

Lottery Scheduling: Simple Mechanism



- $N_{ticket} = \sum N_i$
- Pick a number d in $1 \,..\, N_{ticket}$ as the random "dart"
- Jobs record their N_i of allocated tickets
- Order them by N_i
- Select the first j such that $\sum N_i$ up to j exceeds *d*.

Unfairness

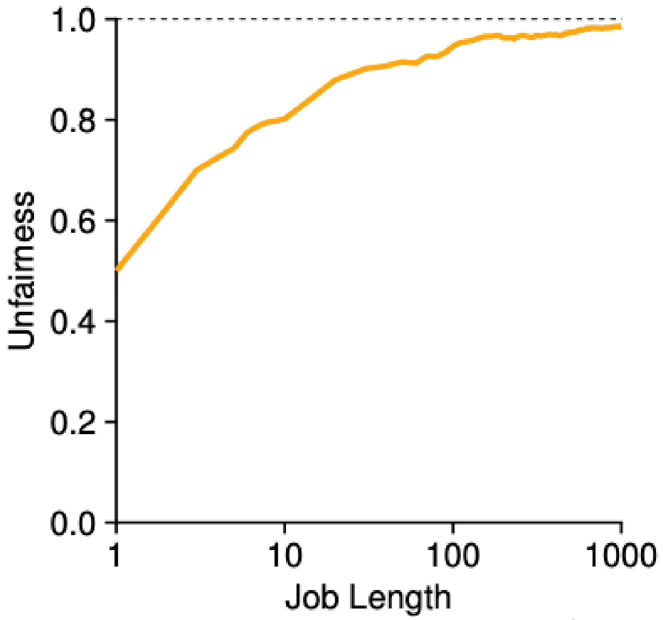


Figure 9.2: **Lottery Fairness Study**

- E.g., Given two jobs A and B of same run time (# Qs) that are each supposed to receive 50%,

  U = finish time of first / finish time of last
- As a function of run time

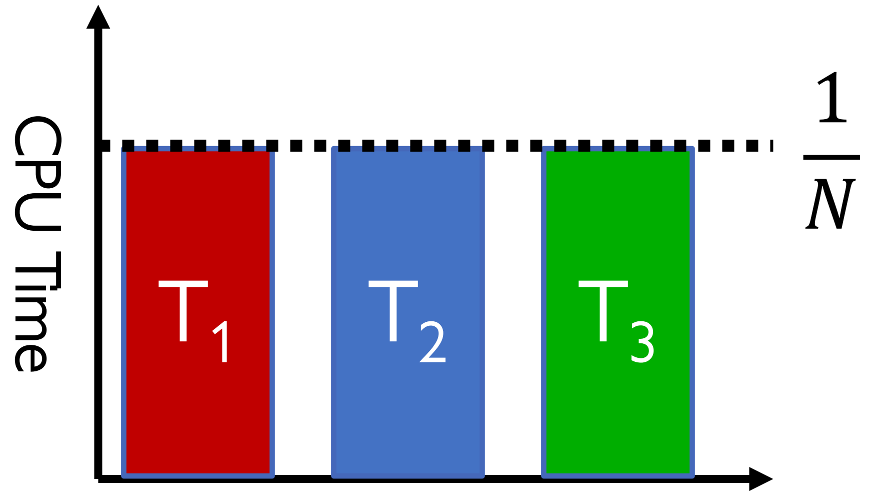
Stride Scheduling

- Achieve proportional share scheduling without resorting to randomness, and overcome the "law of small numbers" problem.
- "Stride" of each job is $\frac{big\#W}{N_i}$
  - The larger your share of tickets, the smaller your stride
  - Ex: W = 10,000, A=100 tickets, B=50, C=250
  - A stride: 100, B: 200, C: 40
- Each job has a "pass" counter
- Scheduler: pick job with lowest *pass*, runs it, add its *stride* to its *pass*
- Low-stride jobs (lots of tickets) run more often
  - Job with twice the tickets gets to run twice as often
- Some messiness of counter wrap-around, new jobs, …

Linux Completely Fair Scheduler (CFS)

- Goal: Each process gets an equal share of CPU
  - N threads "simultaneously" execute on $\frac{1}{N}$ of CPU
  - The *model* is somewhat like simultaneous multithreading – each thread gets $\frac{1}{N}$ of the cycles
- In general, can't do this with real hardware
  - OS needs to give out full CPU in time slices
  - Thus, we must use something to keep the threads roughly in sync with one another

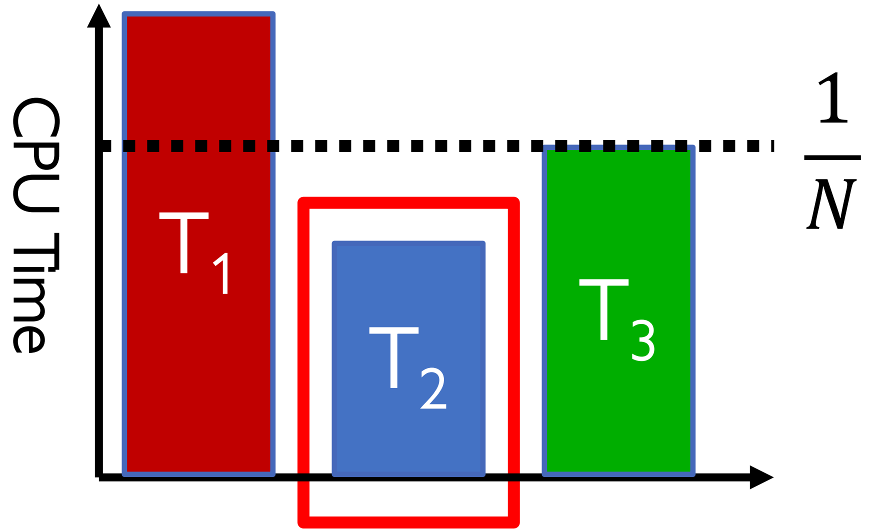
Model: "Perfectly" subdivided CPU:



Linux Completely Fair Scheduler (CFS)

- Basic Idea: track CPU time per thread and schedule threads to match up average rate of execution
- Scheduling Decision:
  - "Repair" illusion of complete fairness
  - Choose thread with minimum CPU time
  - Closely related to Fair Queueing
- Use a heap-like scheduling queue for this…
  - O(log N) to add/remove threads, where N is number of threads
- Sleeping threads don't advance their CPU time, so they get a boost when they wake up again…
  - Get interactivity automatically!

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



Linux CFS: Responsiveness/Starvation Freedom

- In addition to fairness, we want **low response time** and starvation freedom
  - Make sure that everyone gets to run at least a bit!
- Constraint 1: *Target Latency*
  - Period of time over which every process gets service
  - 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 (!!!)
  - Recall Round-Robin: large context switching overhead if slice gets to small

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

Aside: Priority in Unix – Being Nice

- The industrial operating systems of the 60s and 70's provided priority to enforced desired usage policies.
  - When it was being developed at Berkeley, instead it provided ways to "be nice".
- `nice` values range from -20 to 19
  - Negative values are "not nice"
  - If you wanted to let your friends get more time, you would nice up your job
- Scheduler puts higher nice-value tasks (lower priority) to sleep more …
  - In O(1) scheduler, this translated fairly directly to priority (and time slice)
- How does this idea translate to CFS?
  - Change the rate of CPU cycles given to threads to change relative priority

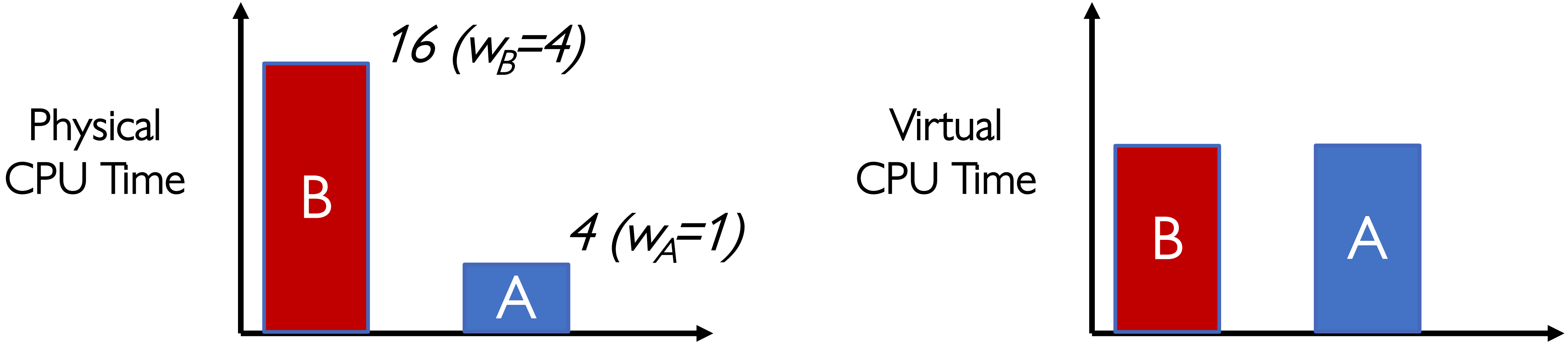
Linux CFS: Proportional Shares

- What if we want to give more CPU to some and less to others in CFS (proportional share) ?
  – Allow different threads to have different *rates* of execution (cycles/time)
- Use weights! Key Idea: Assign a weight w_i to each process *I* to compute the switching quanta Q_i
  – Basic equal share: $Q_i = \textbf{Target Latency} \cdot \frac{1}{N}$
  – Weighted Share: $Q_i = \left({}^{w_i}/_{\sum_p w_p}\right) \cdot \textbf{Target Latency}$
- Reuse `nice` value to reflect share, rather than priority,
  – Remember that lower nice value $\Rightarrow$ higher priority
  – CFS uses nice values to scale weights exponentially: Weight=1024/(1.25)$^{\text{nice}}$
    » Two CPU tasks separated by nice value of 5 $\Rightarrow$
    Task with lower nice value has 3 times the weight, since $(1.25)^5 \approx 3$
- So, we use "Virtual Runtime" instead of CPU time

Example: Linux CFS: Proportional Shares

- Target Latency = 20ms
- Minimum Granularity = 1ms
- Example: Two CPU-Bound Threads
  - Thread A has weight 1
  - Thread B has weight 4
- Time slice for A? 4 ms
- Time slice for B? 16 ms

Linux CFS: Proportional Shares



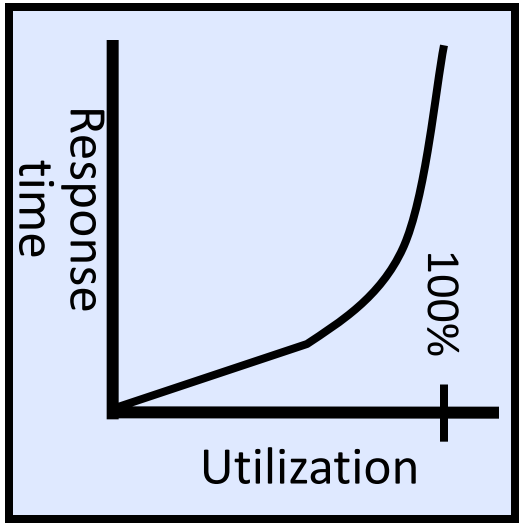
- Track a thread's *virtual* runtime rather than its true physical runtime
  – Higher weight: Virtual runtime increases more slowly
  – Lower weight: Virtual runtime increases more quickly
- Scheduler's Decisions are based on Virtual CPU Time
- Use of Red-Black tree to hold all runnable processes as sorted on vruntime variable
  – O(1) time to find next thread to run (top of heap!)
  – O(log N) time to perform insertions/deletions
    » Cache the item at far left (item with earliest vruntime)
  – When ready to schedule, grab version with smallest vruntime (which will be item at the far left).

Choosing the Right Scheduler

I Care About:	Then Choose:
CPU Throughput	FCFS
Avg. Response Time	SRTF Approximation
I/O Throughput	SRTF Approximation
Fairness (CPU Time)	Linux CFS
Fairness – Wait Time to Get CPU	Round Robin
Meeting Deadlines	EDF
Favoring Important Tasks	Priority

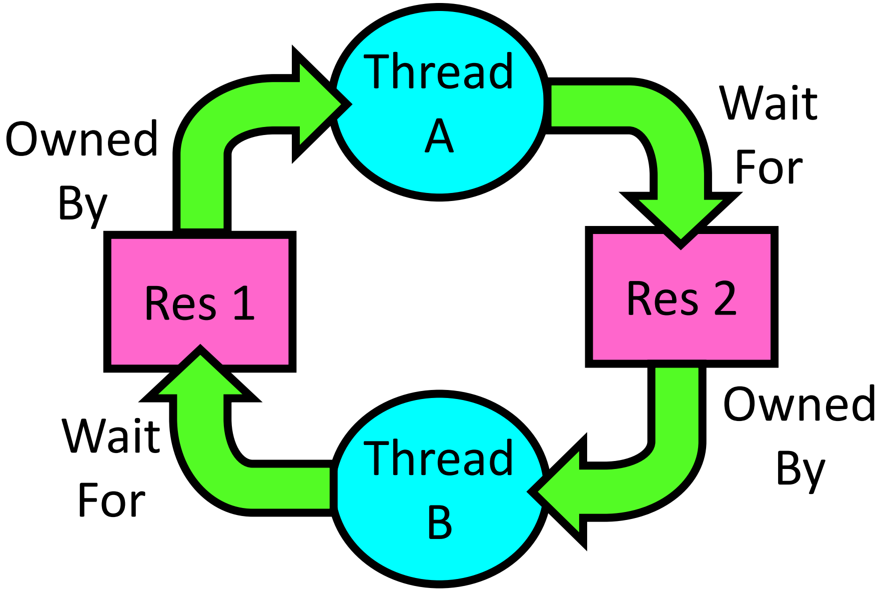
A Final Word On Scheduling

- When do the details of the scheduling policy and fairness really matter?
  – When there aren't enough resources to go around
- When should you simply buy a faster computer?
  – (Or network link, or expanded highway, or …)
  – One approach: Buy it when it will pay for itself in improved response time
    » Perhaps you're paying for worse response time in reduced productivity, customer angst, etc…
    » Might think that you should buy a faster X when X is utilized 100%, but usually, response time goes to infinity as utilization⇒100%
- An interesting implication of this curve:
  – Most scheduling algorithms work fine in the "linear" portion of the load curve, fail otherwise
  – Argues for buying a faster X when hit "knee" of curve



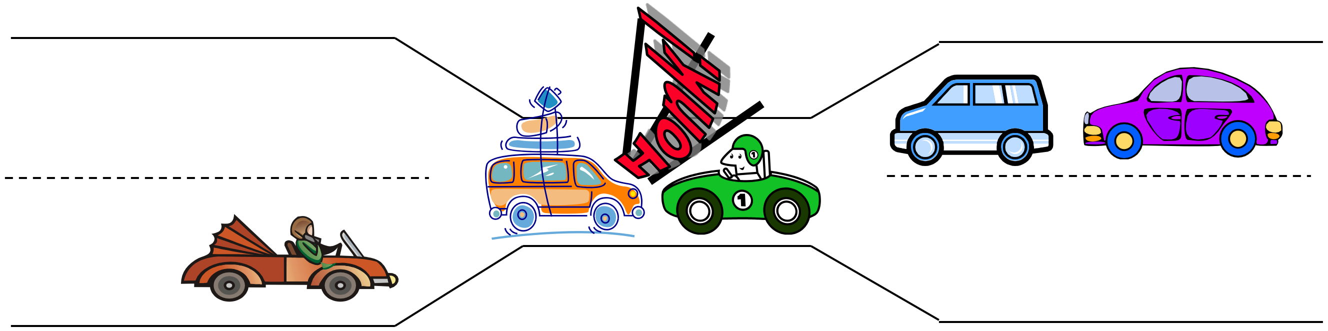
Deadlock: A Deadly type of Starvation

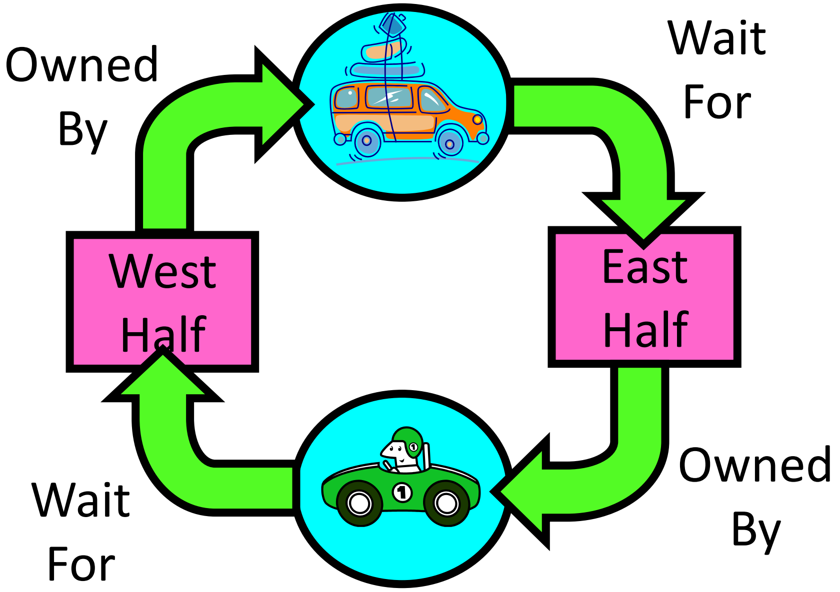
- Starvation: thread waits indefinitely
  - Example, low-priority thread waiting for resources constantly in use by high-priority threads
- Deadlock: circular waiting for resources
  - Thread A owns Res 1 and is waiting for Res 2
    Thread B owns Res 2 and is waiting for Res 1
- Deadlock ⇒ Starvation but not vice versa
  - Starvation can end (but doesn't have to)
  - Deadlock can't end without external intervention



Bridge Crossing Example

- Each segment of road can be viewed as a resource
  - Car must own the segment under them
  - Must acquire segment that they are moving into
- For bridge: must acquire both halves
  - Traffic only in one direction at a time



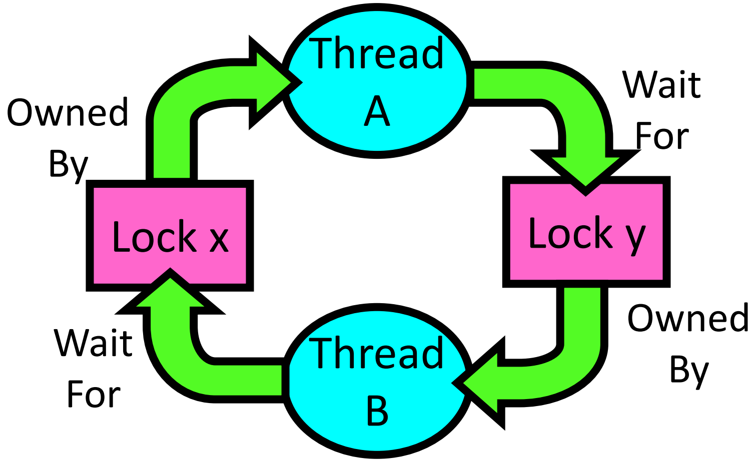


- Deadlock: Shown above when two cars in opposite directions meet in middle
  - Each acquires one segment and needs next
  - Deadlock resolved if one car backs up (preempt resources and rollback)
    - » Several cars may have to be backed up
- Starvation (not Deadlock):
  - East-going traffic really fast $\Rightarrow$ no one gets to go west

Deadlock with Locks

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

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



- This lock pattern exhibits *non-deterministic deadlock*
  - Sometimes it happens, sometimes it doesn't!
- This is really hard to debug!

Deadlock with Locks: “Unlucky” Case

Thread A:

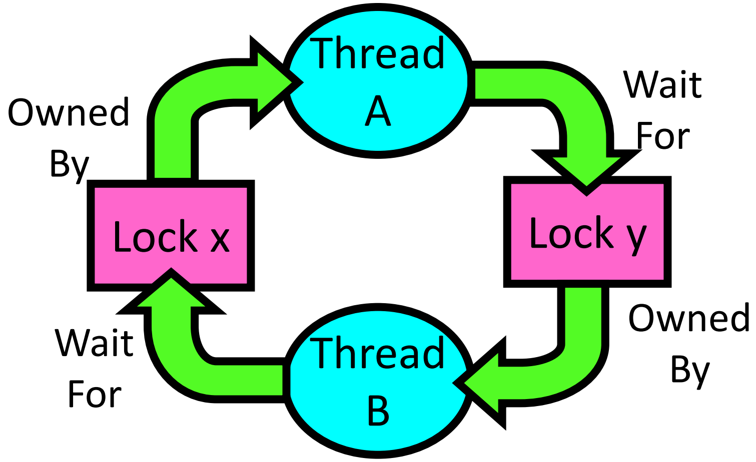
```
x.Acquire();

y.Acquire(); <stalled>
<unreachable>
…
y.Release();
x.Release();
```

Thread B:

```
y.Acquire();

x.Acquire(); <stalled>
<unreachable>
…
x.Release();
y.Release();
```



Neither thread will get to run ⇒ Deadlock

Deadlock with Locks: "Lucky" Case

<u>Thread A</u>:

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

<u>Thread B</u>:

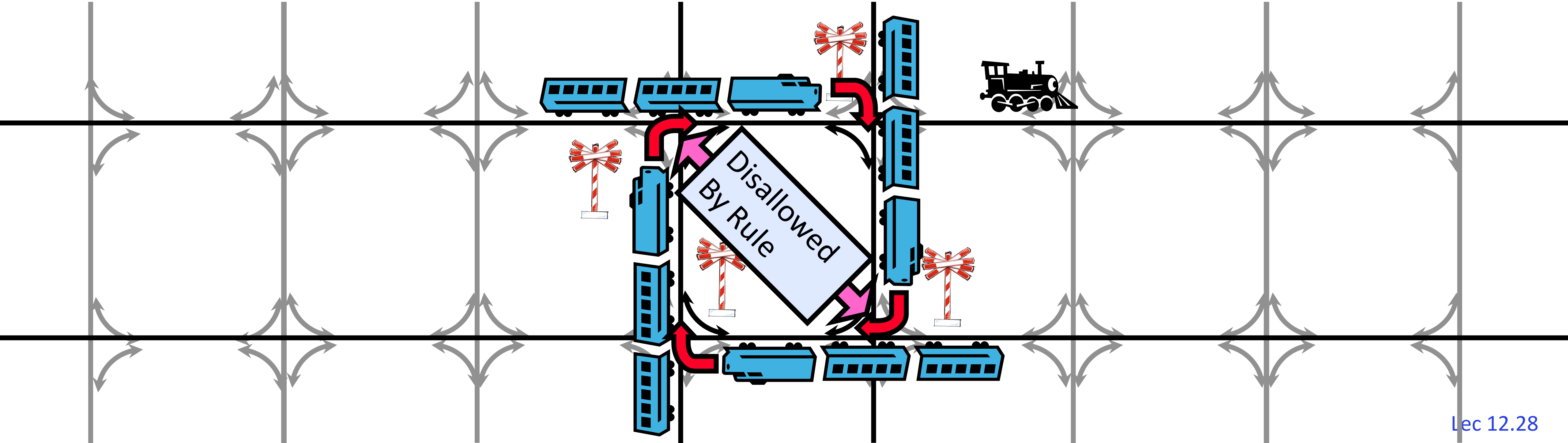
```
y.Acquire();

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

Sometimes, schedule won't trigger deadlock!

Train Example (Wormhole-Routed Network)

- Circular dependency (Deadlock!)
  - Each train wants to turn right, but is blocked by other trains
- Similar problem to multiprocessor networks
  - Wormhole-Routed Network: Messages trail through network like a "worm"
- Fix? Imagine grid extends in all four directions
  - Force ordering of channels (tracks)
    - » Protocol: Always go east-west first, then north-south
  - Called "dimension ordering" (X then Y)



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!

Deadlock with Space

Thread A:

```
AllocateOrWait(1 MB)
AllocateOrWait(1 MB)
Free(1 MB)
Free(1 MB)
```

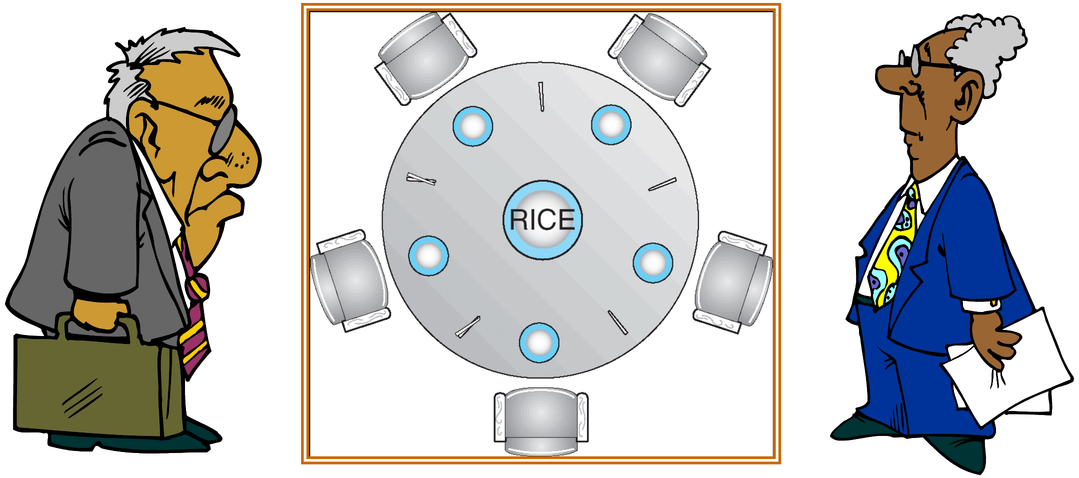
Thread B

```
AllocateOrWait(1 MB)
AllocateOrWait(1 MB)
Free(1 MB)
Free(1 MB)
```

If only 2 MB of space, we get same deadlock situation

Dining Lawyers Problem

- Five chopsticks/Five lawyers (really cheap restaurant)
  - Free-for all: Lawyer will grab any one they can
  - Need two chopsticks to eat
- What if all grab at same time?
  - Deadlock!
- How to fix deadlock?
  - Make one of them give up a chopstick (Hah!)
  - Eventually everyone will get chance to eat
- How to prevent deadlock?
  - Never let lawyer take last chopstick if no hungry lawyer has two chopsticks afterwards
  - Can we formalize this requirement somehow?



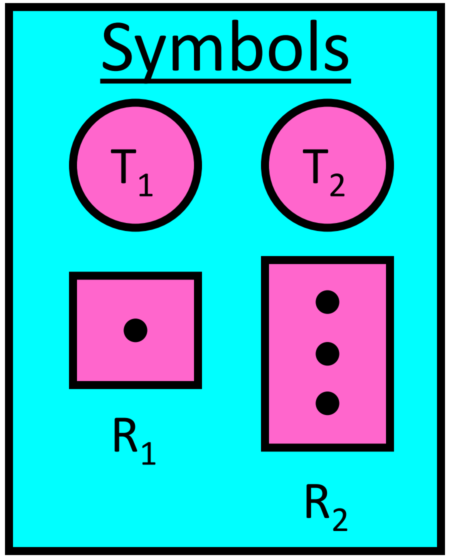
Four requirements for occurrence of Deadlock

- Mutual exclusion
  - Only one thread at a time can use a resource.
- Hold and wait
  - Thread holding at least one resource is waiting to acquire additional resources held by other threads
- No preemption
  - Resources are released only voluntarily by the thread holding the resource, after thread is finished with it
- Circular wait
  - There exists a set $\{T_1, \ldots, T_n\}$ 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

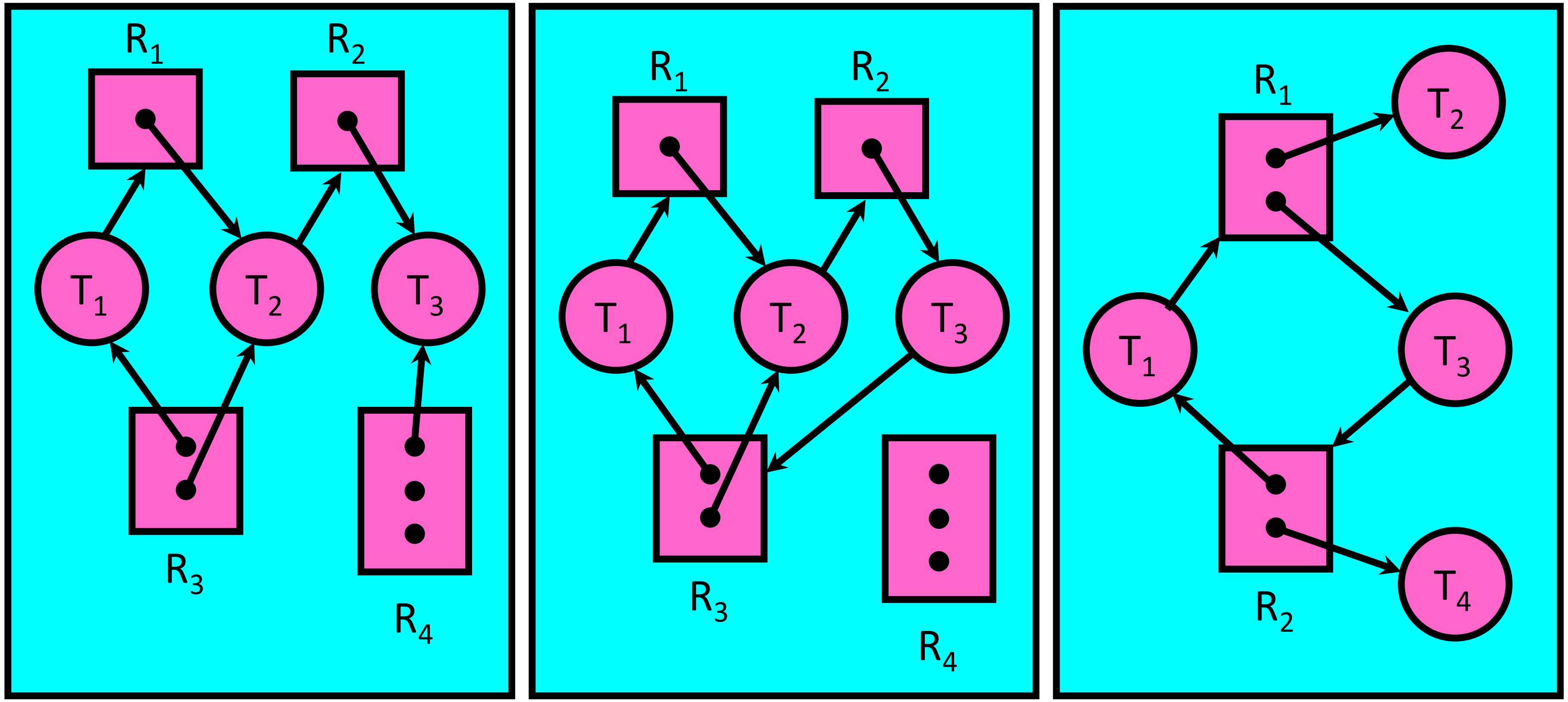
- System Model
  - A set of Threads $T_1, T_2, \ldots, T_n$
  - Resource types $R_1, R_2, \ldots, R_m$

    CPU cycles, memory space, I/O devices
  - Each resource type R_i has W_i instances
  - Each thread utilizes a resource as follows:
    - » `Request() / Use() / Release()`
- 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

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



Simple Resource Allocation Graph

Allocation Graph With Deadlock

Allocation Graph With Cycle, but No Deadlock

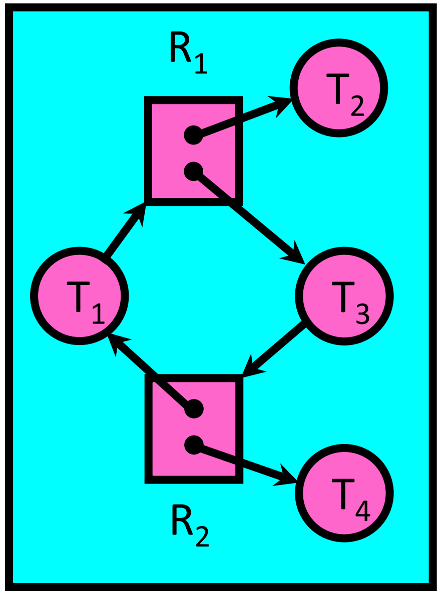
Deadlock Detection Algorithm

- 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

- See if tasks can eventually terminate on their own

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



- Nodes left in `UNFINISHED` $\Rightarrow$ deadlocked

How should a system deal with deadlock?

- Four different approaches:

1. Deadlock prevention: write your code in a way that it isn't prone to deadlock
2. Deadlock recovery: let deadlock happen, and then figure out how to recover from it
3. Deadlock avoidance: dynamically delay resource requests so deadlock doesn't happen
4. Deadlock denial: ignore the possibility of deadlock

- Modern operating systems:
  - Make sure the *system* isn't involved in any deadlock
  - Ignore deadlock in applications
    - "Ostrich Algorithm"

Techniques for Preventing Deadlock

- Infinite resources
  - Include enough resources so that no one ever runs out of resources. Doesn't have to be infinite, just large
  - Give illusion of infinite resources (e.g. virtual memory)
  - Examples:
    - » Bay bridge with 12,000 lanes. Never wait!
    - » Infinite disk space (not realistic yet?)
- No Sharing of resources (totally independent threads)
  - Not very realistic
- Don't allow waiting
  - How the phone company avoids deadlock
    - » Call Mom in Toledo, works way through phone network, but if blocked get busy signal.
  - Technique used in Ethernet/some multiprocessor nets
    - » Everyone speaks at once. On collision, back off and retry
  - Inefficient, since have to keep retrying
    - » Consider: driving to San Francisco; when hit traffic jam, suddenly you're transported back home and told to retry!

(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 just succeed, thus above example won’t deadlock
  - Of course, it isn’t actually infinite, but certainly larger than 2MB!

Techniques for Preventing Deadlock

- Make all threads request everything they'll need at the beginning.
  - Problem: Predicting future is hard, tend to over-estimate resources
  - Example:
    - » If need 2 chopsticks, request both at same time
    - » Don't leave home until we know no one is using any intersection between here and where you want to go; only one car on the Bay Bridge at a time
- Force all threads to request resources in a particular order preventing any cyclic use of resources
  - Thus, preventing deadlock
  - Example (`x.Acquire()`, `y.Acquire()`, `z.Acquire()`,…)
    - » Make tasks request disk, then memory, then…
    - » Keep from deadlock on freeways around SF by requiring everyone to go clockwise

Summary

- Four conditions for deadlocks
  - Mutual exclusion
  - Hold and wait
  - No preemption
  - Circular wait
- Techniques for addressing Deadlock
  - Deadlock prevention:
    - » write your code in a way that it isn't prone to deadlock
  - Deadlock recovery:
    - » let deadlock happen, and then figure out how to recover from it
  - Deadlock avoidance:
    - » dynamically delay resource requests so deadlock doesn't happen
    - » Banker's Algorithm provides on algorithmic way to do this
  - Deadlock denial:
    - » ignore the possibility of deadlock