Lecture 08: Advanced Scheduling

CS343 – Operating Systems

Branden Ghena – Spring 2022

Some slides borrowed from:
Wang Yi (Uppsala), and UC Berkeley CS149 and CS162

Northwestern

Administrivia

- Midterm exam Thursday!
    - Starts at 9:30am sharp
    - Bring a pencil and one sheet of paper with notes
    - How to prepare
        - Lecture materials on Canvas homepage
        - Practice exam on Canvas
        - Discussion recording from Friday

Today’s Goals

- Describe real-time systems

- Understand scheduling policies based on deadlines

- Explore modern operating system schedulers

Outline

- **Real Time Operating Systems**
  - Earliest Deadline First scheduling
  - Rate Monotonic scheduling
- Modern Operating Systems
  - Linux O(1) scheduler
  - Lottery and Stride scheduling
  - Linux Completely Fair Scheduler

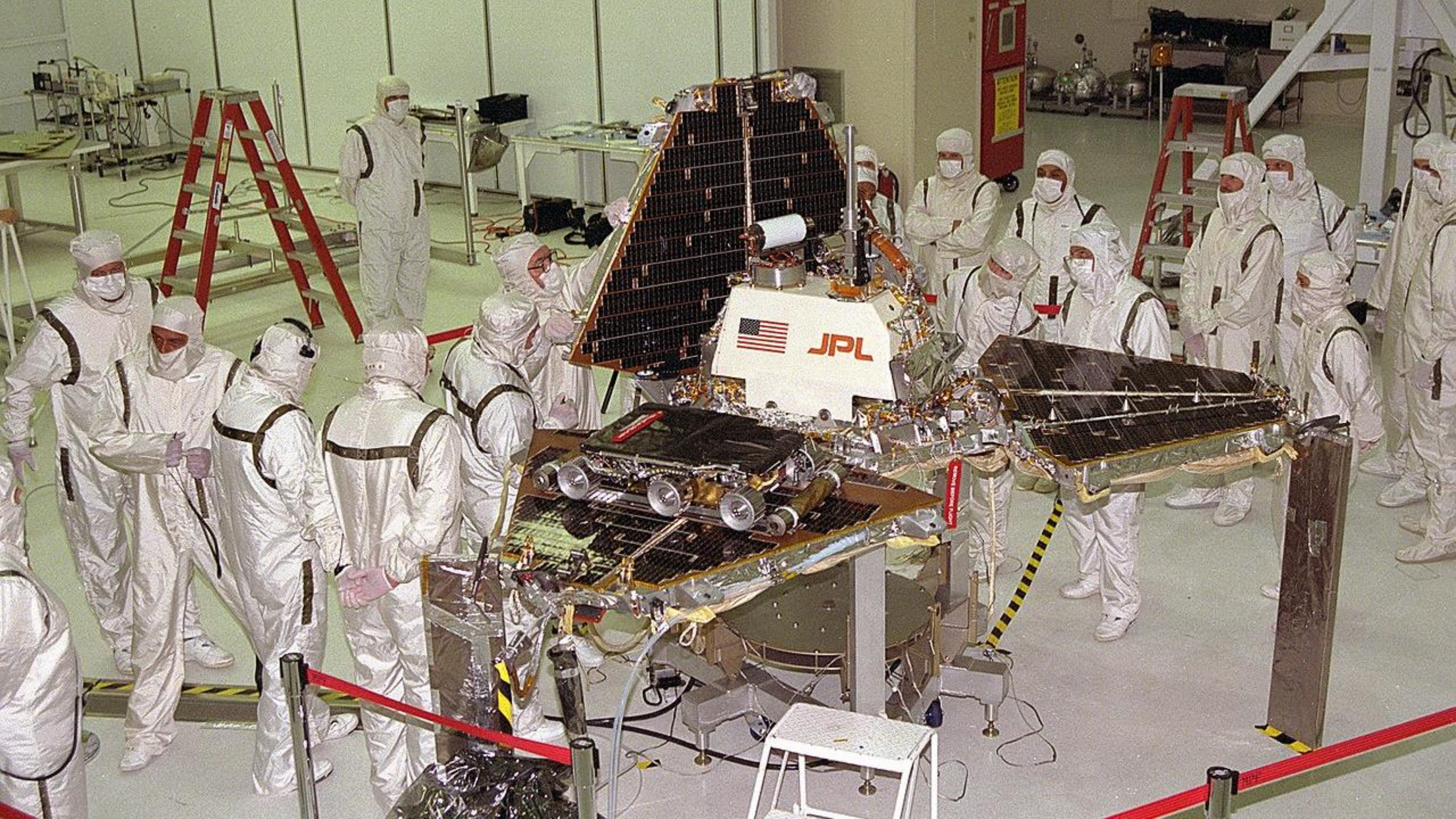
Normal OSes don't cut it for all use cases

- Some environments need very specialized systems
  - Flight controls
  - Autonomous vehicles
  - Space exploration

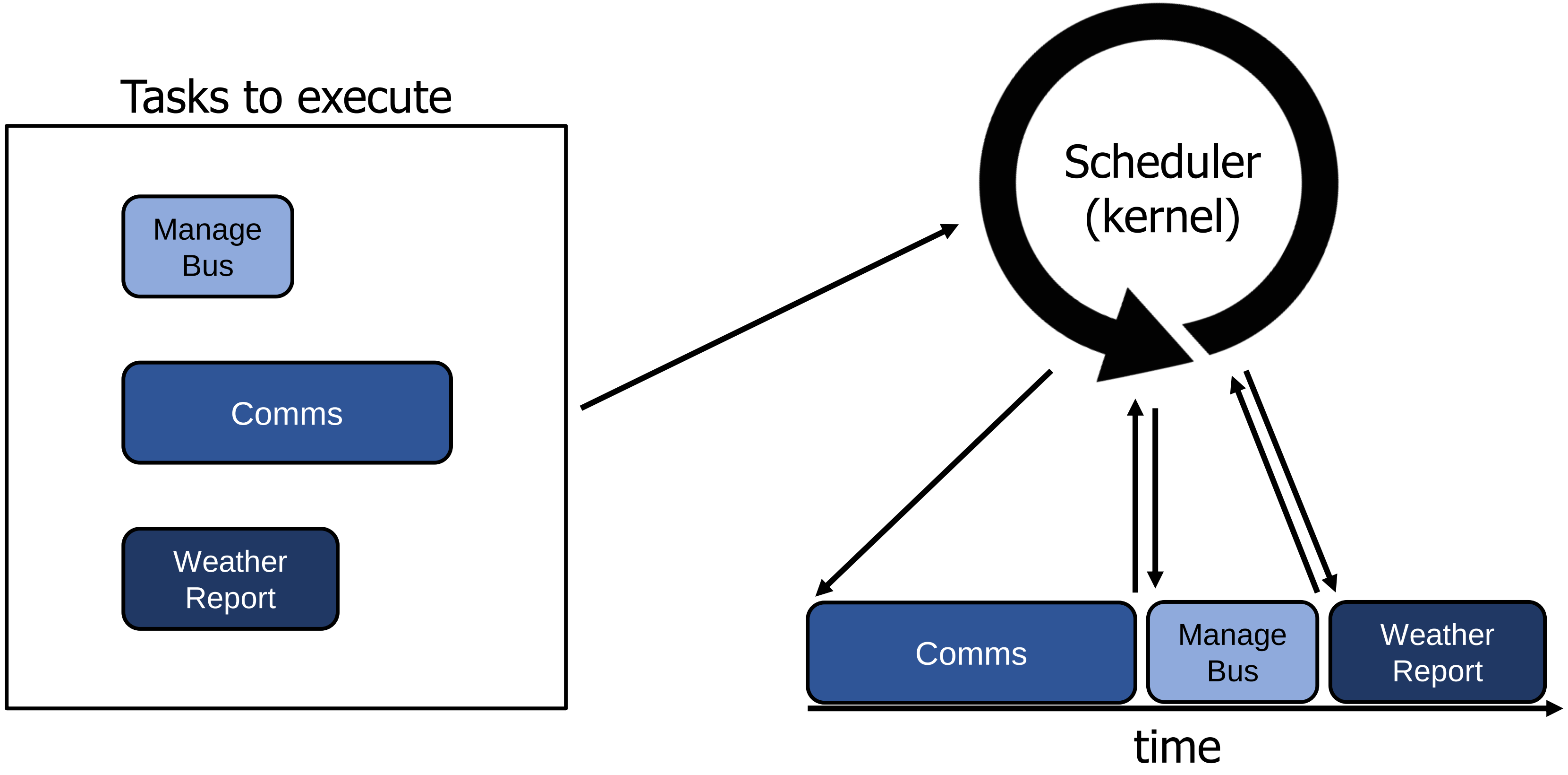
- In each of these scenarios
  - Computer failures are unacceptable
  - Humans can't intervene to resolve issues
  - We're going to need a computer system with performance *guarantees*

Example: Pathfinder

Radiation-hardened IBM CPU


JPL

Pathfinder had periodic tasks that must be executed



Real-Time Operating Systems

- Goal: guaranteed performance
  - Meet *deadlines* even if it means being unfair or slow
  - Limit how bad the *worst case* is
    - Usually mathematically

- It’s not about speed, it’s about guaranteed performance
  - Good turnaround and response time are nice, but insufficient
  - Predictability is key to providing a guarantee

- RTOS is actually a whole other class worth of material
  - Last taught by Peter Dinda in 2005…

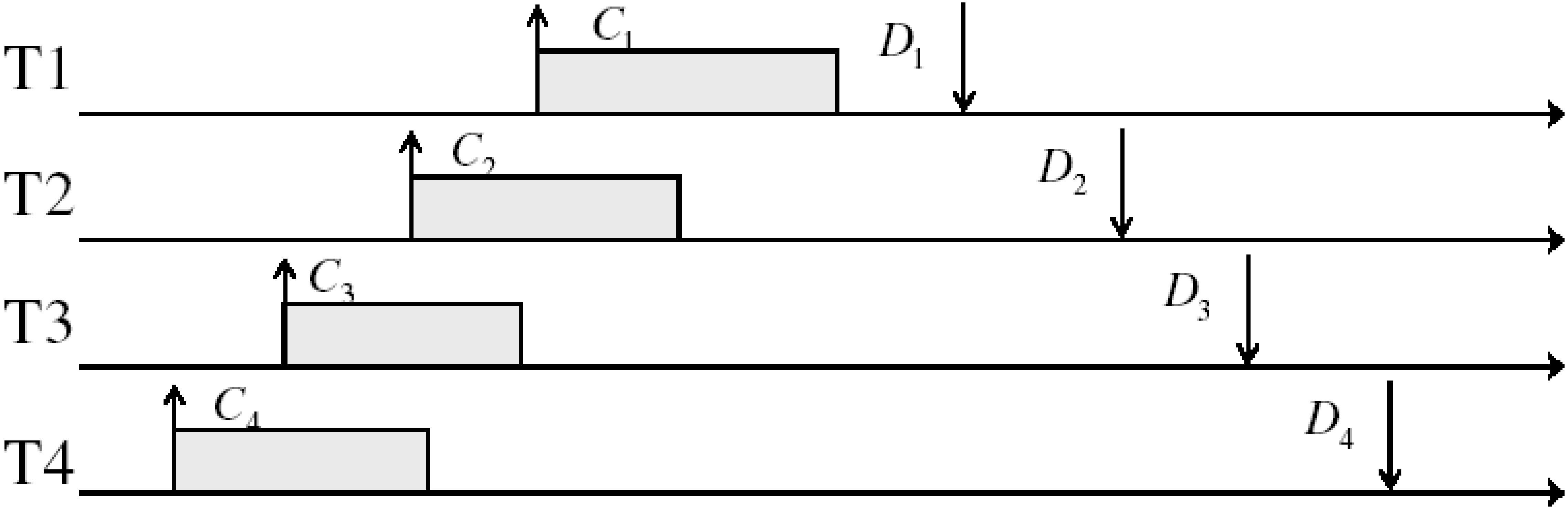
Types of real-time schedulers

- Hard real-time:
  - Meet **all deadlines**
    - Otherwise decline to accept the job
  - Ideally: determine in advance if deadlines will be met

- Soft real-time
  - Attempt to meet deadlines with high probability
  - Often good enough for many non-safety-critical applications
    - Quadcopter software

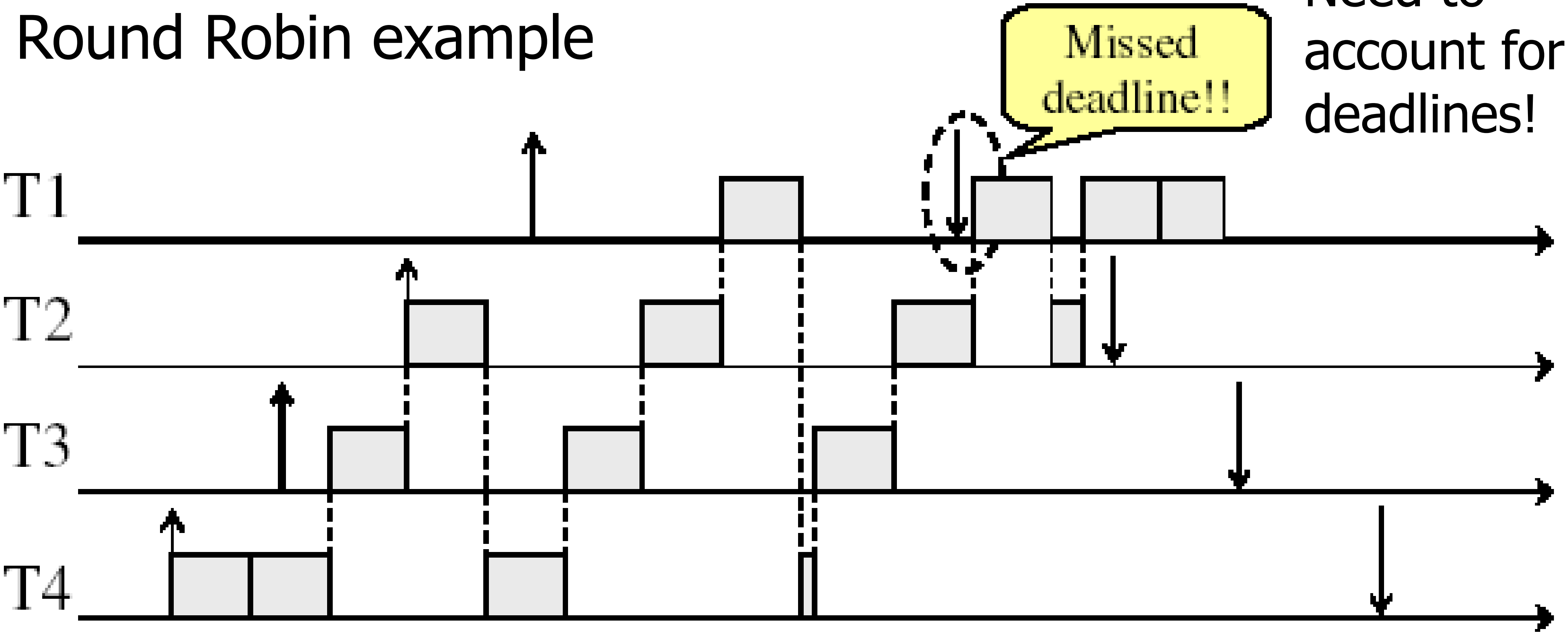
Real-time example

- Preemptable jobs with known deadlines (D) and computation (C)
  - Durations here are worst-case execution times



Prior scheduling policies don't apply here

Round Robin example



Need to account for deadlines!

Types of real-time jobs

- Aperiodic
  - Jobs we are already accustomed to
  - Unpredictable start times, no deadlines
- Periodic (we'll focus on these)
  - Recurs at a certain time interval
  - Deadline for completion is before the start of the next time interval
    - i.e. deadline equals the period
  - Can decide *feasibility* of schedule at compile-time
- Sporadic
  - Unpredictable start time, has a deadline
  - Must decide feasibility at runtime and either accept or reject job

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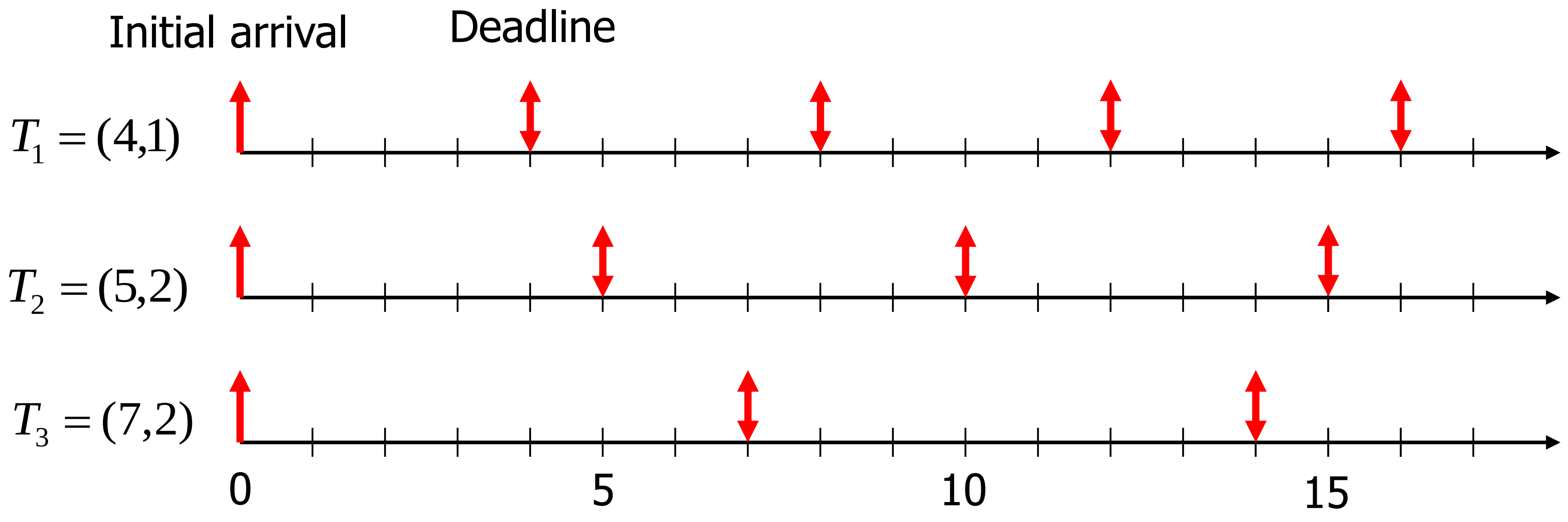
Earliest Deadline First (EDF) Scheduling

- Priority scheduling with pre-emption
- Highest priority given to task with soonest deadline
  - Task = (Period, Duration)



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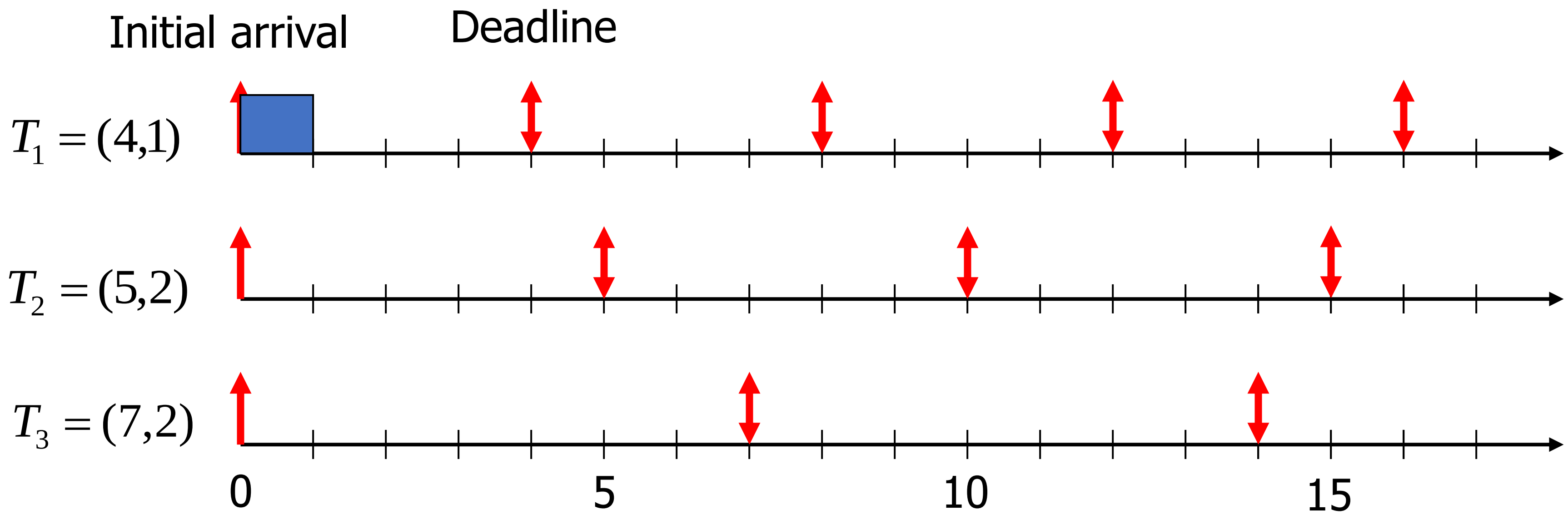

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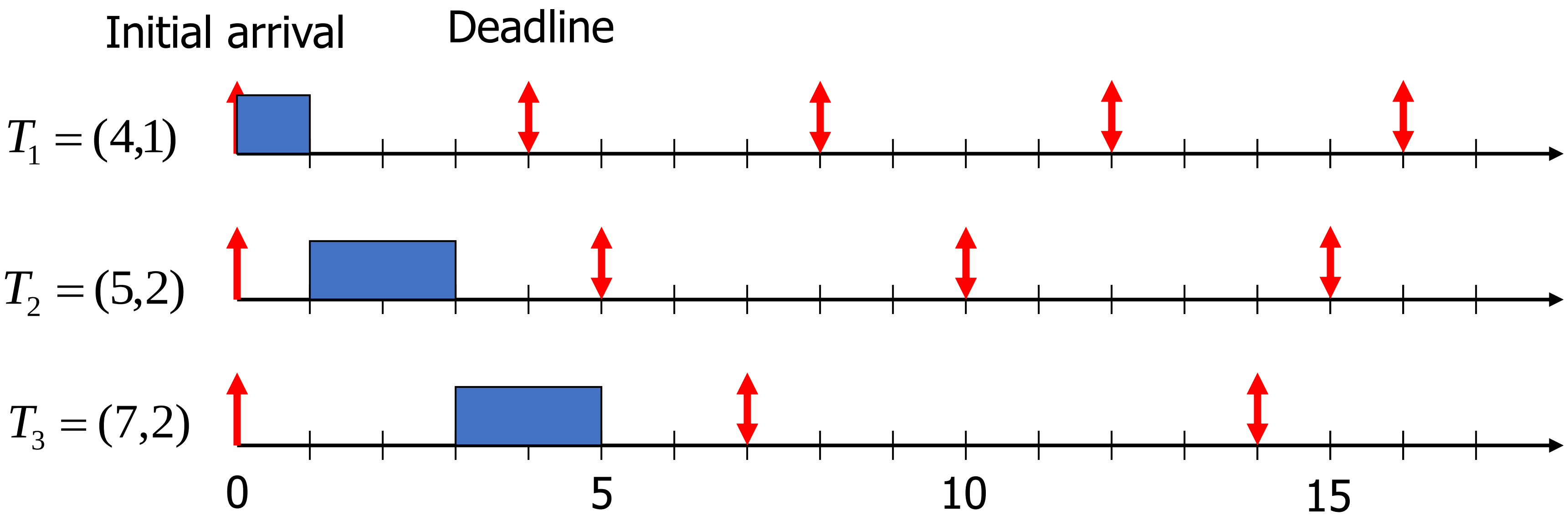

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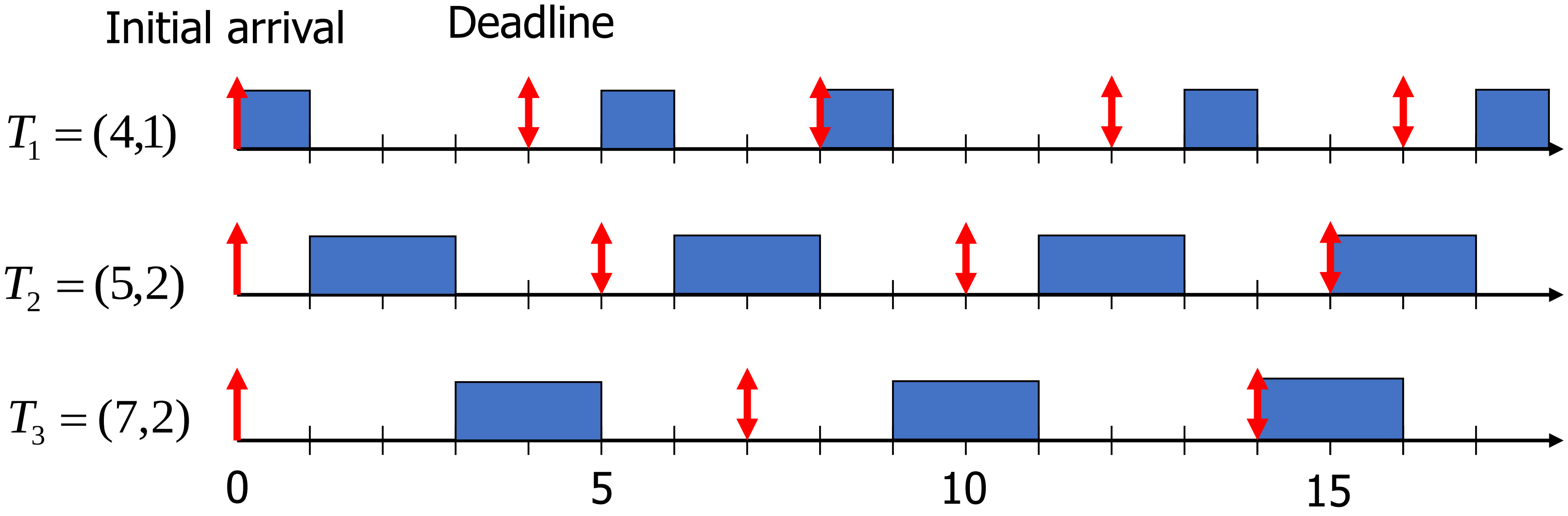


Schedulability test for EDF

- Guarantees schedule feasibility if total load is not more than 100%
  - All deadlines **will** be met

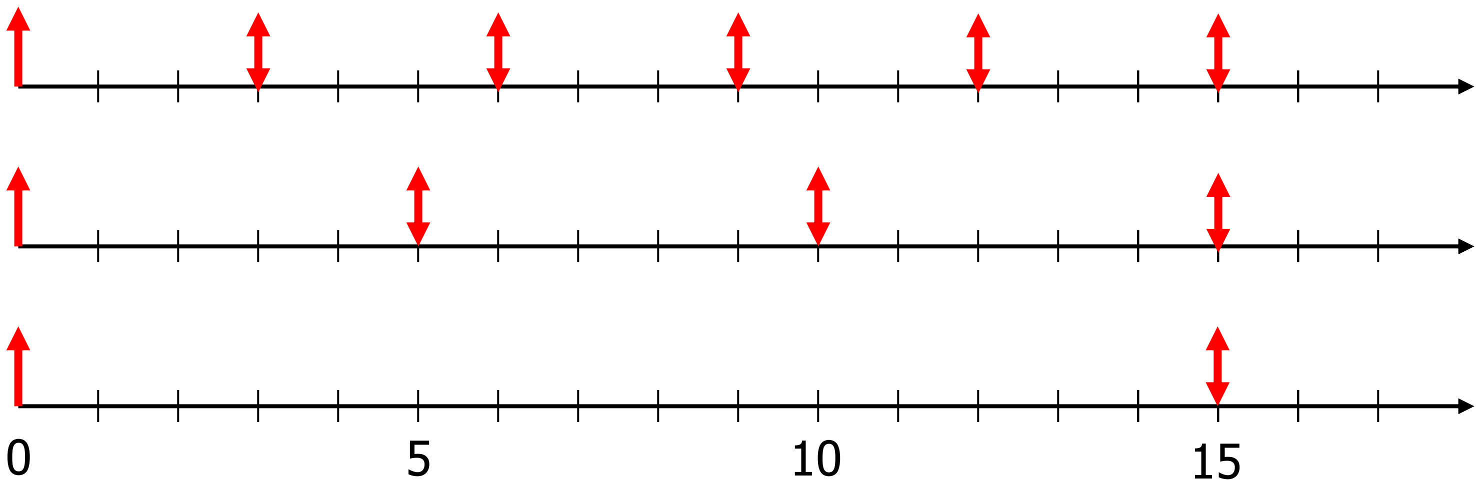
- For *n* tasks with computation time *C* and deadline (period) *D*
  - A feasible schedule exists if utilization is less than or equal to one:

$$U = \sum_{i=1}^{n} \left(\frac{C_i}{D_i} \right) \leq 1$$

Check your understanding

- Can we schedule the following workload?
  - Job A: period 3, computation 1
  - Job B: period 5, computation 2
  - Job C: period 15, computation 4

$$U = \sum_{i=1}^{n} \left(\frac{C_i}{D_i}\right) \leq 1$$



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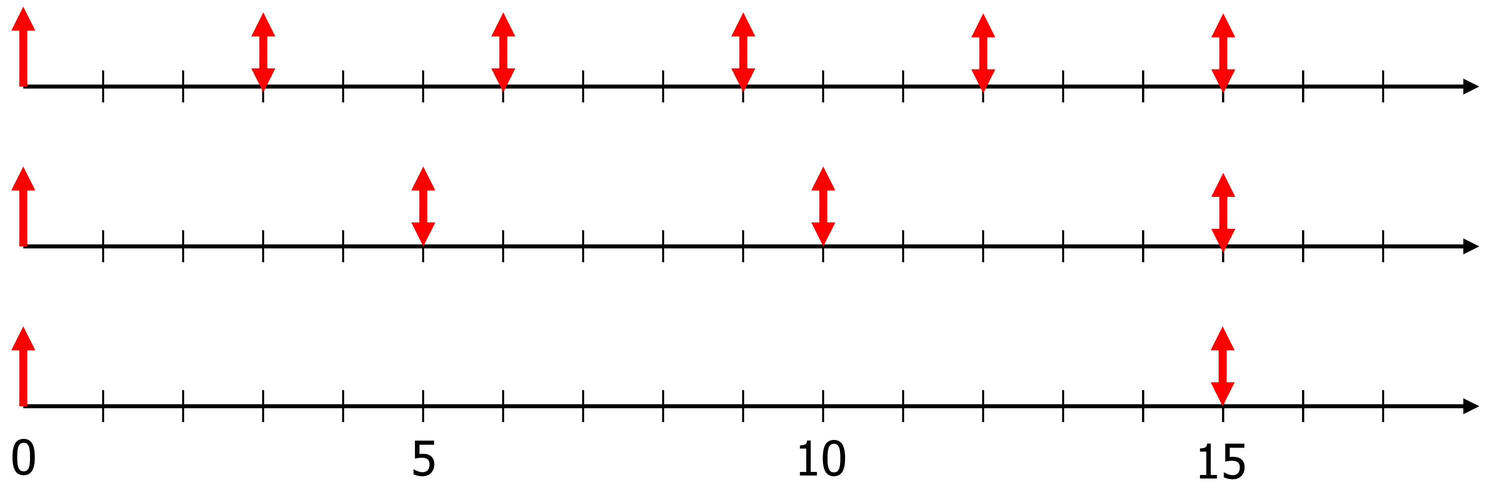
1/3 + 2/5 + 4/15 = 1



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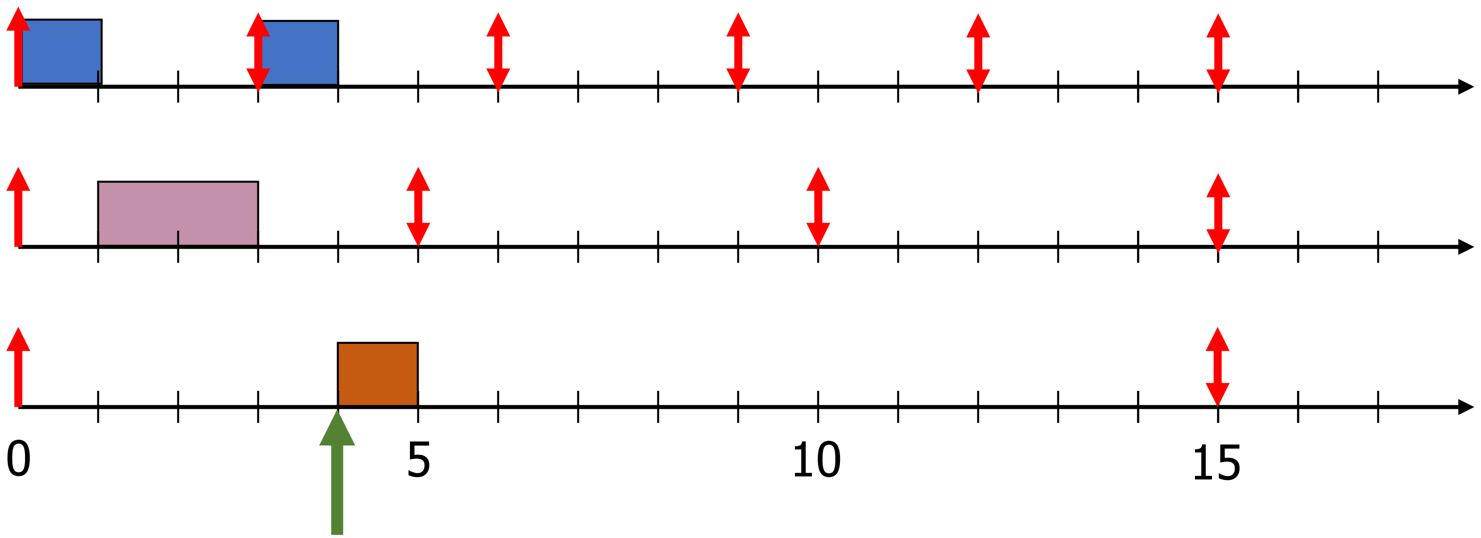

Can't start a job *before* its period

Check your understanding

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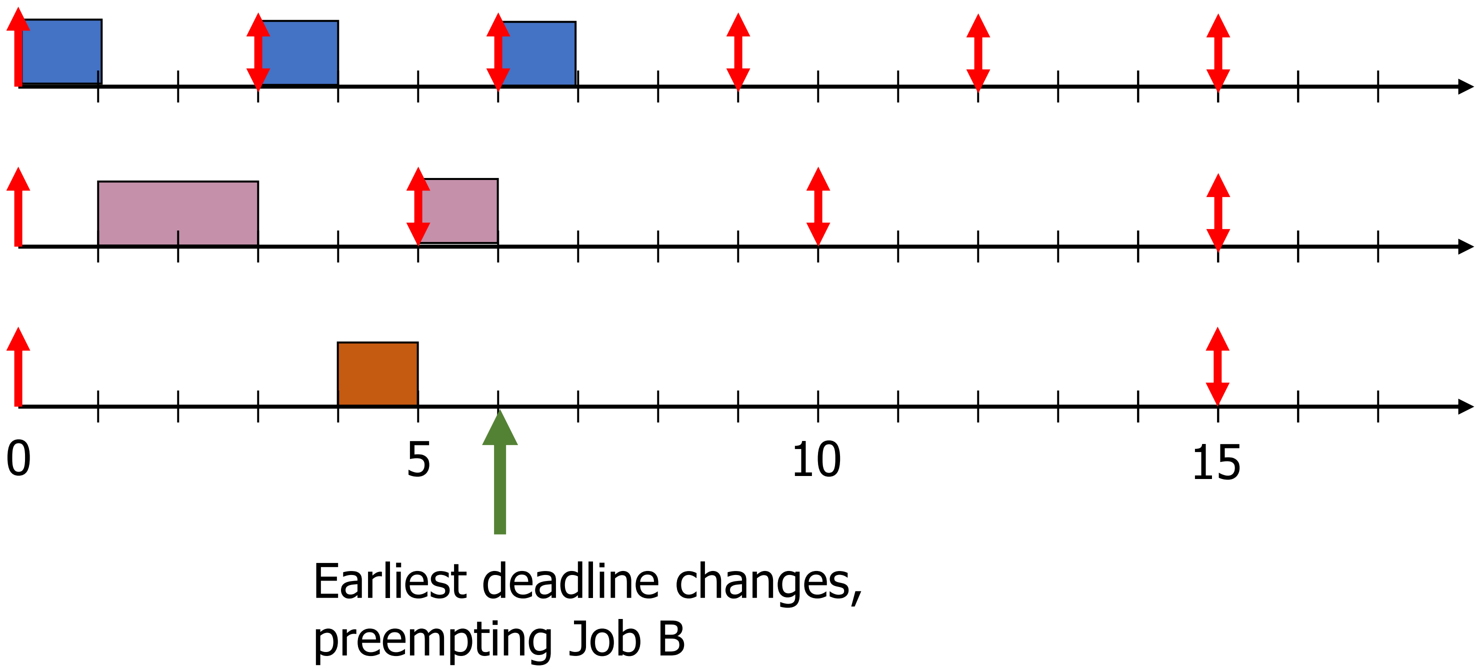

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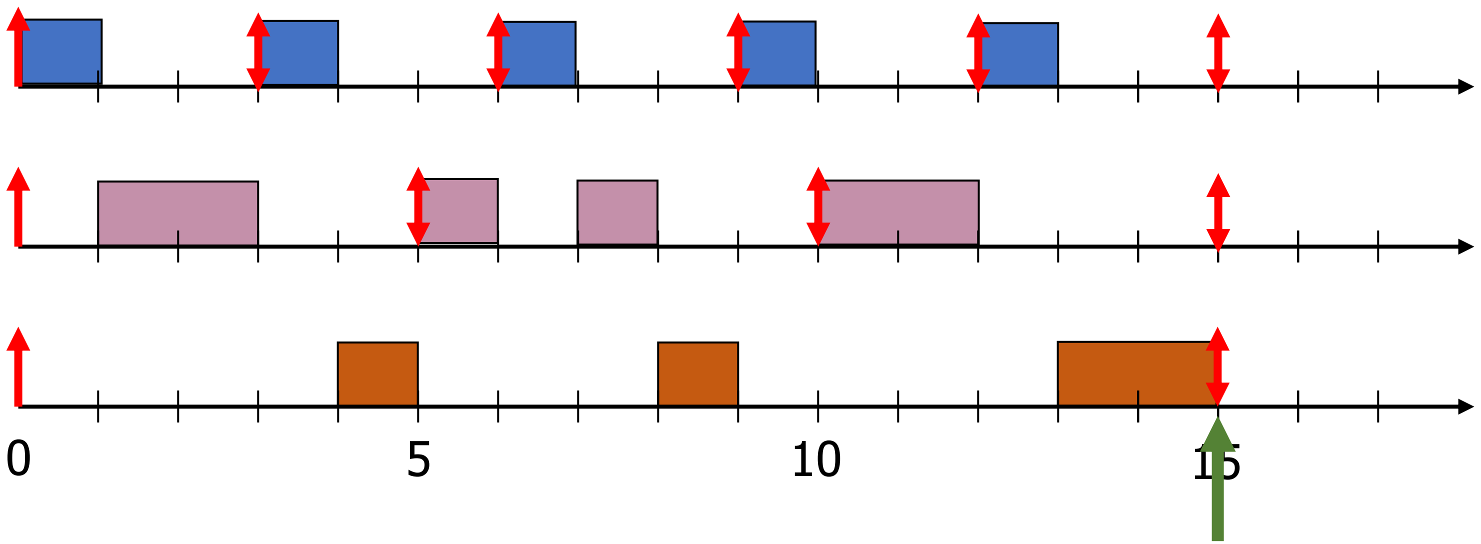
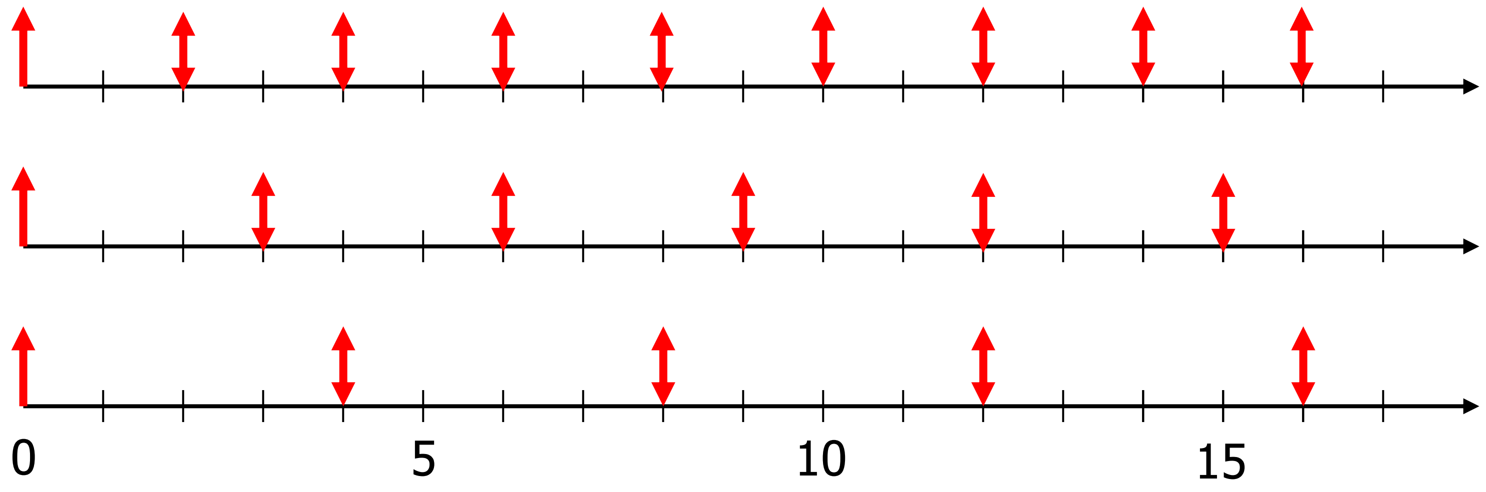


Schedule repeats at least common multiple

Check your understanding

- Can we schedule the following workload?
  - Job A: period 2, computation 1
  - Job B: period 3, computation 1
  - Job C: period 4, computation 1

$$U = \sum_{i=1}^{n} \left(\frac{C_i}{D_i}\right) \leq 1$$



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  - Job B: period 3, computation 1
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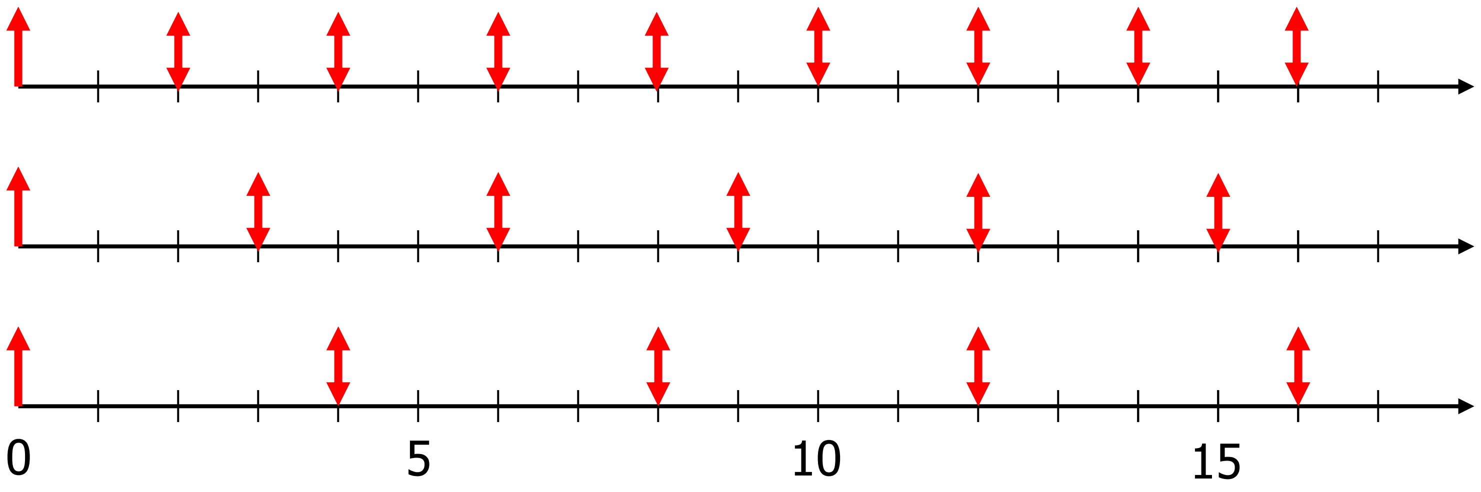
$$U = \sum_{i=1}^{n} \left(\frac{C_i}{D_i}\right) \le 1$$

1/2 + 1/3 + 1/4 = 1.08



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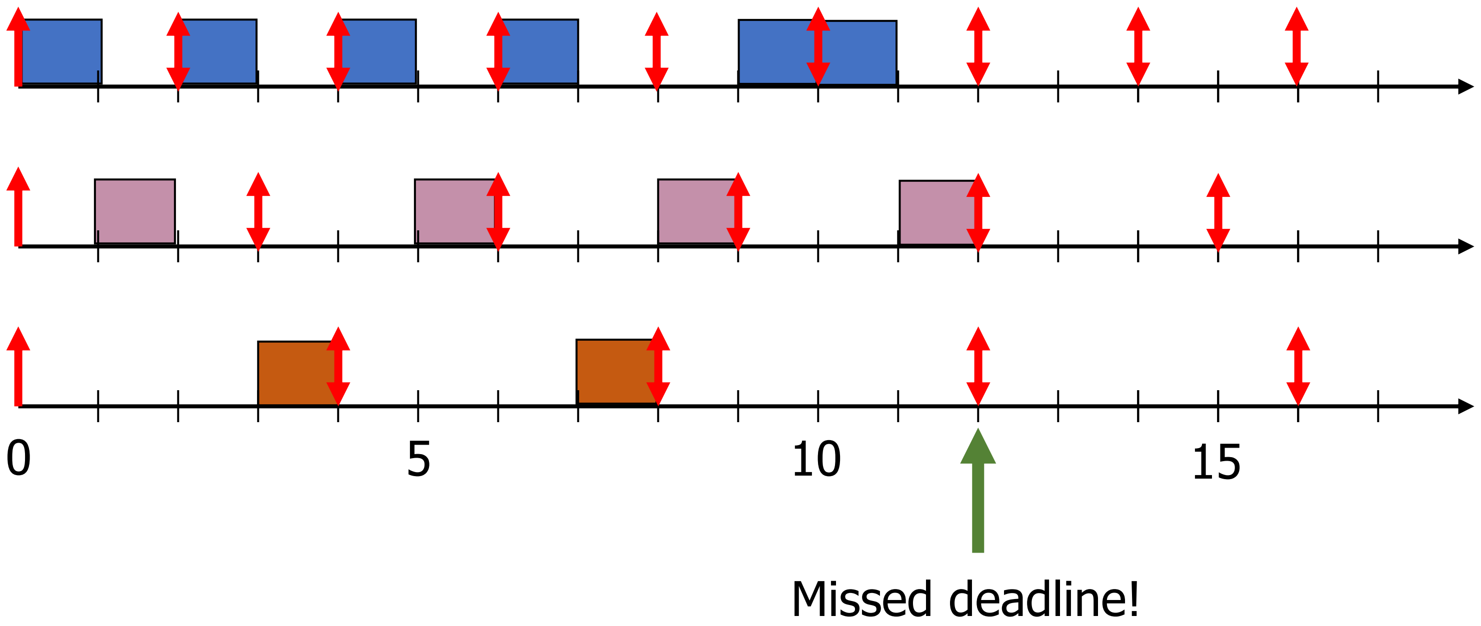

Break + Thinking

- Where do the job deadlines come from? Provide an example.

Break + Thinking

- Where do the job deadlines come from? Provide an example.
  - Real-world constraints!
  - Autonomous vehicle:
    - "If I don't finish the detection algorithm by time N,
      then I will no longer be able to stop in time to avoid what it detects."
    - In this example, deadline might vary with velocity,
      or maybe we just choose a deadline based on fastest velocity.

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Earliest Deadline First tradeoffs

Good qualities

- Simple concept and simple schedulability test
- Excellent CPU utilization

Bad qualities

- Hard to implement in practice
  - Need to constantly recalculate task priorities
  - CPU time spent in scheduler needs to be counted against load
- Unstable: Hard to predict which job will miss deadline
  - Utilization was greater than 1, so we knew there was a problem
  - But we had to work out the whole schedule to see Job C missed

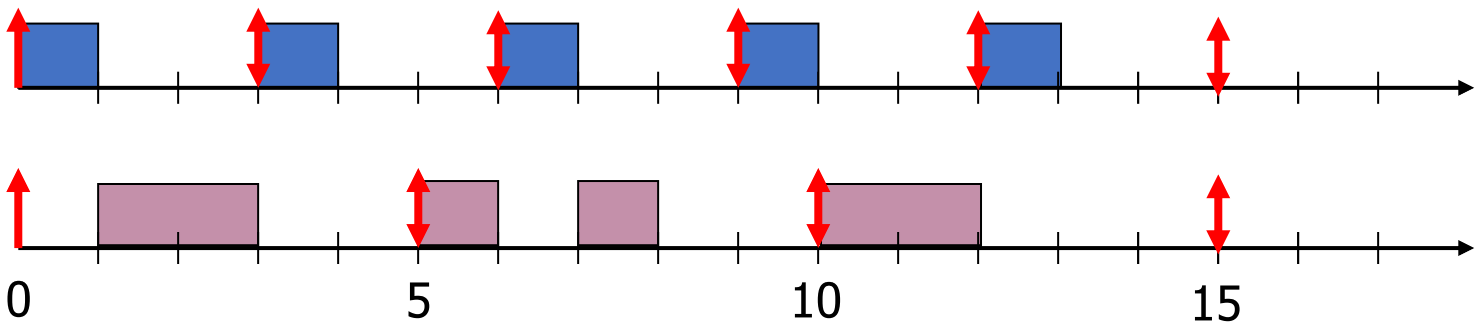
Rate Monotonic Scheduling (RMS)

- Priority scheduling
- Assign fixed priority of 1/Period for each job
  - Makes the scheduling algorithm simple and stable
  - Only lowest priority jobs might miss deadlines

- If ***any*** fixed-priority scheduling algorithm can schedule a workload, So can Rate Monotonic Scheduling
  - There could be dynamic-priority systems that beat it
  - But they would be more complicated and take more cycles to run

Rate Monotonic Scheduling example

- Schedule the following workload with RMS
  - Job A: period 3, computation 1 -> Priority 1/3
  - Job B: period 5, computation 2 -> Priority 1/5

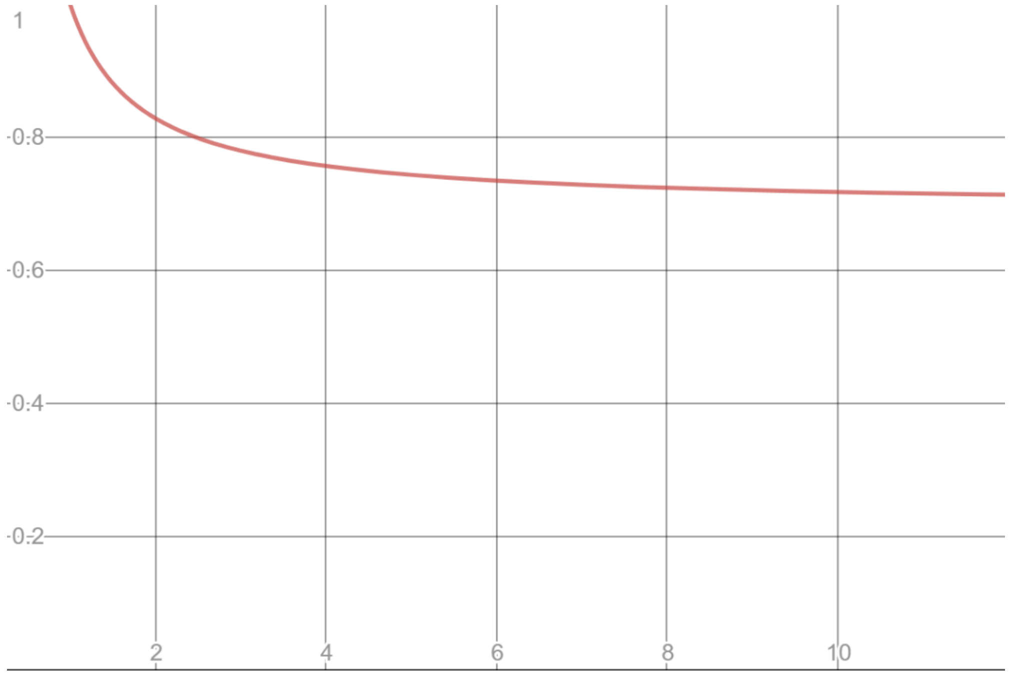


Schedulability test for RMS

- Schedulability is more complicated for RMS unfortunately
  - For a workload of ***n*** jobs with computation time ***C*** and period ***D***

$$U = \sum_{i=1}^{n} \left(\frac{C_i}{D_i} \right) \leq n * (2^{\frac{1}{n}} - 1)$$

Lower Bound on schedulability



- U(1) = 1.0
- U(2) = 0.828
- U(3) = 0.779

  …
- U(∞) = 0.693

RMS schedulability test is conservative

$$U = \sum_{i=1}^{n} \left(\frac{C_i}{D_i} \right) \leq n * (2^{\frac{1}{n}} - 1)$$

- $0 \leq U \leq n * (2^{\frac{1}{n}} - 1)$
  - Schedulable! (so less than 69% is always schedulable)
- $n * (2^{\frac{1}{n}} - 1) < U \leq 1$
  - Maybe schedulable
- $1 < U$
  - Not schedulable

Check your understanding

- Can we schedule the following workload with RMS?
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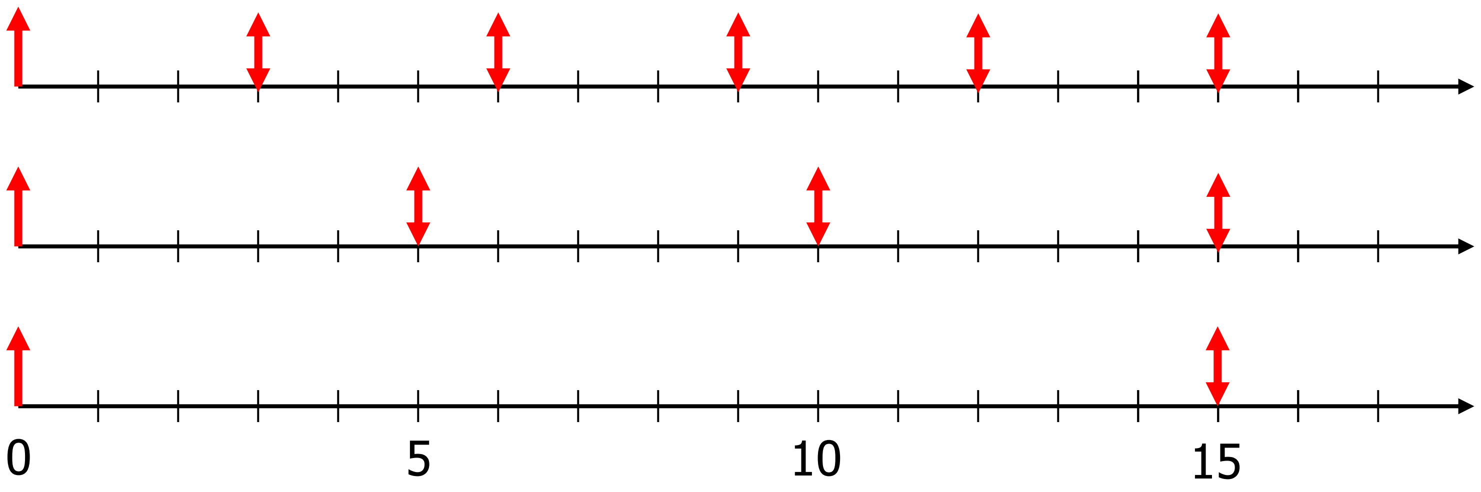

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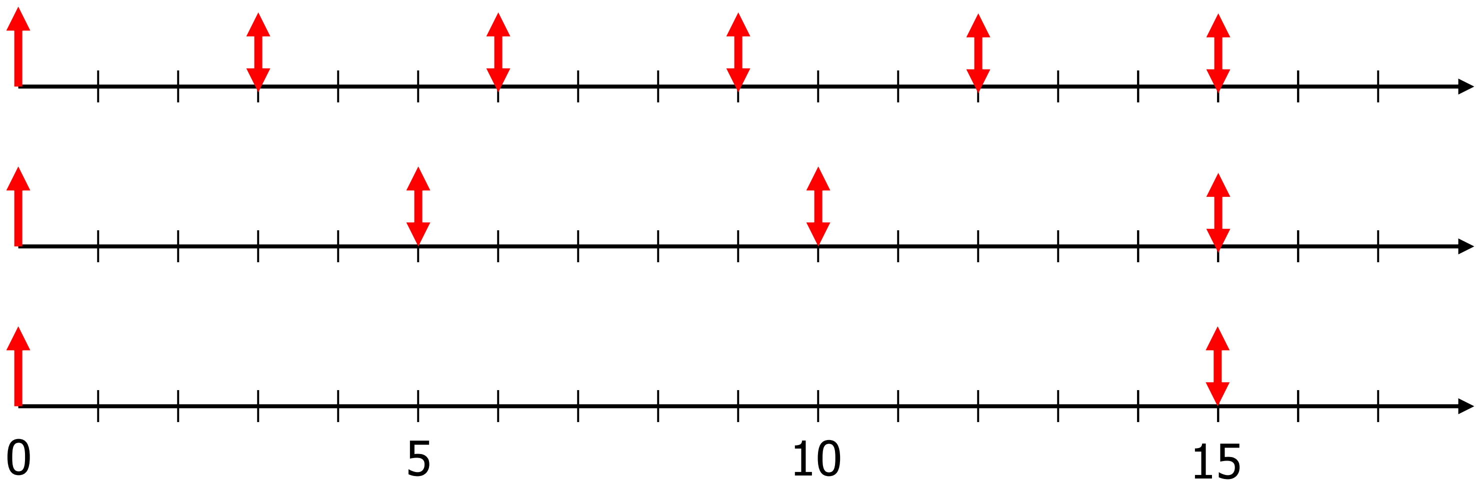
1/3 + 2/5 + 4/15 = 1

U = 1
Maybe schedulable!

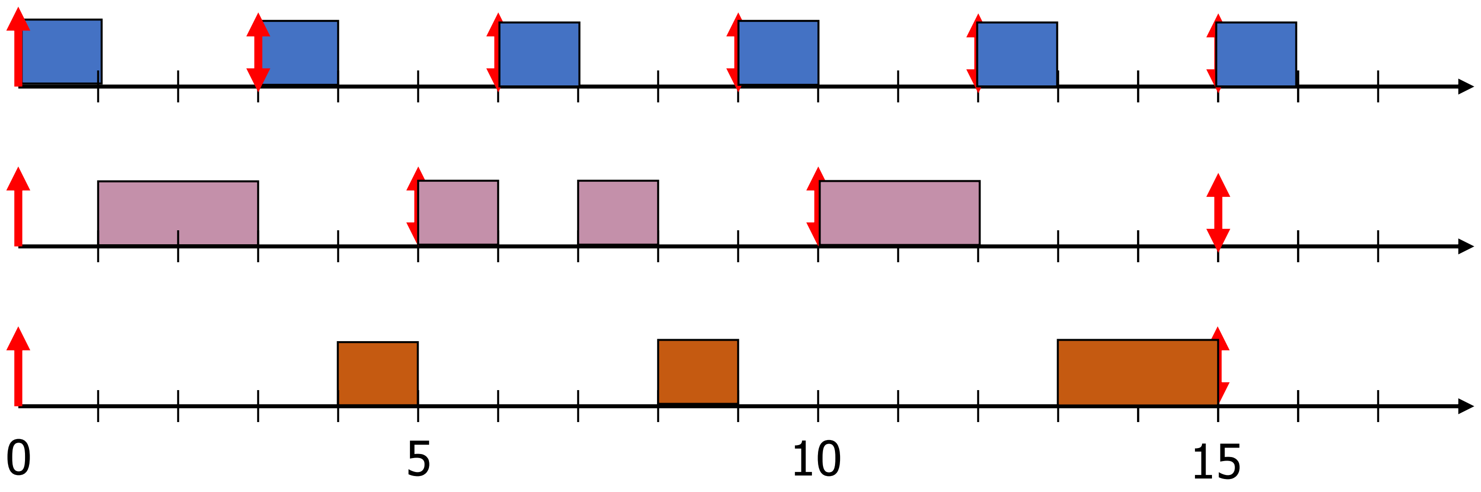


Check your understanding

- Can we schedule the following workload with RMS?
  - Job A: period 3, computation 1 -> Highest priority
  - Job B: period 5, computation 2 -> Middle priority
  - Job C: period 15, computation 4 -> Lowest priority

1/3 + 2/5 + 4/15 = 1

U = 1
Maybe schedulable!



Rate Monotonic Scheduling tradeoffs

Upsides

- Still conceptually simple
- Easy to implement
- Stable (lower priority jobs will fail to meet deadlines in overload)

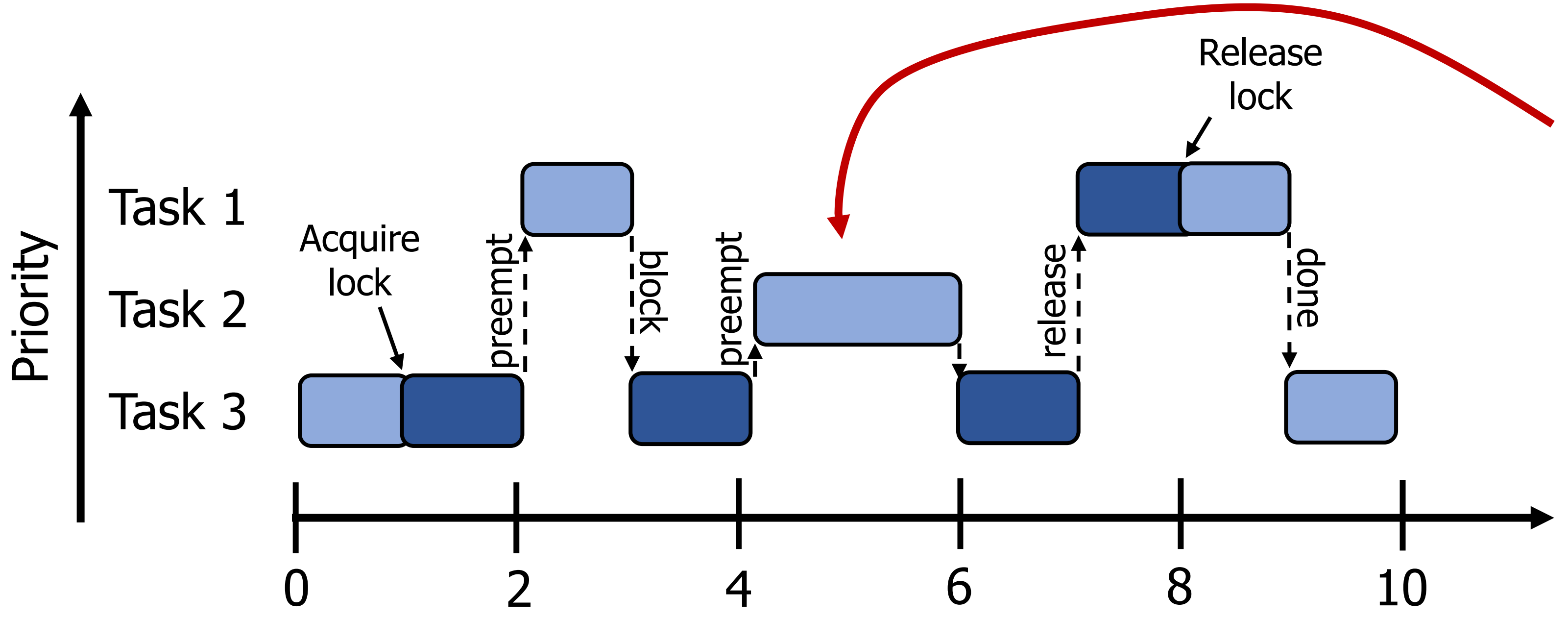
Downsides

- Lower CPU utilization
  - Might not be able to utilize more than 70% of the processor
- Non-precise schedulability analysis

A problem with priority schedulers: priority inversion

- Other concepts from OS still apply when we're scheduling
  - Particularly locks and synchronization

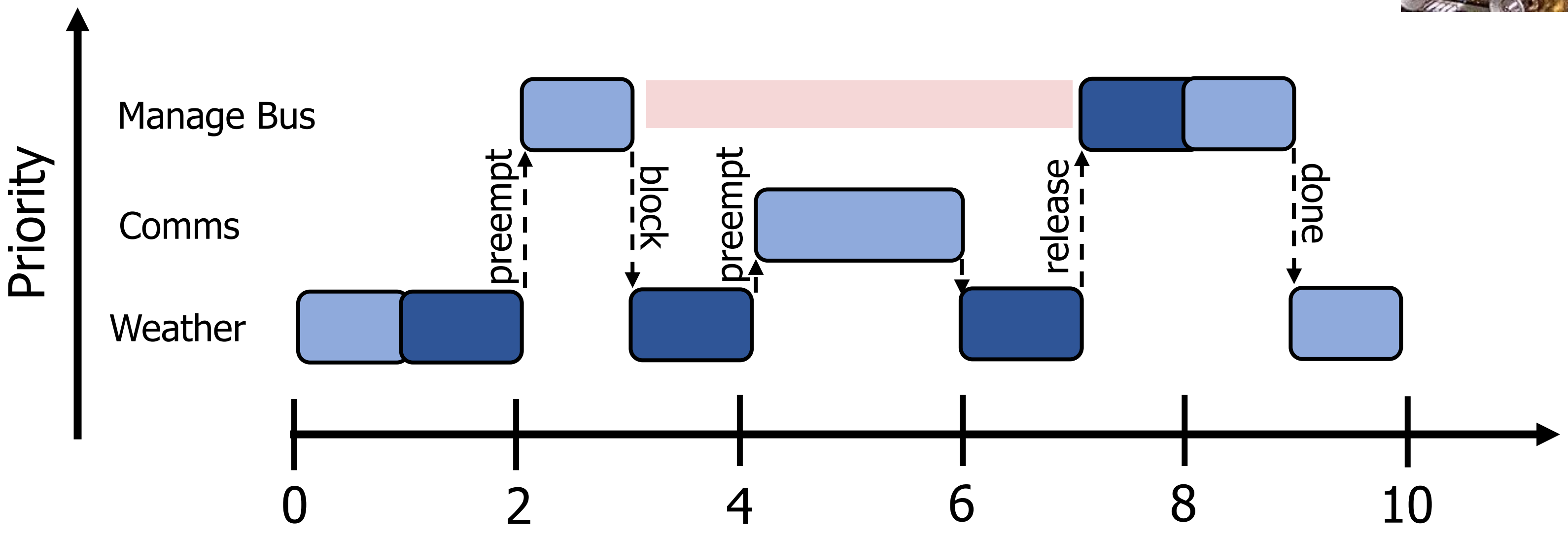
- Imagine Task 1 and Task 3 both need to share a lock



Task 1 is waiting on Task 2!!

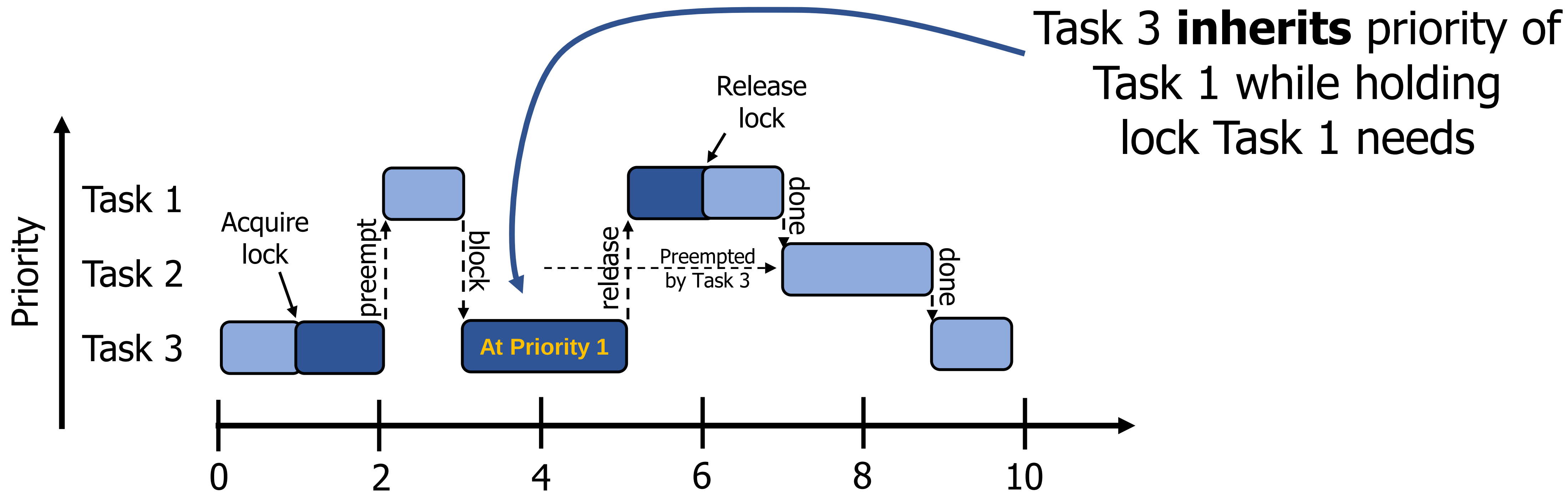
Priority inversion occurred on Pathfinder!

- Bus management missed deadlines while waiting on meteorology because medium-priority tasks were taking too long
  - System rebooted when deadline was missed



Priority inheritance solution to priority inversion

- A solution is to temporarily increase priority for tasks holding resources that high priority tasks need



Break + Chat/Relax

- Let's take a mental break while switching sections

- If you really want guidance:
  - Share one thing to remember to write on your notes sheet

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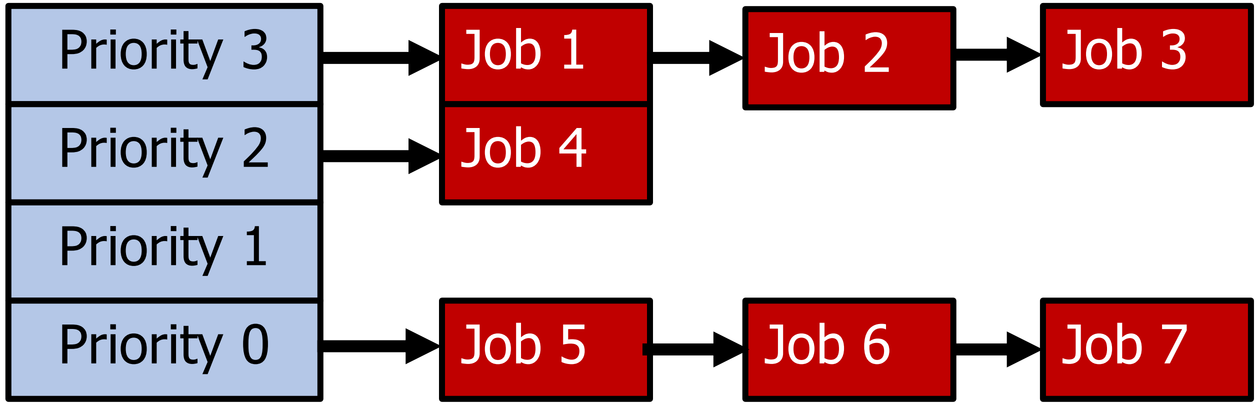
Priority scheduling policies

- Systems may try to set priorities according to some **policy goal**
- MLFQ Example:
  - Give interactive jobs higher priority than long calculations
  - Prefer jobs waiting on I/O to those consuming lots of CPU
- Try to achieve fairness:
  - elevate priority of threads that don't get CPU time (ad-hoc, bad if system overloaded)



Linux O(1) scheduler (Linux 2.6)

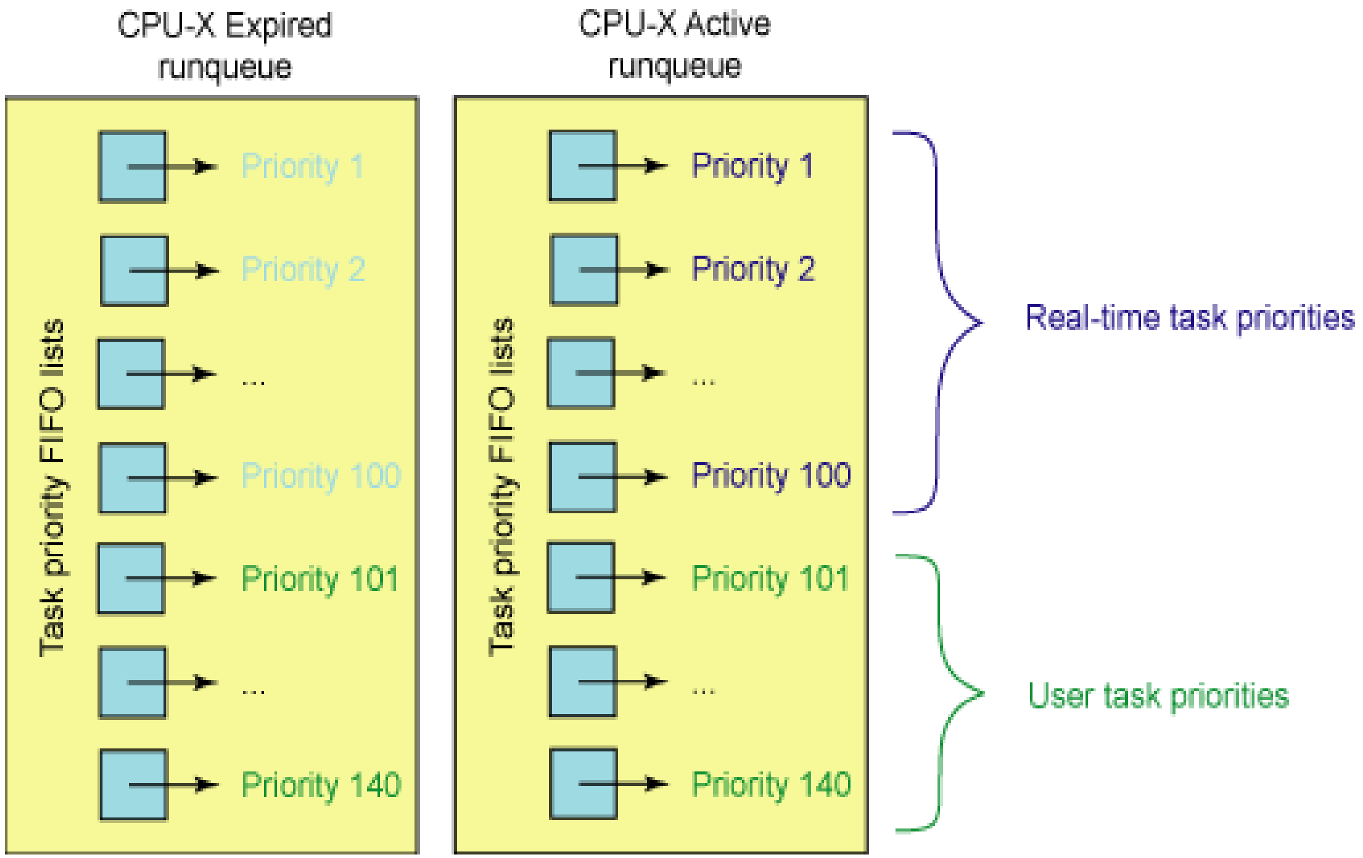
- Goals
  - Keep the runtime of the scheduler itself short
    - Avoid O(n) algorithms
    - Instead only make adjustments to a single job when it is swapped
  - Predictable algorithm
  - Identify interactive versus noninteractive processes with heuristics
    - Processes with long average sleep time get a priority boost

- Note my machines right now:
  - Ubuntu VM: 332 processes (867 threads)
  - Windows: 224 processes (2591 threads)
  - MacOS: 430 processes (2249 threads)
  - **Major concern:** many processes mean O(n) could be very long…

Priority in Linux O(1) scheduler

- MLFQ-Like Scheduler with 140 Priority Levels
  - 40 for user tasks, 100 soft "realtime" tasks
- Timeslice depends on priority – linearly mapped onto timeslice range

Workings of the O(1) scheduler



- Round robin at priority levels like MLFQ
- Each priority level gets a run quota
- On expiration of quota
  - Recalculate priority
  - Insert in expired queue
- When all jobs are gone from active queue
  - Swap expired and active queue pointers

Priorities can lead to starvation

- 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
- The **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

Idea: proportional-share scheduling

- Many of the policies we’ve studied always prefer to give CPU to a prioritized job
  - Non-prioritized jobs may never get to run

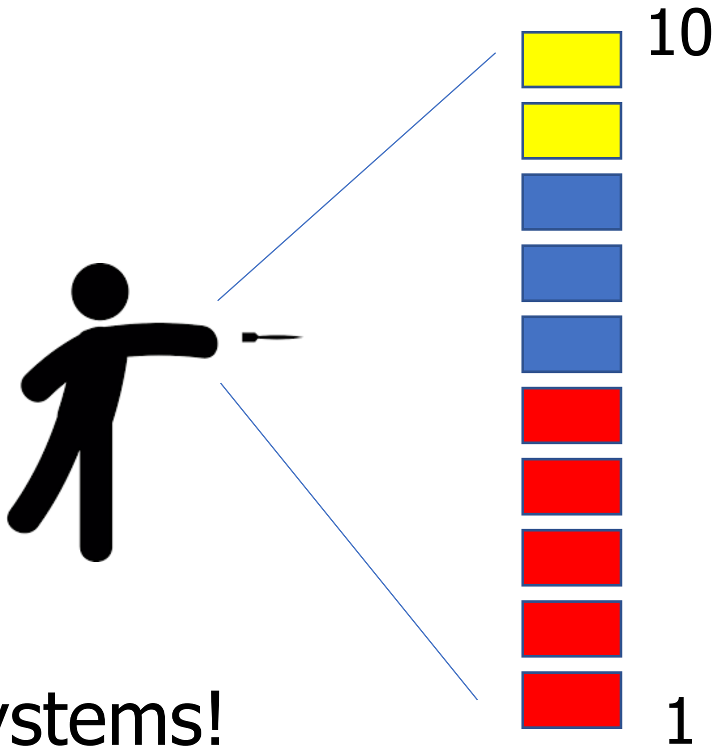
- Instead, we can share the CPU proportionally
  - Give each job a share of the CPU according to its priority
  - Low-priority jobs get to run less often
  - But all jobs can at least make progress (no starvation)

Lottery Scheduling

- Give out "tickets" according to proportion each job should receive
- Every quantum:
  - Draw one ticket at random
  - Schedule that job to run
- If there are N jobs,
  probability of pick a job is:

$$\frac{priority(jobi)}{\sum_{j=0}^{n-1} priority(jobj)}$$

- Definitely not suitable for real-time systems!



Stride Scheduling

- Same idea, but remove the random element
- Give each job a stride number inversely proportional to tickets
  - A=100 tickets, B=50 tickets, C=250 tickets
  - A=100 stride, B=200 stride, C= 40 stride
- Scheduler
  - Pick job with lowest cumulative strides and run it
  - Increment its cumulative strides by its stride number

- Essentially: low-stride (high-ticket) jobs get run more often

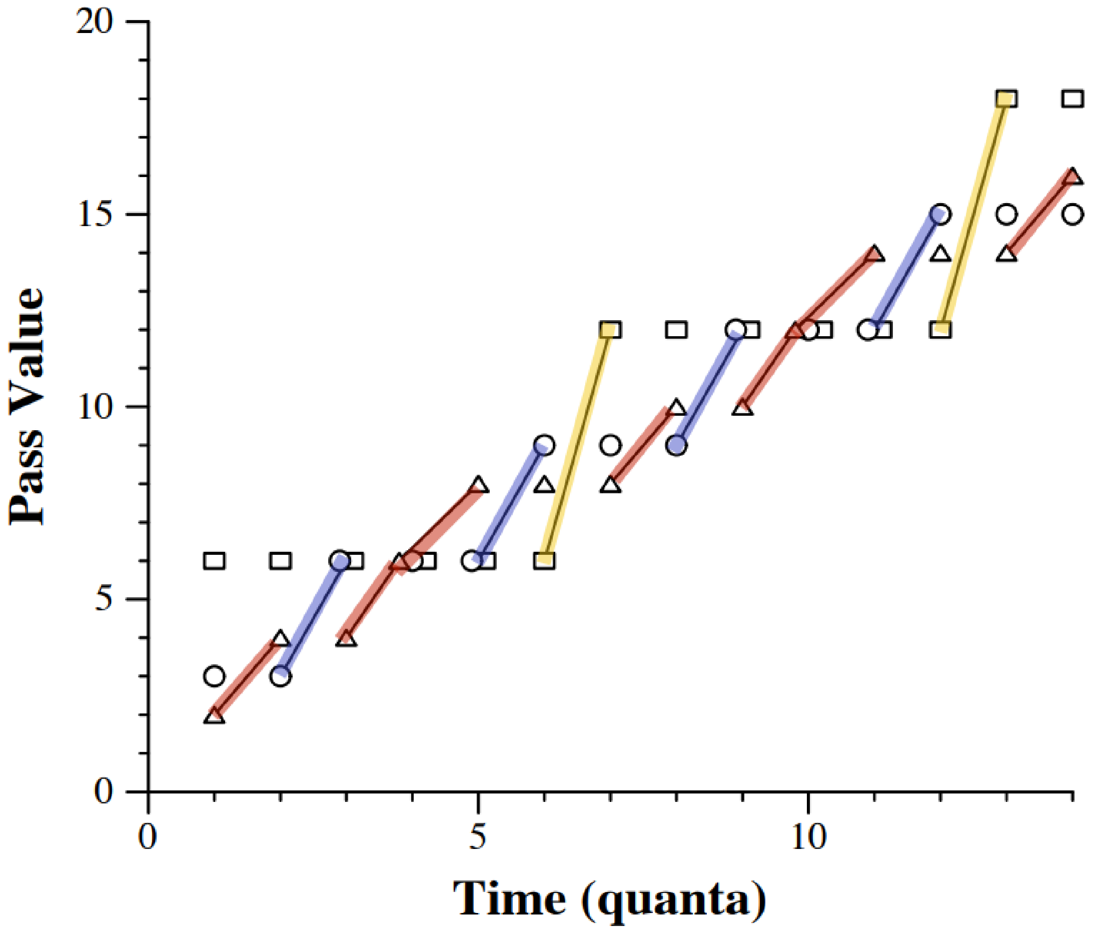
Stride scheduling in practice

Triangle is high priority (low stride)

Circle is medium priority

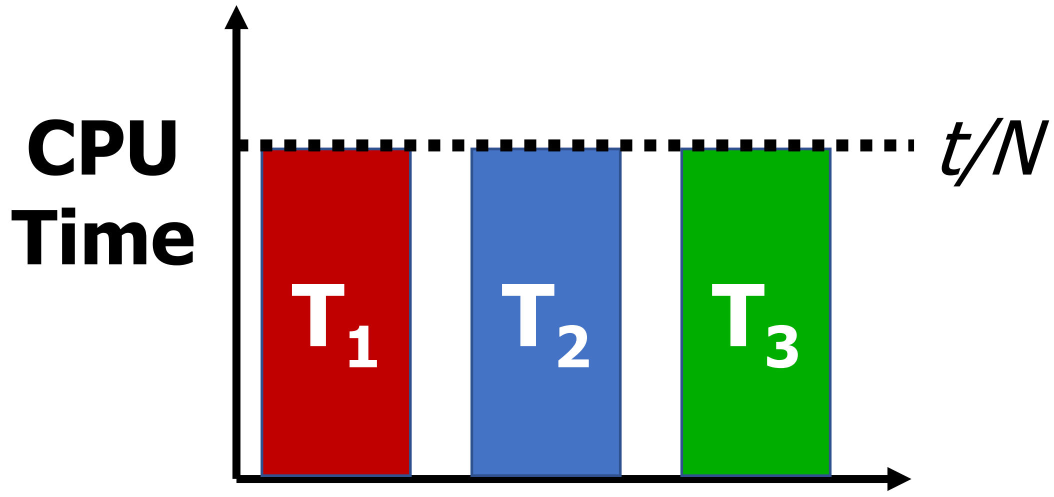
Square is low priority (high stride)

- "Pass value" is the cumulative stride count
- Each colored line is an instance where a job runs
  - And stride count is increased afterwards



Proportional-share scheduling is impossible instantaneously

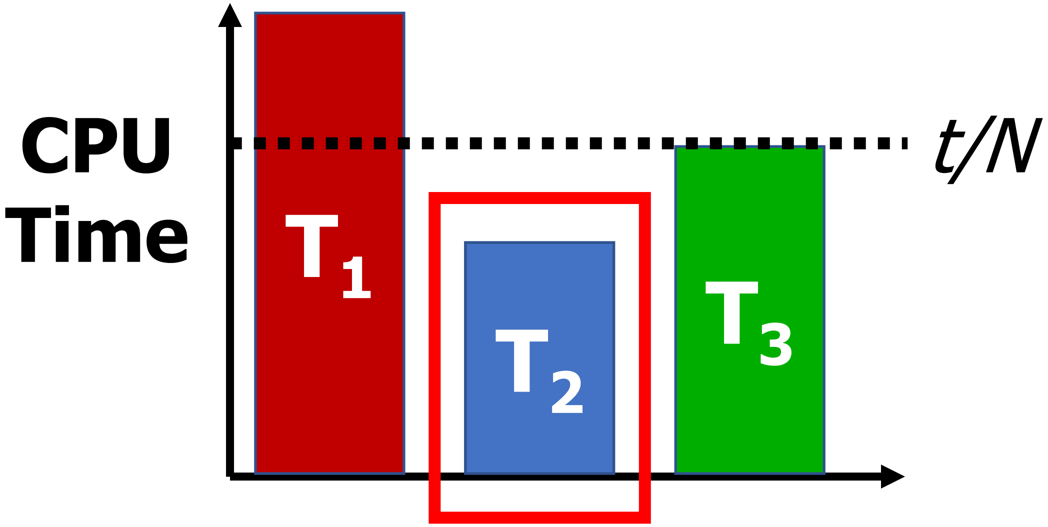
At *any* time *t*
we want to observe:



- Goal: each process gets an equal share of processor
- N threads "simultaneously" execute on 1/Nth of processor
- Doesn't work in the real world
  - Jobs block on I/O
  - OS needs to give out timeslices

Linux Completely Fair Scheduler (CFS)

What if we make shares proportional over a longer period?



- Track processor time given to job so far
- Scheduling decision
  - Choose thread with minimum processor time to schedule
  - “Repairs” illusion of fairness
- Update processor time when the job finishes
  - Timeslice expiration is a big update
  - Blocking I/O results in maintaining small processor time

Linux CFS: responsiveness and throughput

- Constraint 1: target latency
  - Want a maximum duration before a job gets some service
  - Dynamically set timeslice based on number of jobs
  - Quanta = Target_latency / N
  - 20 ms max latency => 5 ms timeslice for 4 jobs, or 0.1 ms for 200 jobs

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- Check your understanding. What's the problem here?

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  - Timeslice needs to stay much greater than context switch time

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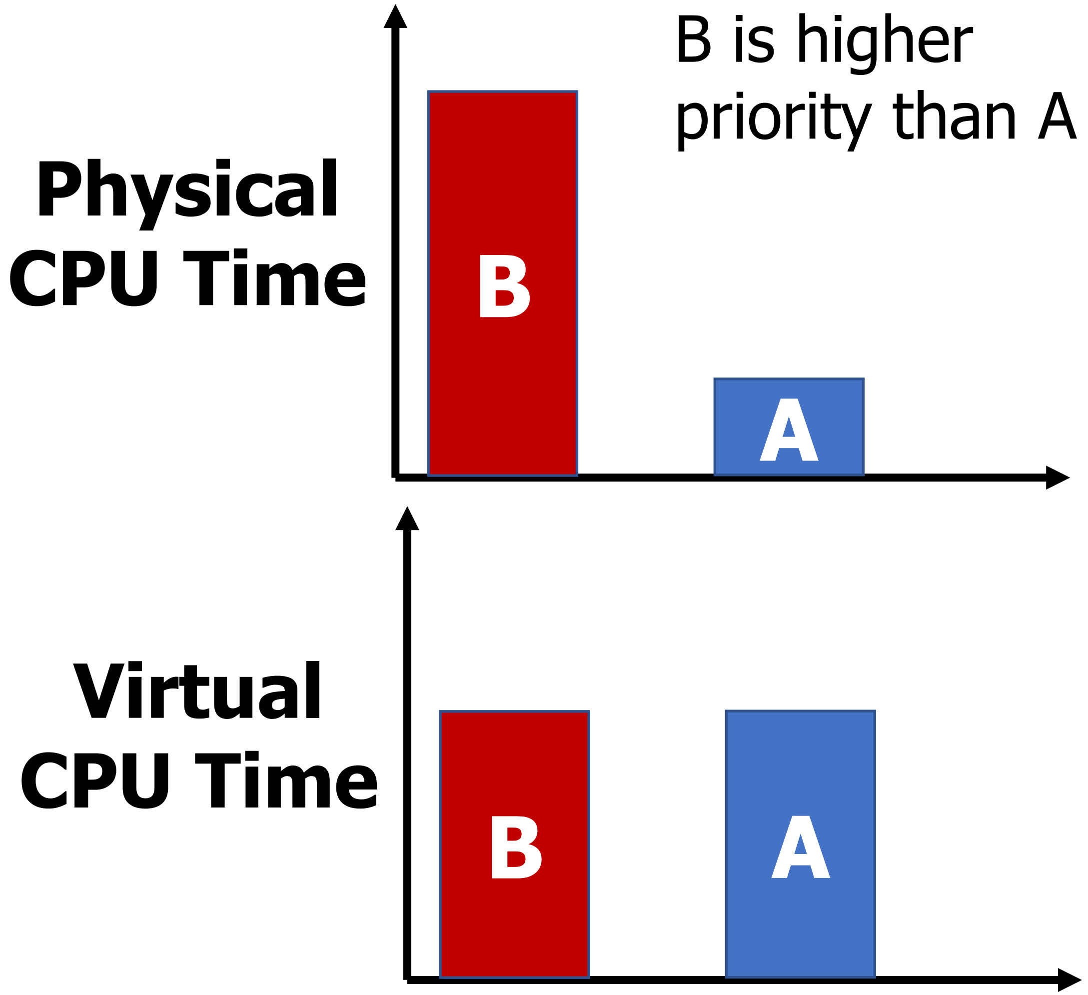
- Constraint 2: avoid excessive overhead
  - Don’t want to spend all our time context switching if there are many jobs
  - Set a minimum length for timeslices
  - Quanta = max(Target_latency/N, minimum_length)

CFS priorities are applied as "virtual runtime"

- Virtual runtime doesn't have to match wall time

- Change time to match priority
  - Higher priority jobs have slower virtual runtime
  - Lower priority have faster virtual runtime

- Scheduler's decisions on made to evenly proportion virtual runtime



Multicore scheduling

- *Affinity scheduling*: once a thread is scheduled on a CPU, OS tries to reschedule it on the same CPU
  - Cache reuse
  - Grouping threads could help or hurt…

- Implementation-wise, helpful to have *per-core* scheduling data structures
  - Each core can make its own scheduling decisions
  - Can steal work from other cores, if nothing to do

Active work in scheduling

- Getting scheduling right on multicore can be difficult
  - No way to know whether a process will be more I/O or CPU bound in the future
  - Want to keep threads on the same core, but also not waste cores

- In 2016, researchers found issues in Linux scheduler implementation that lead to 13%+ slowdown in jobs
  - https://blog.acolyer.org/2016/04/26/the-linux-scheduler-a-decade-of-wasted-cores/

- Another metric: energy use

Summary on schedulers

If You care About:	Then Choose:
CPU Throughput	First-In-First-Out
Average Turnaround Time	Shortest Remaining Processing Time
Average Response Time	Round Robin
Favoring Important Tasks	Priority
Fair CPU Time Usage	Linux CFS
Meeting Deadlines	EDF or RMS

Outline

- Real Time Operating Systems
  - Earliest Deadline First scheduling
  - Rate Monotonic scheduling

- Modern Operating Systems
  - Linux O(1) scheduler
  - Lottery and Stride scheduling
  - Linux Completely Fair Scheduler