CS162
Operating Systems and Systems Programming
Lecture 12

Scheduling
Core Concepts and Classic Policies

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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

Recall: STCF

Schedule jobs in order of shortest completion time

Requires knowledge of job completion time

⇩

Approximate duration of CPU burst; encode it in priorities

Subject to Starvation

⇩

Dynamically adapt priorities

Recall: Multi Level Feedback Queue

Rule 1

If Priority(A) > Priority(B), A runs (B doesn't).

Rule 2

If Priority(A) = Priority(B), A & B run RR using quantum of queue.

Rule 3

A new job is placed in the topmost queue.

Rule 4

If a job uses up its time allotment at a given level (regardless of how many times it has given up the CPU), its priority is reduced.

Rule 5

After some time period S, move all the jobs in the system to the topmost queue.

Recall: Multi Level Feedback Queue

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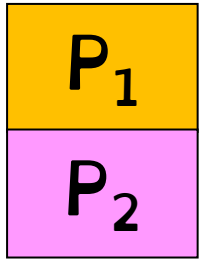
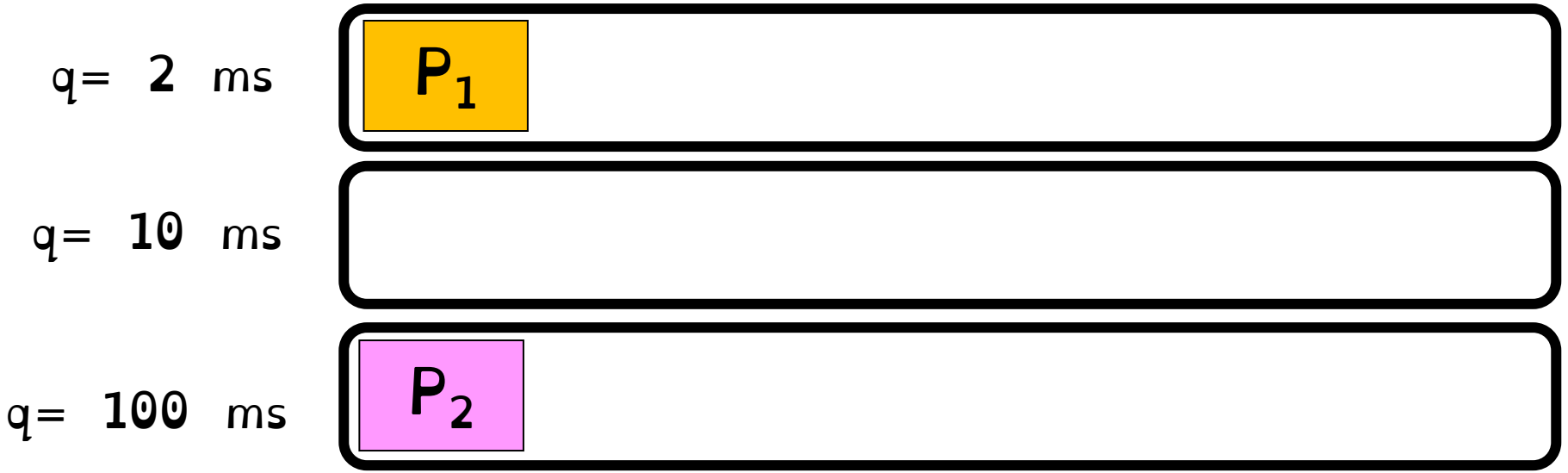
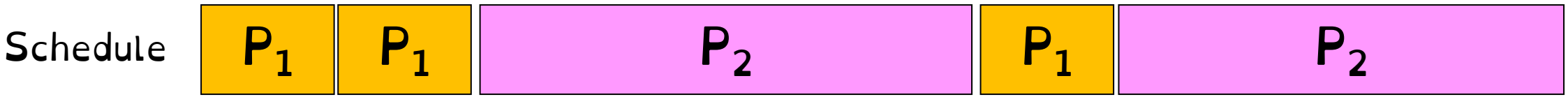
Recall: Learning behaviour



P_1 Computes for 1 ms. Uses disk for 10 ms

P_2 Computes for 50 ms.





Many many different variants of MLQF

Change how prevent starvation

Change constants

Change scheduling policies within each queue

Most modern schedulers are variants of **MLQF** queues

What's important?

IO-bound jobs have high priorities.
Get scheduled quickly. Run for short quantas.

Compute-bound jobs have low priority. Run with low time quantas. Run when IO bound jobs blocked on IO.

To prevent starvation, all jobs get a chance to run in a given period S.

No job says in the lower queue for ever. Account for changes in workload.

Goals for Today

- What did "older" Linux schedulers do?
- Introducing the concept of proportional fair sharing and CFS
- Understanding deadlocks more formally

Recall: History of Schedulers in Linux

O(n) scheduler
Linux 2.4 to Linux 2.6

O(1) scheduler
Linux 2.6 to 2.6.22

CFS scheduler
Linux 2.6.23 onwards

Case Study: Linux O(n) Scheduler

At every context switch:

- Scan full list of processes in the ready queue
- Compute relevant priorities
- Select the best process to run

Scalability issues:

- Context switch cost increases as number of processes increase
- Single queue even in multicore systems

Case Study: Linux O(1) Scheduler

Next process to run is chosen in constant time

Priority-based scheduler with 140 different priorities

Real-time/kernel tasks assigned priorities 0 to 99 (0 is highest priority)

User tasks (interactive/batch) assigned priorities 100 to 139 (100 is highest priority)

Case Study: O(1) Scheduler – User tasks

Per priority-level, each CPU has two ready queues

An active queue, for processes which have not used up their time quanta

An expired queue, for processes who have

Timeslices/priorities/interactivity credits all computed when jobs finishes timeslice

Timeslice depends on priority

User tasks – Priority Adjustment

User-task priority adjusted ±5 based on heuristics

- » p->sleep_avg = sleep_time – run_time
- » Higher sleep_avg ⇒ more I/O bound the task, more reward (and vice versa)

Interactive Credit

- » Earned when a task sleeps for a "long" time
- » Spend when a task runs for a "long" time
- » IC is used to provide hysteresis to avoid changing interactivity for temporary changes in behavior

However, "interactive tasks" get special dispensation

- » To try to maintain interactivity
- » Placed back into active queue, unless some other task has been starved for too long...

O(1) Scheduler – Real tasks

Real-Time Tasks always preempt non-RT tasks

No dynamic adjustment of priorities

Scheduling schemes:

- SCHED_FIFO: preempts other tasks, no timeslice limit
- SCHED_RR: preempts normal tasks, RR scheduling amongst tasks of same priority

An aside: Real-Time Scheduling

Goal

Predictability of Performance!

We need to predict with confidence worst case response times for systems!

Real-time is about enforcing predictability, and does not equal fast computing.

Introducing the Completely Fair Scheduler

Key idea:

Proportional Fair Sharing

Give each job a share of the CPU according to its priority

Proportional Fair Sharing

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)

Early Example: Lottery Scheduling

Give each job some number of lottery tickets

On each time slice, randomly pick a winning ticket

Each job gets at least one ticket

On average, CPU time is proportional to number of tickets given to each job

How to assign tickets?

Give Job A 50% of CPU, Job B 25%, Job C 10%

How can we use tickets to allow IO/interactive tasks to run quickly?

Assign tasks more tickets!

Can lottery scheduling lead to starvation?

a) Yes b) No

Can lottery scheduling lead to priority inversion?

Temporary Unfairness

Lose control over which job gets scheduled next.

Can suffer temporary bouts of unfairness

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

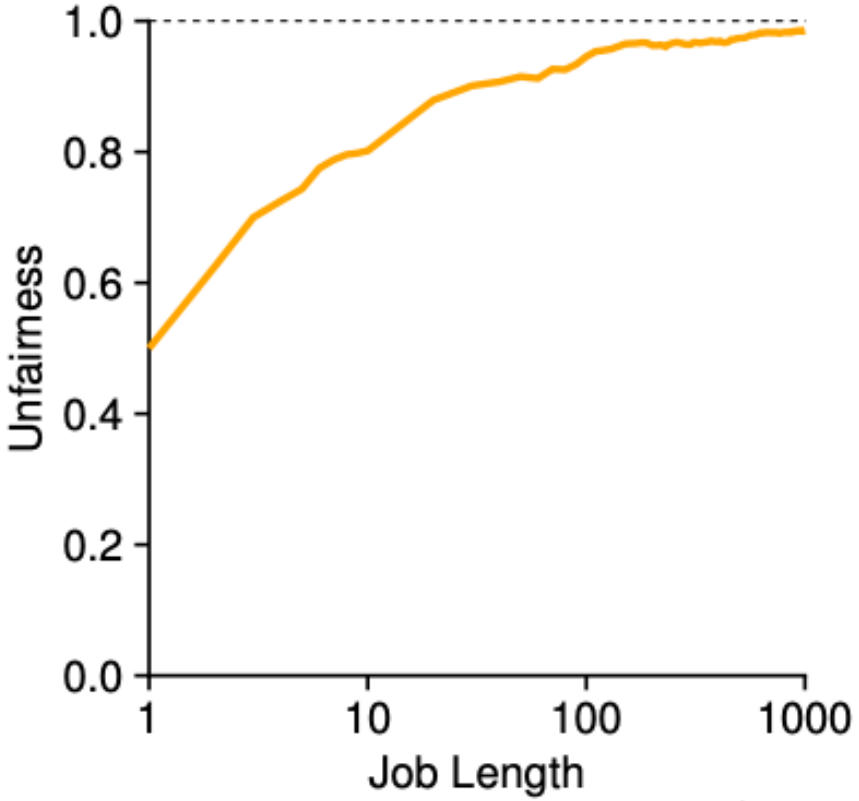


Figure 9.2: **Lottery Fairness Study**

Stride Scheduling

Deterministic proportional fair sharing

Stride of each job is $\frac{big\#W}{N_i}$

The larger your share of tickets Ni, the smaller your stride

W = 10,000,
A=100 tickets, B=50, C=250
A stride: 100, B: 200, C: 40

Stride Scheduling

Each job as a pass counter.

Scheduler picks a job with lowest *pass*, runs it, add its *stride* to its *pass*

Low-stride jobs (lots of tickets) run more often

Stride Scheduling

W = 10,000,
A=200 tickets, B=100 tickets, C=50 tickets

Strides: 50 100 200

Schedule: 50 100 100 150 200 200 200

Ready Queue:

50	100	100	150	200	200	200	250
100	200	200	200	200	200	250	300
200							

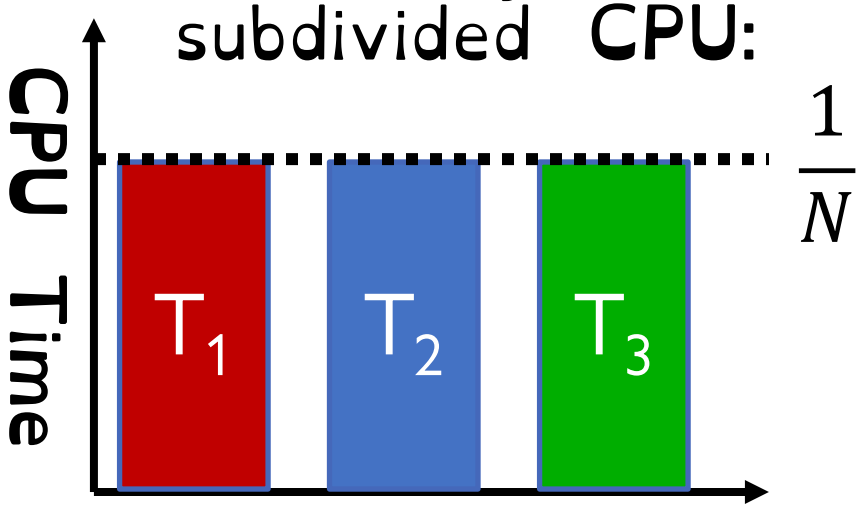
Linux Completely Fair Scheduler (CFS)

CFS models an "ideal, precise multi-tasking CPU"

Each process gets an equal share of CPU

N threads "simultaneously" execute on $\frac{1}{N}$ of CPU

Model:
"Perfectly"
subdivided CPU:



Each thread gets $\frac{1}{N}$ of the cycles

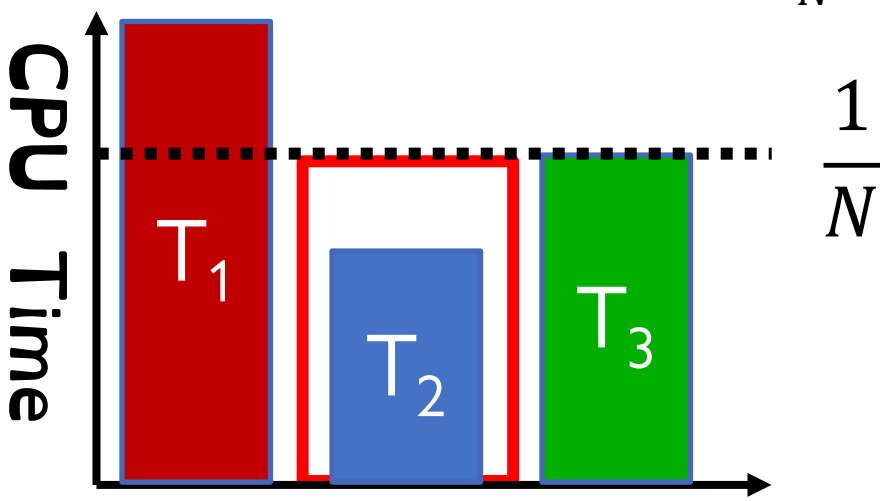
Optimise a global metric, not a local decision

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

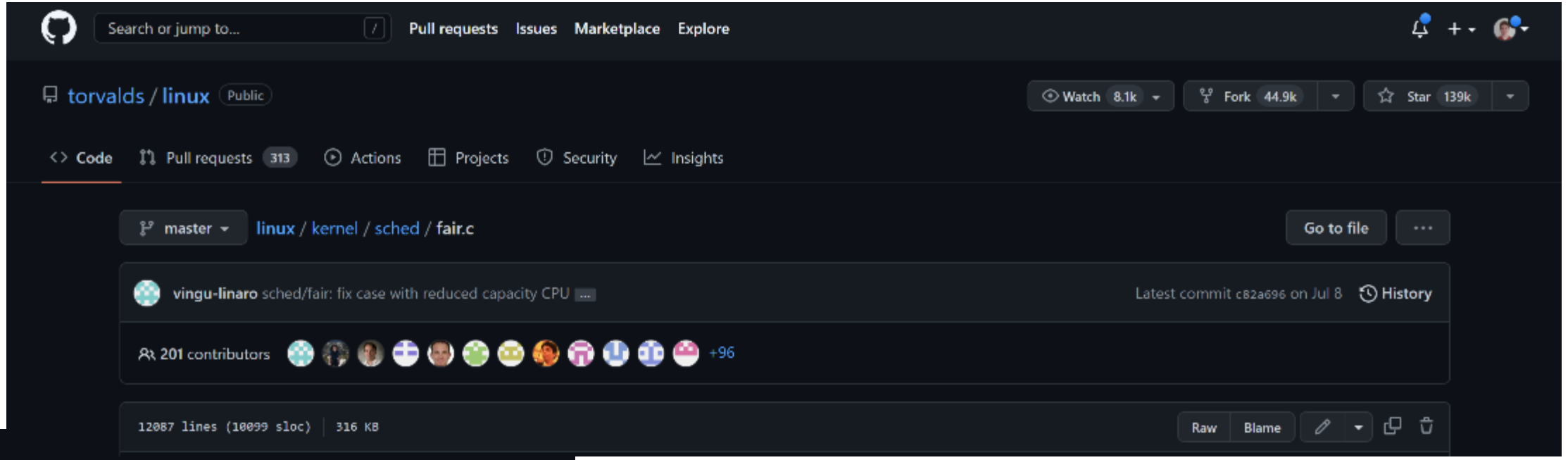
Linux CFS: Throughput

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

Constraints in the Wild (Linux Kernel)




```
/*
 * Targeted preemption latency for CPU-bound tasks:
 *
 * NOTE: this latency value is not the same as the concept of
 * 'timeslice length' - timeslices in CFS are of variable length
 * and have no persistent notion like in traditional, time-slice
 * based scheduling concepts.
 *
 * (to see the precise effective timeslice length of your workload,
 *  run vmstat and monitor the context-switches (cs) field)
 *
 * (default: 6ms * (1 + ilog(ncpus)), units: nanoseconds)
 */
unsigned int sysctl_sched_latency                       = 6000000ULL;
static unsigned int normalized_sysctl_sched_latency     = 6000000ULL;
```

```
/*
 * Minimal preemption granularity for CPU-bound tasks:
 *
 * (default: 0.75 msec * (1 + ilog(ncpus)), units: nanoseconds)
 */
unsigned int sysctl_sched_min_granularity                       = 750000ULL;
static unsigned int normalized_sysctl_sched_min_granularity     = 750000ULL;
```

Priorities in Unix

`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

Easy to implement for O(1) scheduler, how does it work for CFS?

We want to implement proportional fair sharing

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

Reuse `nice` value to reflect share, rather than priority

CFS uses nice values to scale weights exponentially

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

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

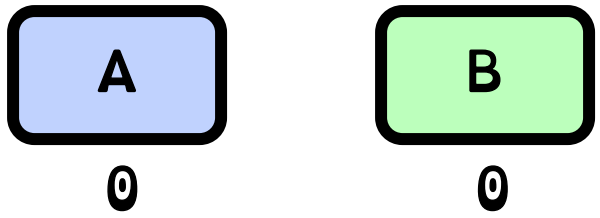
A = (1/5) * 20 = 4

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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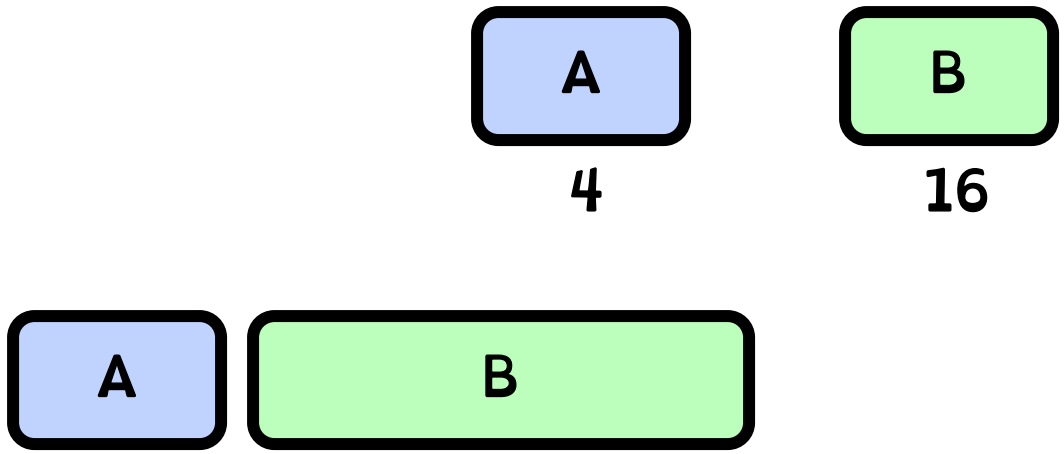

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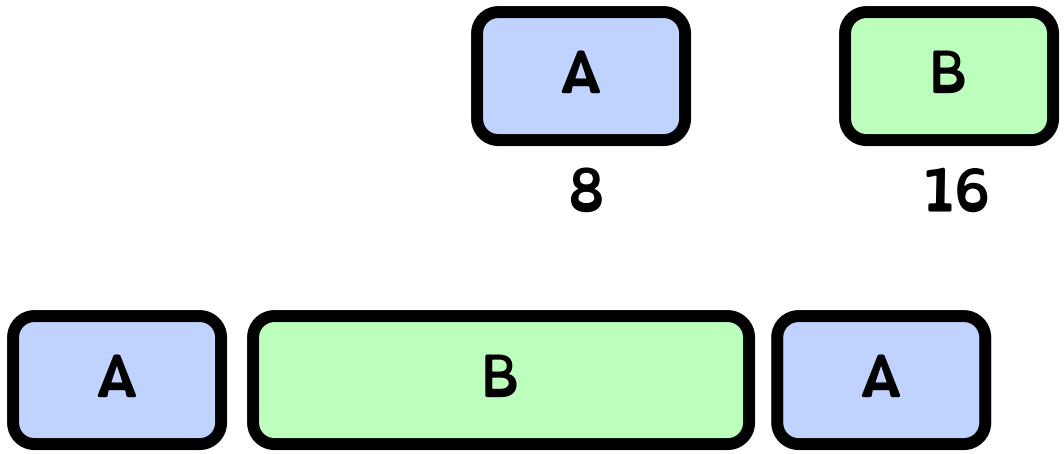

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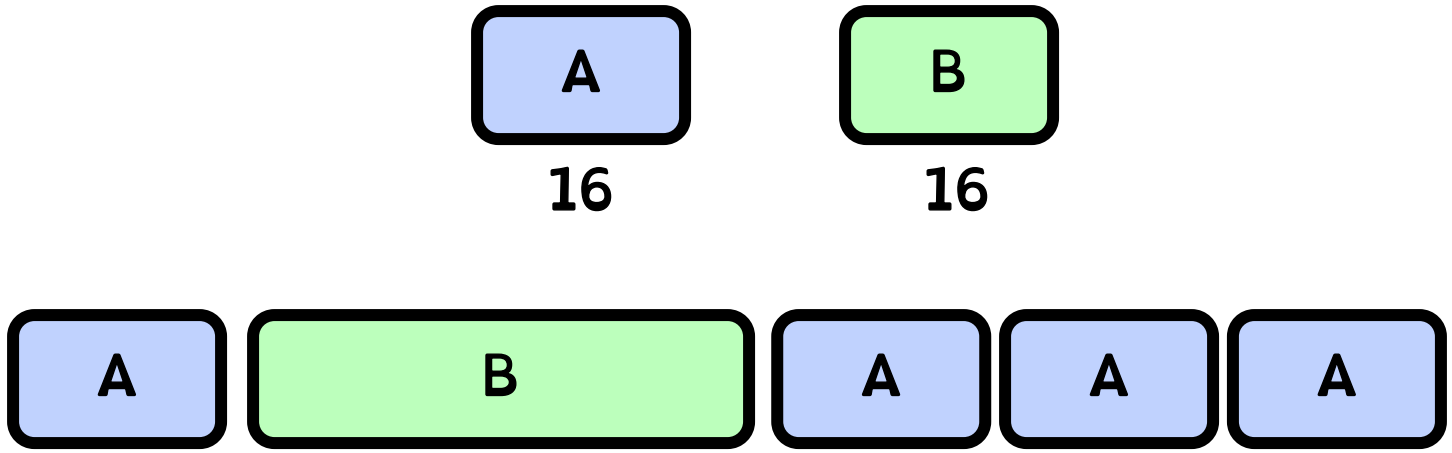
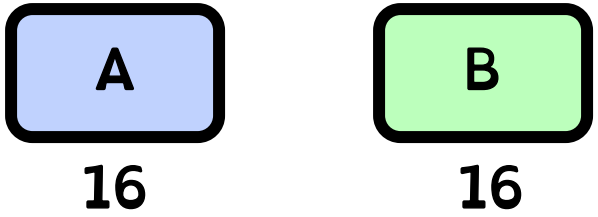
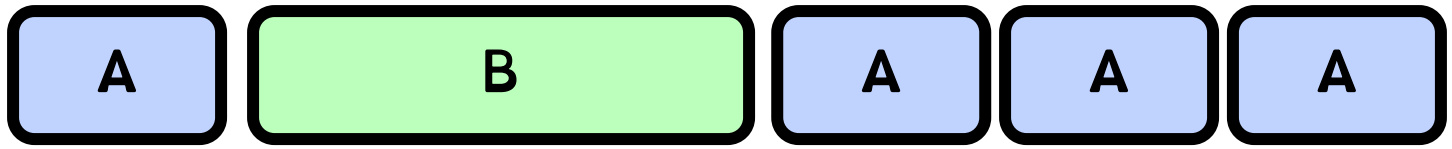


Linux CFS: Proportional Shares

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

Recall: [illegible] 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

$$\text{Virtual Runtime} = \text{Virtual Runtime} + (1/w_i)\ \text{Physical Runtime}$$

Linux CFS: Proportional Shares

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A timeslice = 4ms
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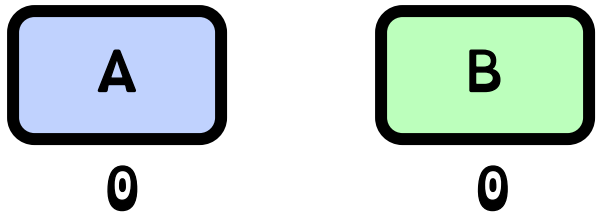
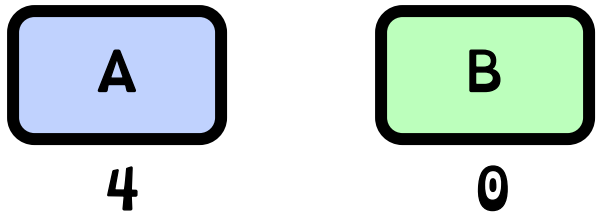
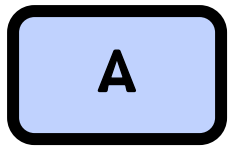


Linux CFS: Proportional Shares

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

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

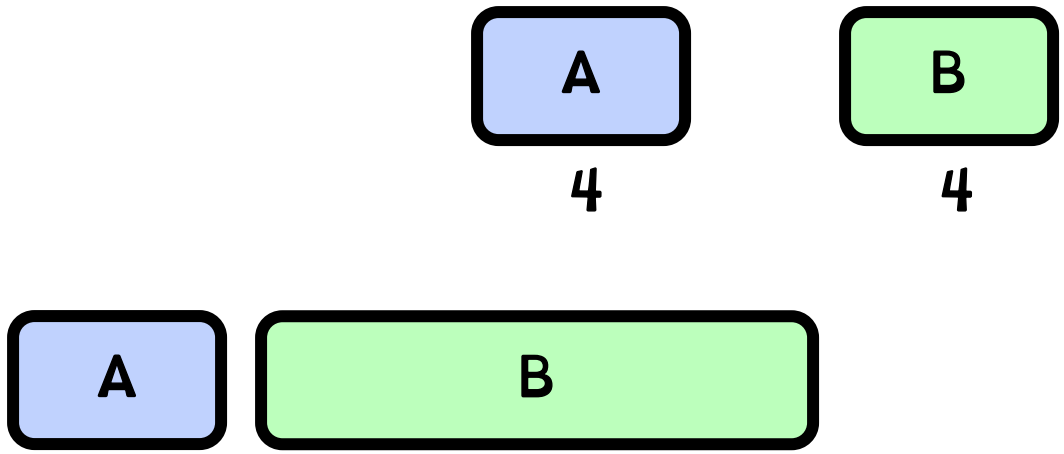




Linux CFS: Proportional Shares

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

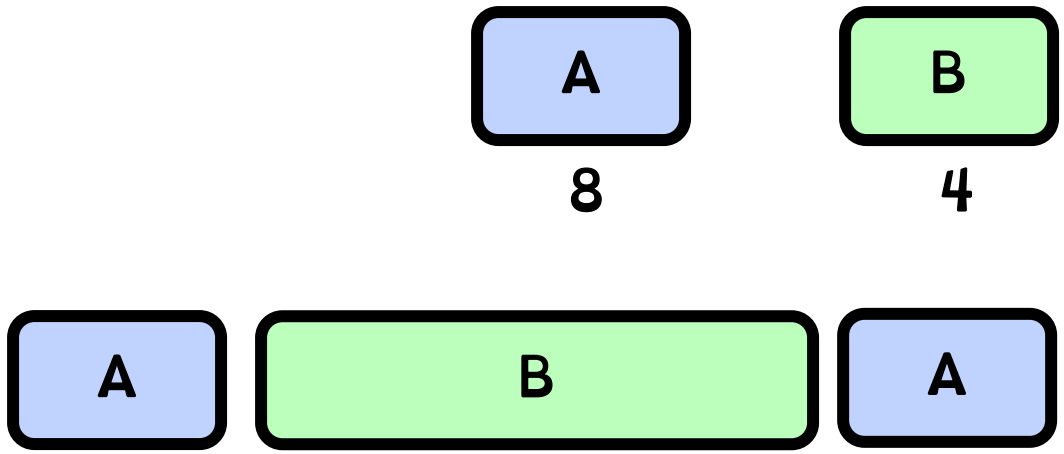
Virtual Runtime = 0 + Physical Runtime / Weight = 0 + 16/4 = 4



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

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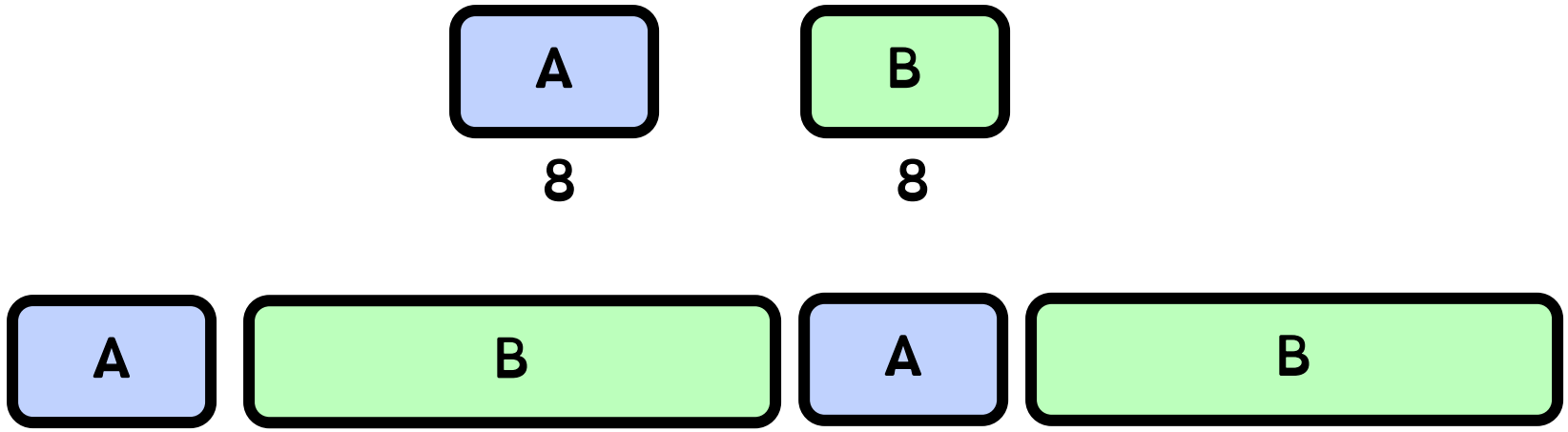
Virtual Runtime = 4 + Physical Runtime / Weight = 4 + 16/4 = 8



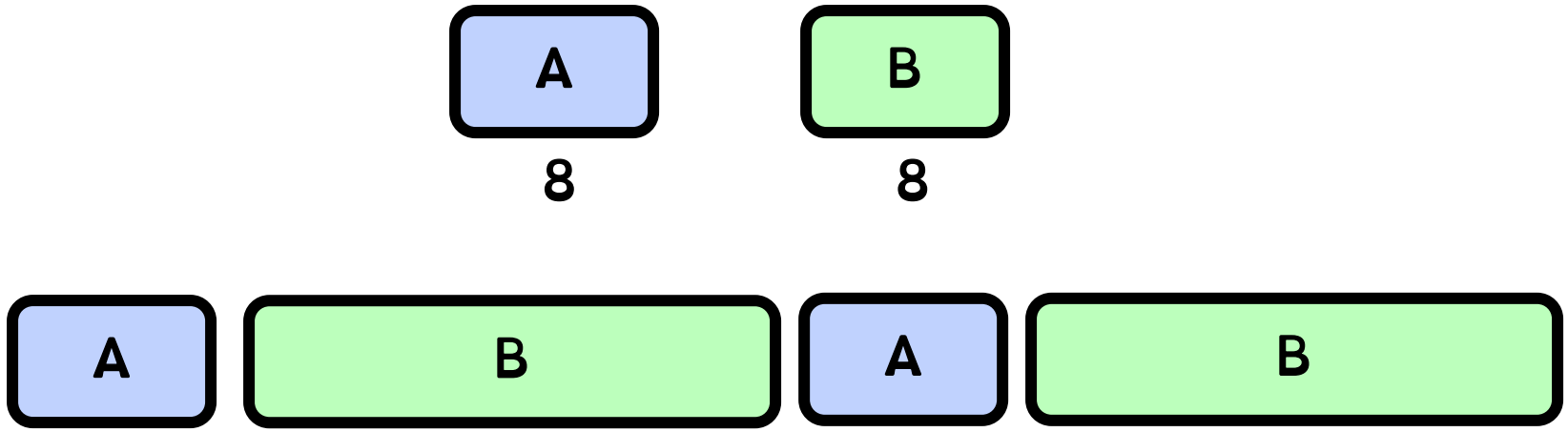
Linux CFS: Proportional Shares

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

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

But equal virtual runtime!

CFS shares vruntime equally



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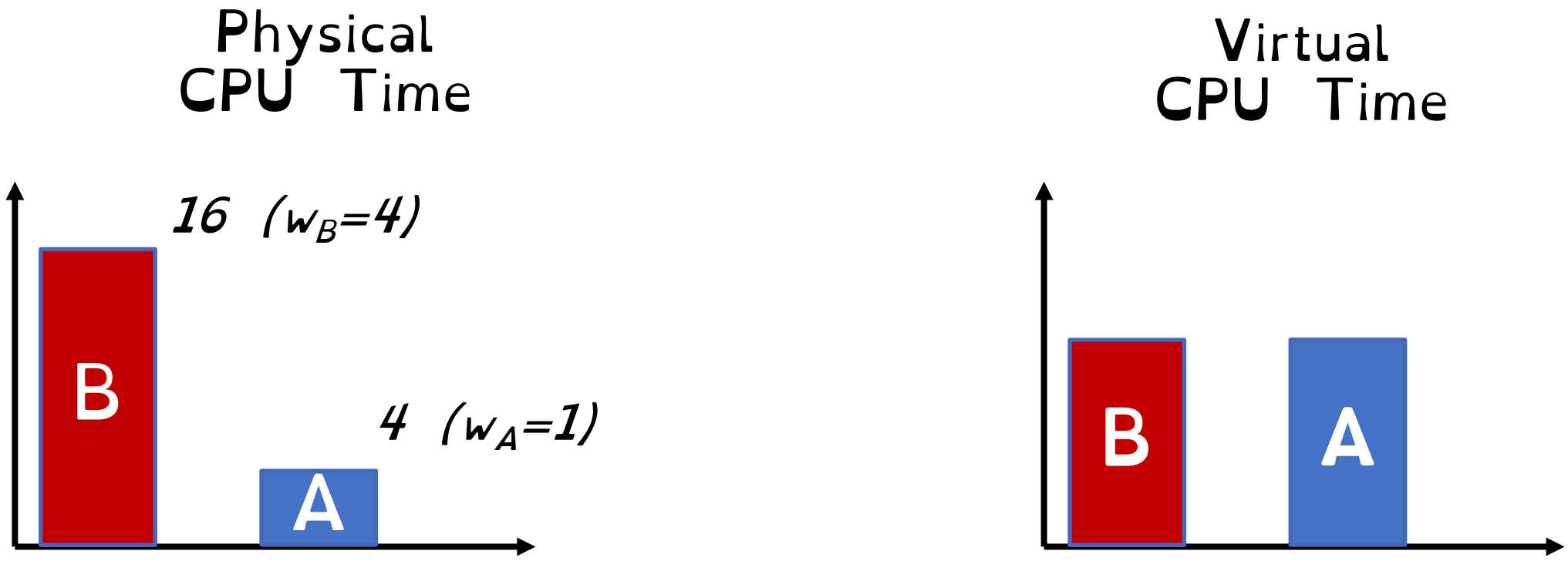

Summary: Schedulers in Linux

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