Changelog

25 Feb 2021 (after lecture): add some explanation slides to CFS exercises

last time

first-come, first-served
- run whatever became ready first until done

round-robin
- choose *time quantum*
- run for time quantum amount of time
- switch to next in list

time quantum tradeoffs
- shorter time quantum = lower throughput + better fairness

priority scheduling

proportional share/lottery scheduling
- weighted random choice

shortest first — minimize mean turnaround time
- avoid convoy effect — short jobs waiting behind long

minimizing turnaround time

recall: first-come, first-served best order:
had shortest CPU bursts first

→ scheduling algorithm: 'shortest job first' (SJF)

= same as priority where CPU burst length determines priority

...but without preemption for now

- priority = job length doesn't quite work with preemption
- (preview: need priority = remaining time)

a practical problem

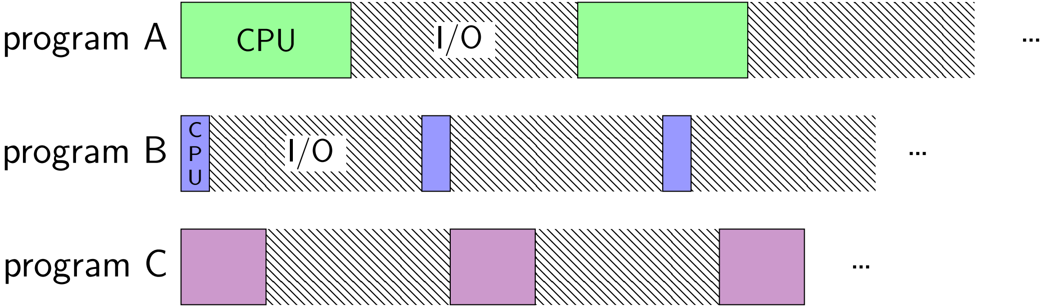
so we want to run the shortest CPU burst first

how do I tell which thread that is?

we'll deal with this problem later

…kinda

alternating I/O and CPU: SJF



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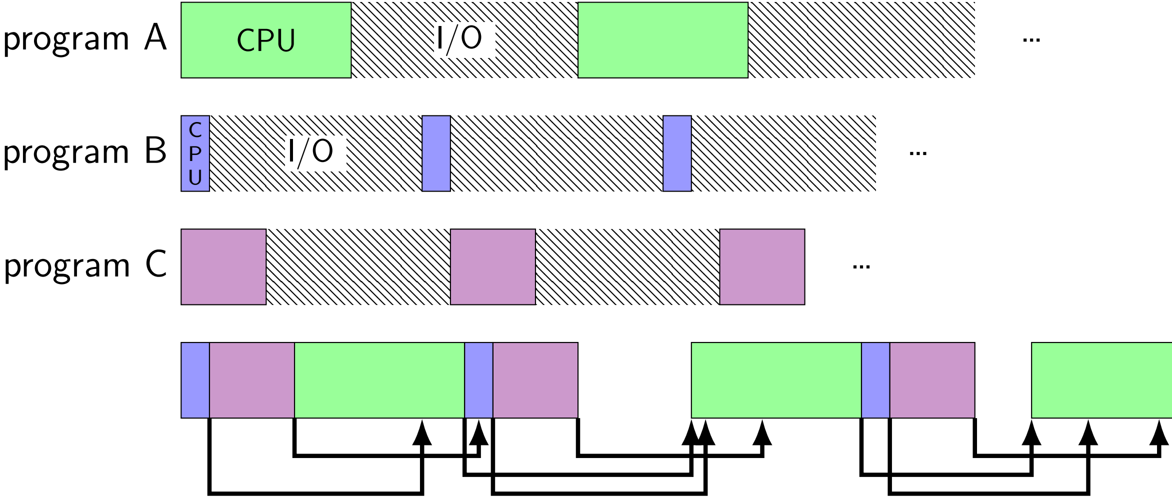

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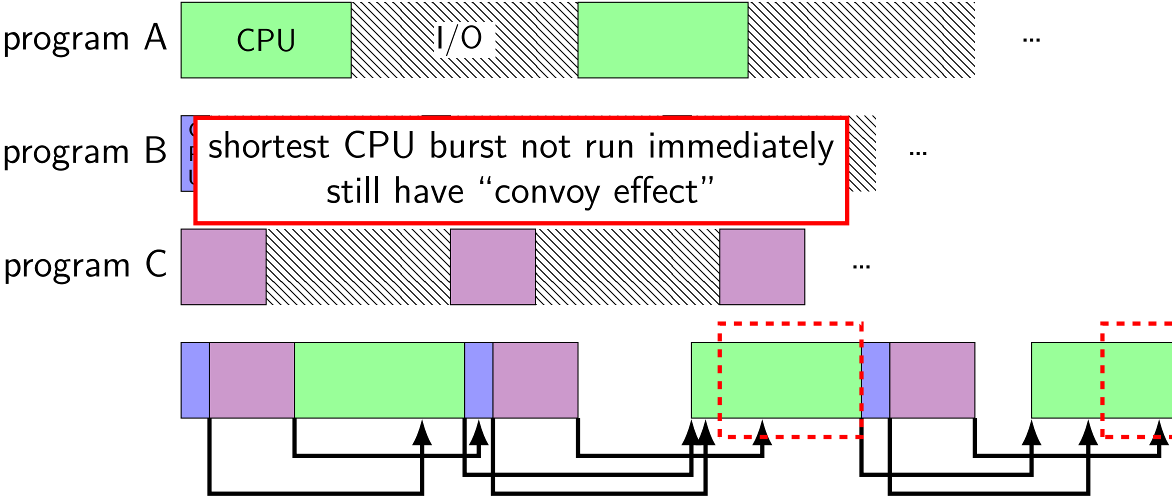


shortest CPU burst not run immediately
still have "convoy effect"

preemption: definition

stopping a running program while it's still runnable

example: FCFS did not do preemption. RR did.

what we need to solve the problem:
'accidentally' ran long task, now need room for short one

adding preemption (1)

what if a long job is running, then a short job interrupts it?

- short job will wait for too long

solution is preemption — reschedule when new job arrives

- new job is shorter — run now!

adding preemption (2)

what if a long job is *almost done* running, then a medium job interrupts it?

- recall: priority = job length
- long job waits for medium job
- …for longer than it would take to finish
- worse than letting long job finish

adding preemption (2)

what if a long job is *almost done* running, then a medium job interrupts it?

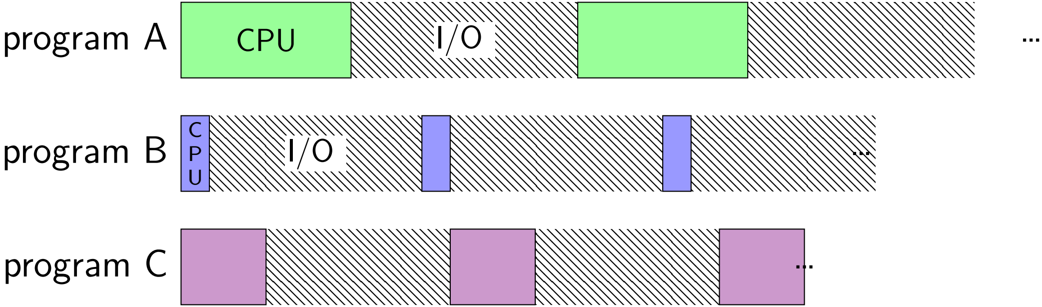
- recall: priority = job length
- long job waits for medium job
- …for longer than it would take to finish
- worse than letting long job finish

solution: priority = remaining time

called shortest *remaining time* first (SRTF)

- prioritize by what's left, not the total

alternating I/O and CPU: SRTF



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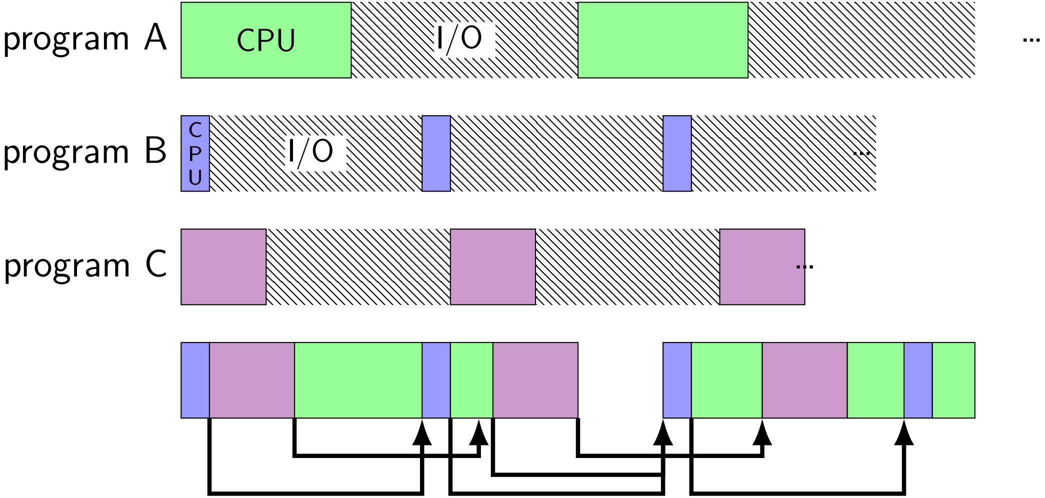

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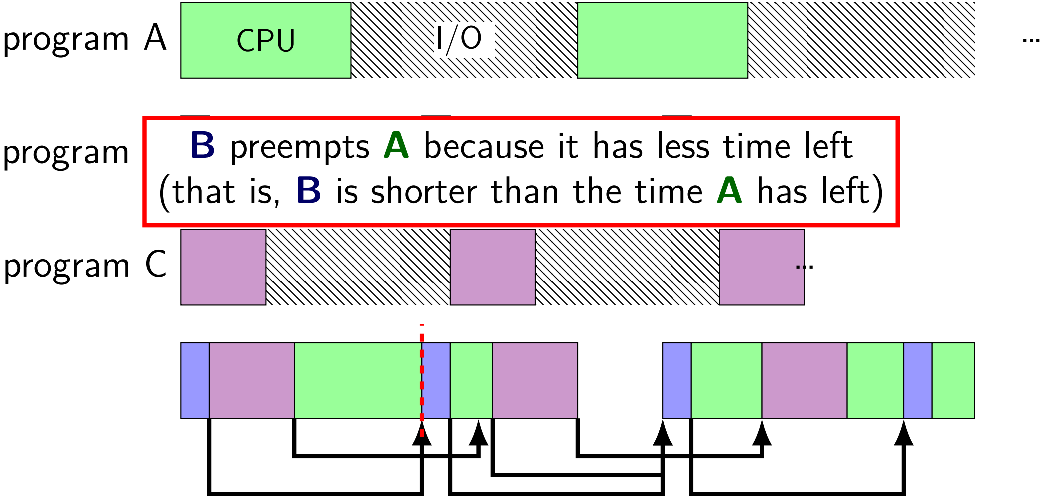
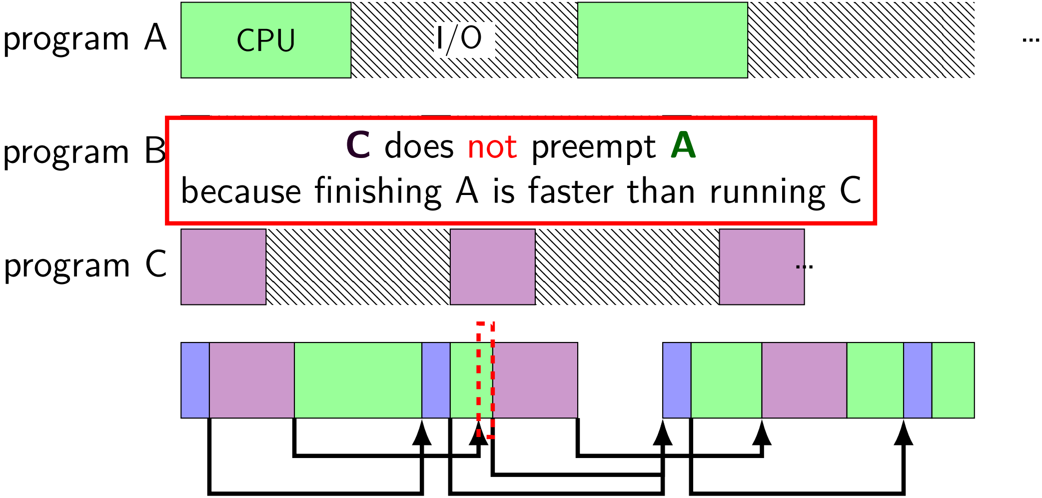


B preempts **A** because it has less time left
(that is, **B** is shorter than the time **A** has left)

alternating I/O and CPU: SRTF



SRTF, SJF are optimal (for turnaround time)

SJF minimizes turnaround time/waiting time
...if you disallow preemption/leaving CPU deliberately idle

SRTF minimizes turnaround time/waiting time
...if you ignore context switch costs

aside on names

we'll use:

SRTF for preemptive algorithm with remaining time

SJF for non-preemptive with total time=remaining time

might see different naming elsewhere/in books, sorry...

knowing job (CPU burst) lengths

seems hard

sometimes you can ask

- common in batch job scheduling systems

and maybe you'll get accurate answers, even

the SRTF problem

want to know CPU burst length

well, how does one figure that out?

the SRTF problem

want to know CPU burst length

well, how does one figure that out?

e.g. not any of these fields

```
uint sz;                        // Size of process memory (bytes)
pde_t* pgdir;                   // Page table
char *kstack;                   // Bottom of kernel stack for this pr
enum procstate state;           // Process state
int pid;                        // Process ID
struct proc *parent;            // Parent process
struct trapframe *tf;           // Trap frame for current syscall
struct context *context;        // swtch() here to run process
void *chan;                     // If non-zero, sleeping on chan
int killed;                     // If non-zero, have been killed
struct file *ofile[NOFILE];     // Open files
struct inode *cwd;              // Current directory
char name[16];                  // Process name (debugging)
```

predicting the future

worst case: need to run the program to figure it out

but heuristics can figure it out
- (read: often works, but no gaurentee)

key observation: CPU bursts now are like CPU bursts later
- intuition: interactive program with lots of I/O tends to stay interactive
- intuition: CPU-heavy program is going to keep using CPU

multi-level feedback queues

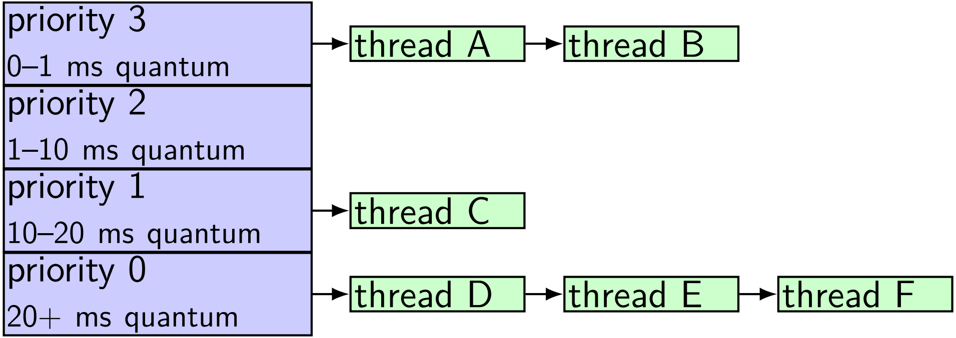
classic strategy based on priority scheduling

combines update time estimates and running shorter times first

key idea: current priority $\approx$ current time estimate

small(ish) number of time estimate “buckets”

multi-level feedback queues: setup



goal: place processes at priority level based on CPU burst time

- just a few priority levels — can't guess CPU burst precisely anyways

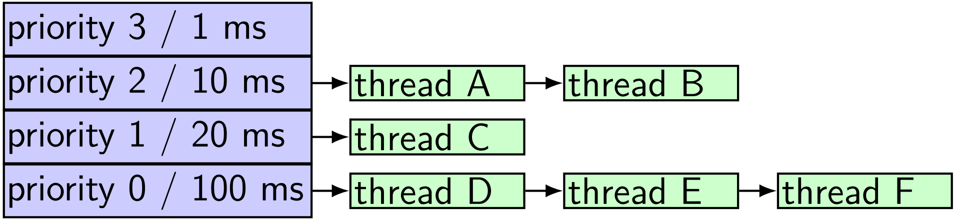
dynamically adjust priorities based on observed CPU burst times

priority level → allowed/expected time quantum

- use more than 1ms at priority 3? — you shouldn't be there
- use less than 1ms at priority 0? — you shouldn't be there

taking advantage of history

idea: priority = CPU burst length



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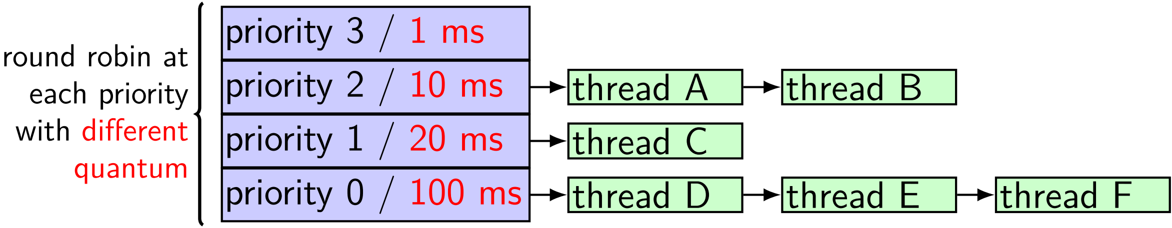

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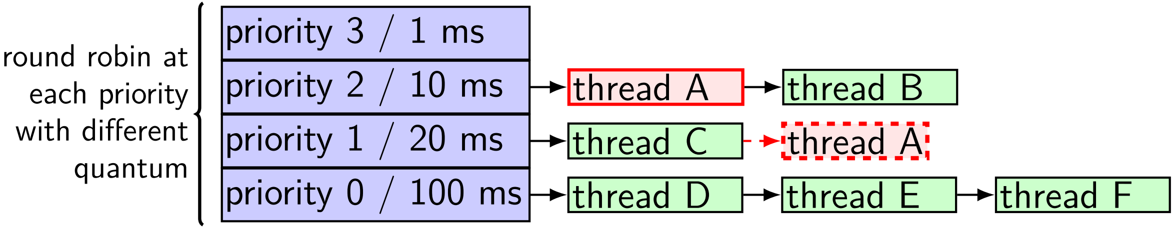

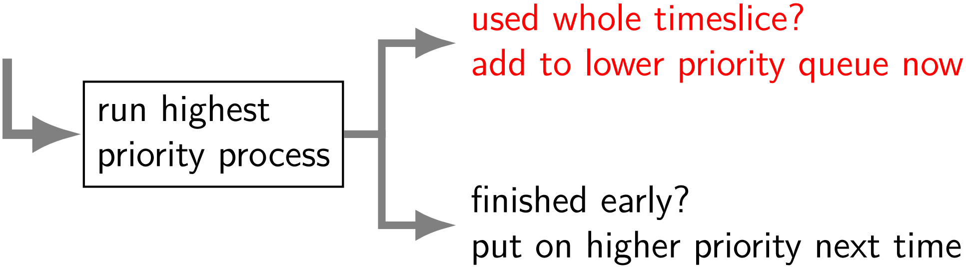

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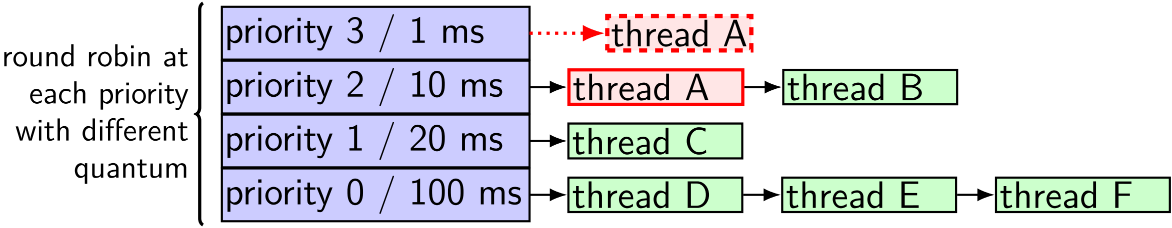
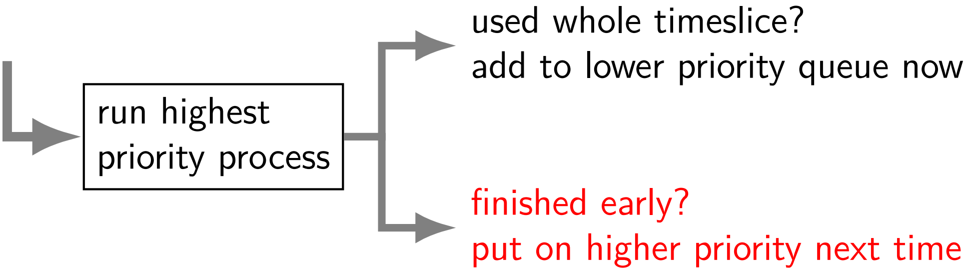




multi-level feedback queue idea

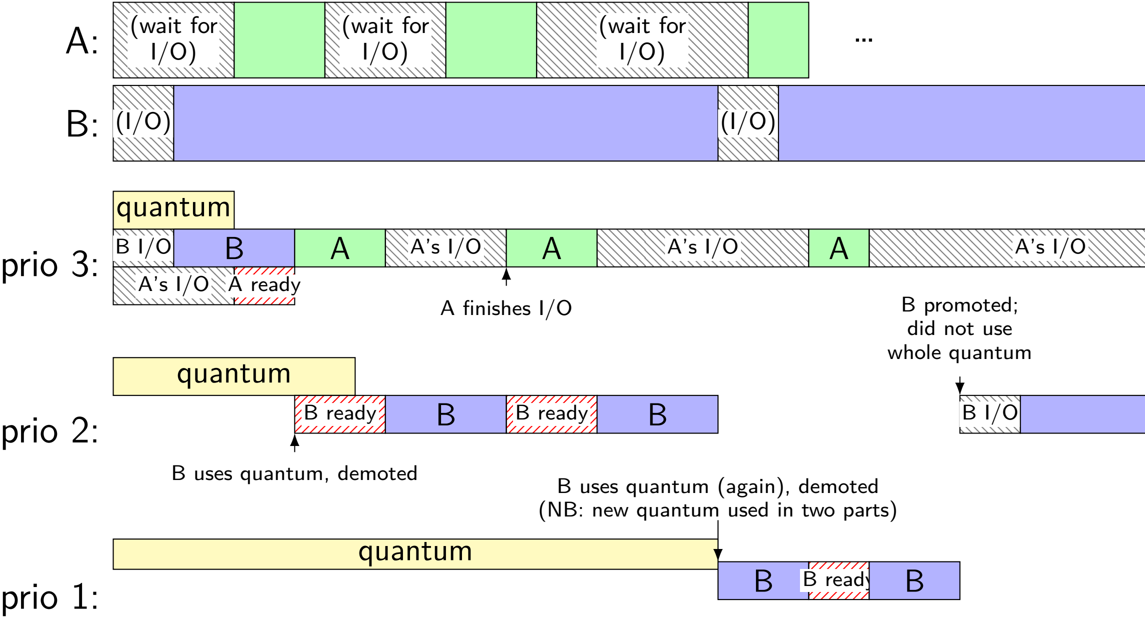
higher priority = shorter time quantum (before interrupted)

adjust priority *and* timeslice based on last timeslice

intuition: thread always uses same CPU burst length?
ends up at "right" priority

- rises up to queue with quantum just shorter than it's burst
- then goes down to next queue, then back up, then down, then up, etc.

MLFQ example



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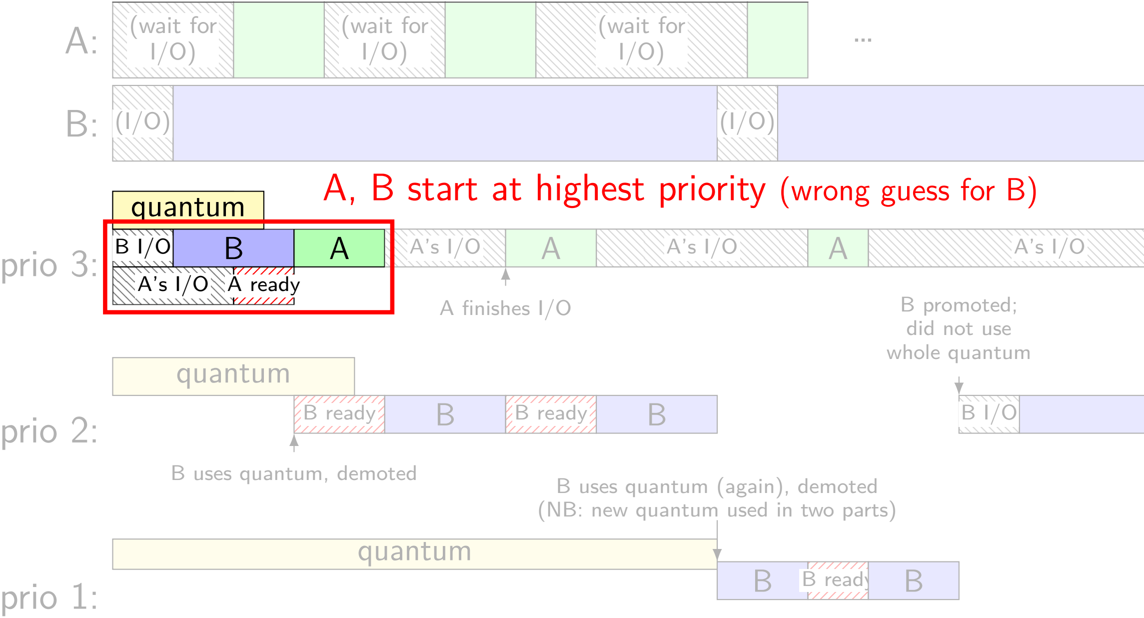

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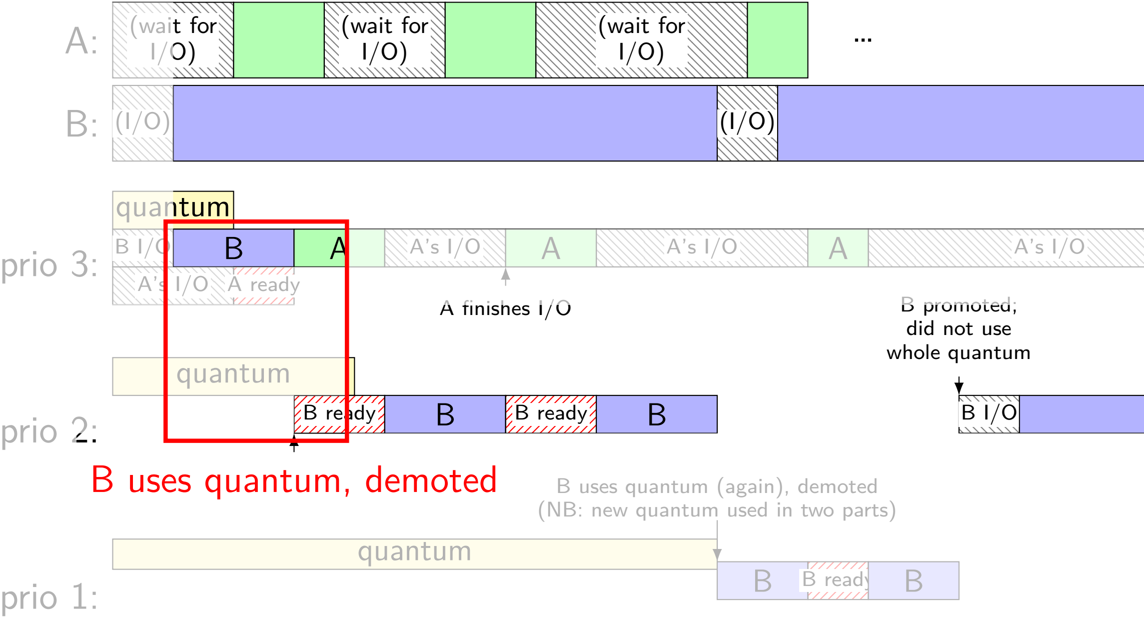

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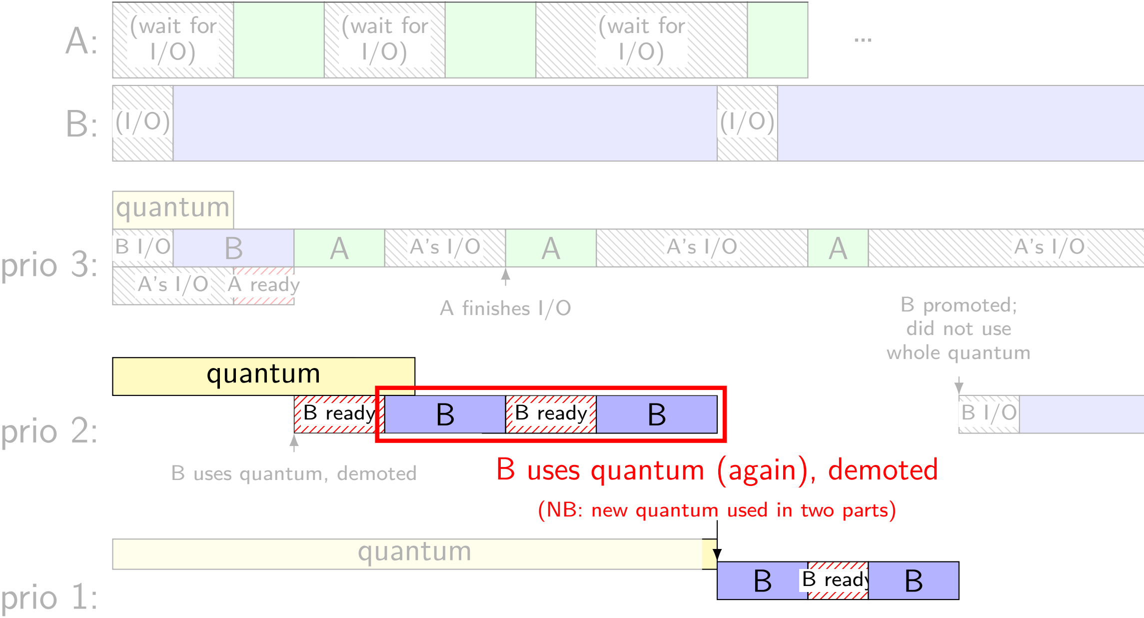

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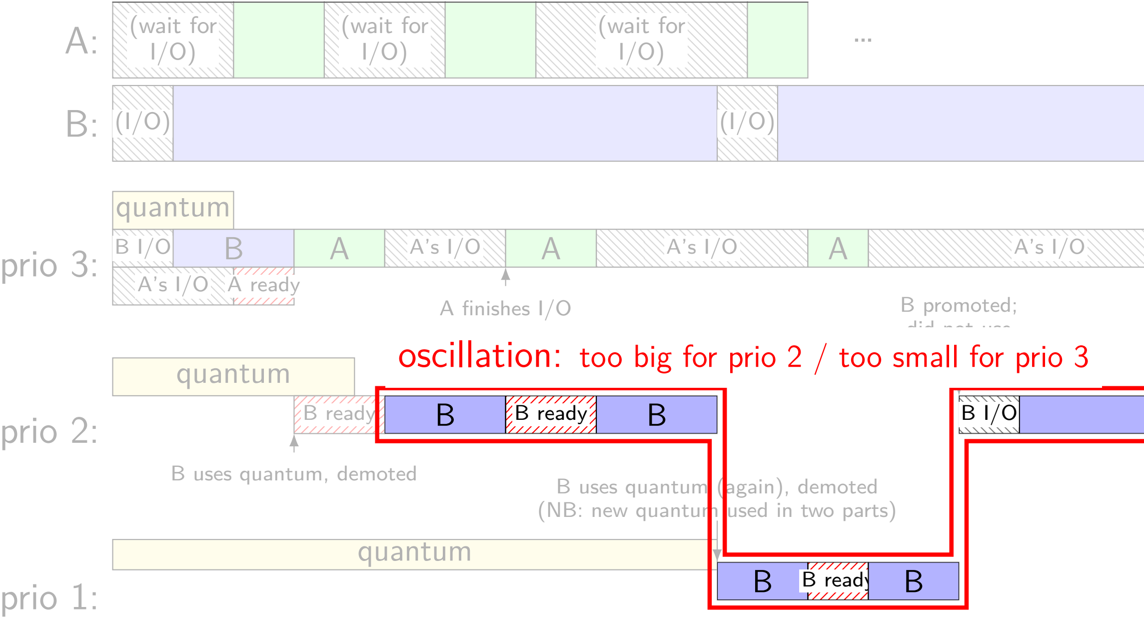

cheating multi-level feedback queuing

algorithm: don't use entire time quantum? priority increases

getting all the CPU:

```
while (true) {
  useCpuForALittleLessThanMinimumTimeQuantum();
  yieldCpu();
}
```

multi-level feedback queuing and fairness

suppose we are running several programs:

A. one very long computation that doesn't need any I/O
B1 through B1000. 1000 programs processing data on disk
C. one interactive program

how much time will A get?

multi-level feedback queuing and fairness

suppose we are running several programs:

- A. one very long computation that doesn't need any I/O
- B1 through B1000. 1000 programs processing data on disk
- C. one interactive program

how much time will A get?

almost none — starvation

- intuition: the B programs have higher priority than A
- because it has smaller CPU bursts

conflicting goals for interactivity heuristics

efficiency

- avoid scanning all threads every few milliseconds

figure out new programs quickly

adapt to changes/spikes in program behavior

avoid pathological behavior

- starvation, hanging when new compute-intensive program starts, etc.

exercise: how to handle each of these well?

- what does MLFQ do well?

Linux's Completely Fair Scheduler (CFS)

Linux's default scheduler is a proportional share scheduler…

…without randomization (consistent)

…with $O(\log N)$ scheduling decision

(handles many threads/processes)

…which favors interactive programs

…which adjusts timeslices dynamically

shorter timeslices if many things to run

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CFS: tracking runtime

each thread has a *virtual runtime* ($\sim$ how long it's run)

incremented when run based how long it runs

scheduling decision: run thread with lowest virtual runtime

- data structure: balanced tree

CFS: tracking runtime

each thread has a *virtual runtime* ($\sim$ how long it's run)

incremented when run based how long it runs

more/less important thread? multiply adjustments by factor

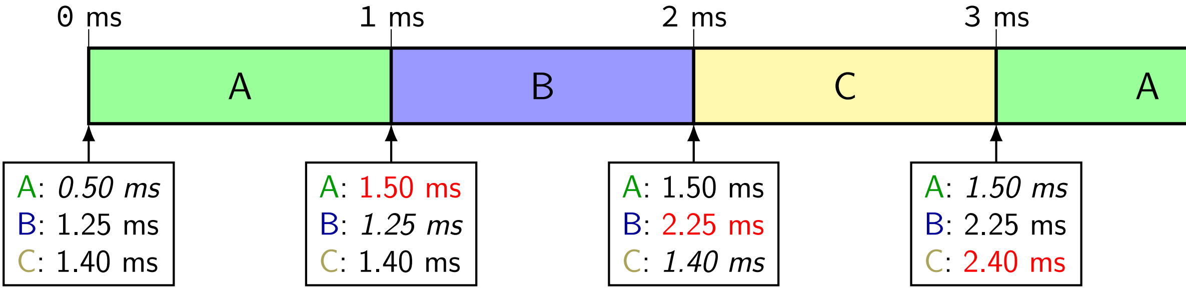
adjustments for threads that are new or were sleeping

- too big an advantage to start at runtime `0`

scheduling decision: run thread with lowest virtual runtime

- data structure: balanced tree

virtual time, always ready, 1 ms quantum



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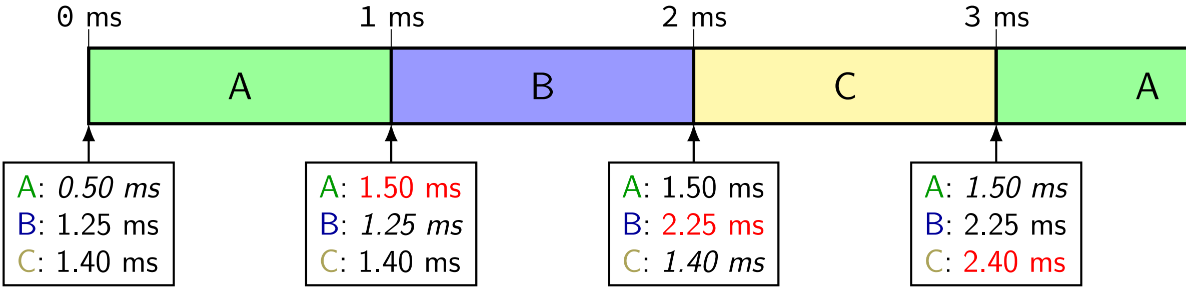
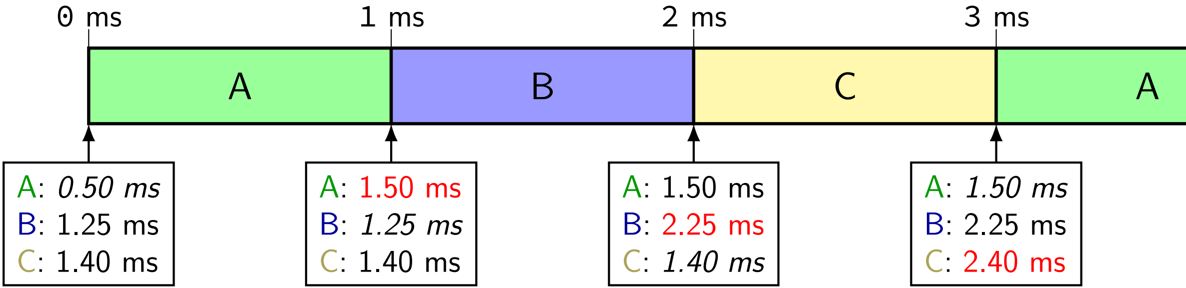


at each time:

update current thread's time

run thread with lowest total time

virtual time, always ready, 1 ms quantum



at each time:

update current thread's time

run thread with lowest total time

same effect as round robin

if everyone uses whole quantum

what about threads waiting for I/O, ...?

should be advantage for processes not using the CPU as much

- haven't used CPU for a while — deserve priority now
- ...but don't want to let them hog the CPU

Linux solution: newly ready task time = max of

- its prior virtual time
- a little less than minimum virtual time (of already ready tasks)

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Linux solution: newly ready task time = max of

- its prior virtual time
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not runnable briefly? still get your share of CPU

- (catch up from prior virtual time)

not runnable for a while? get bounded advantage

A doesn't use whole time...

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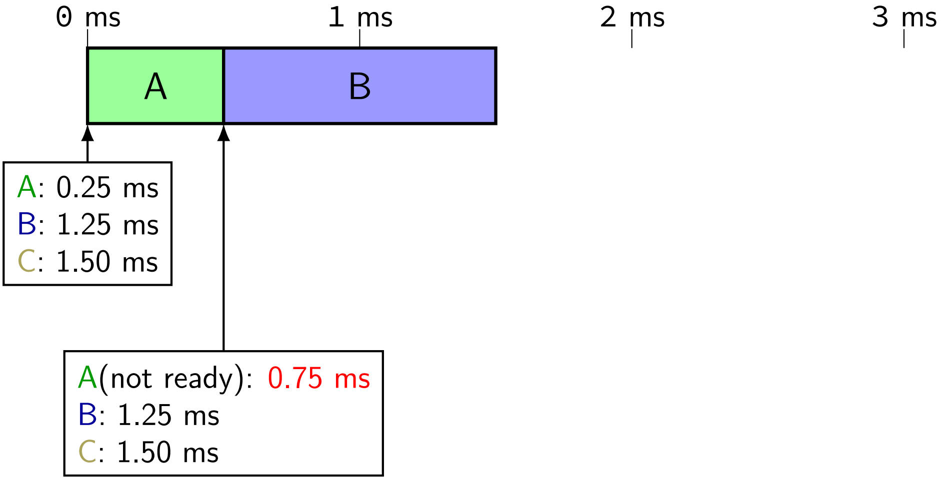

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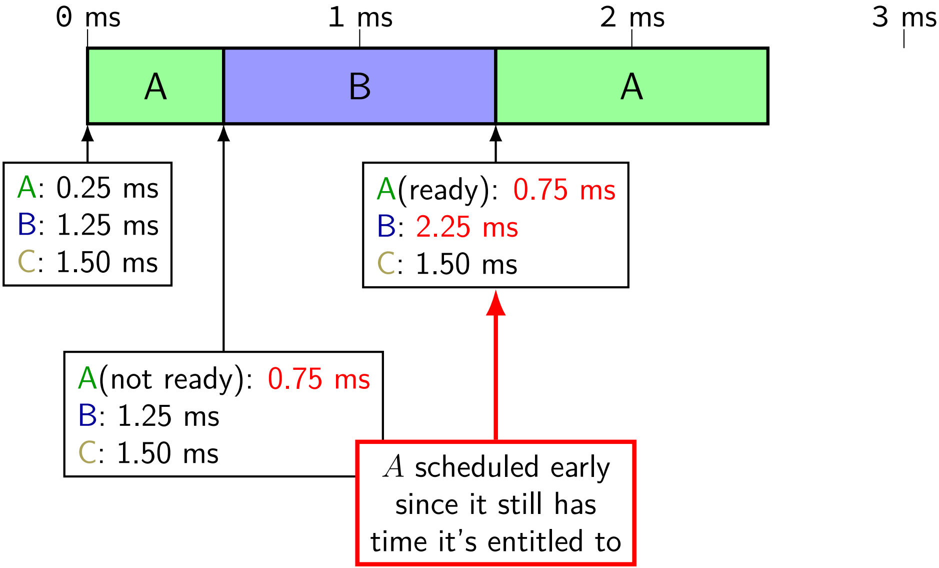

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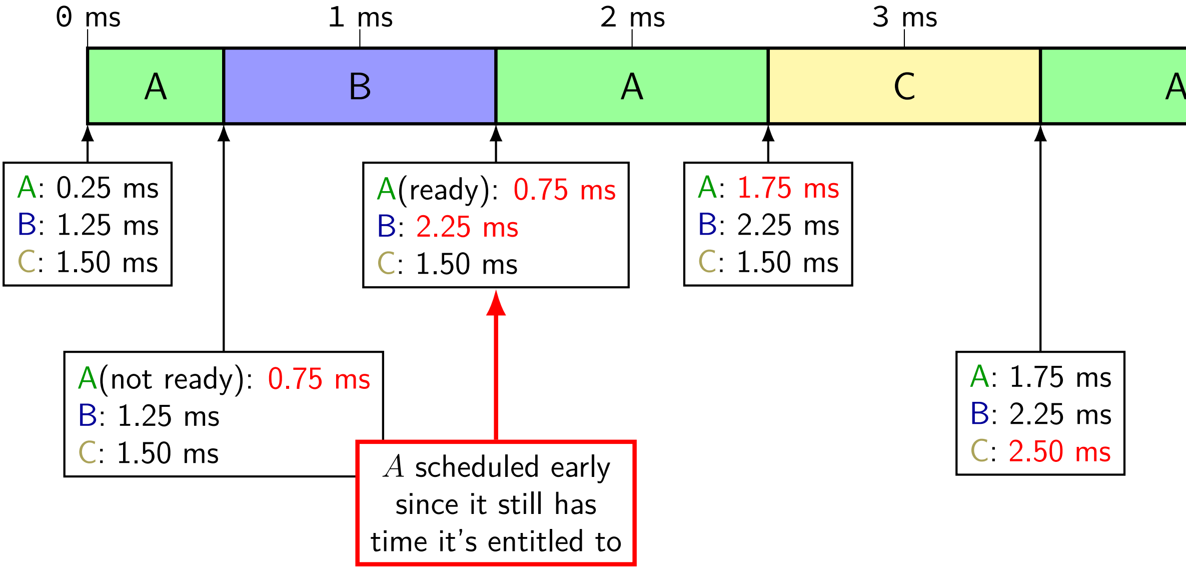
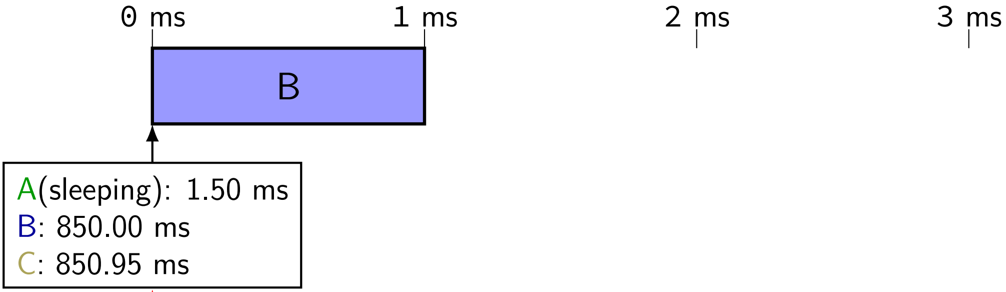


A's long sleep...

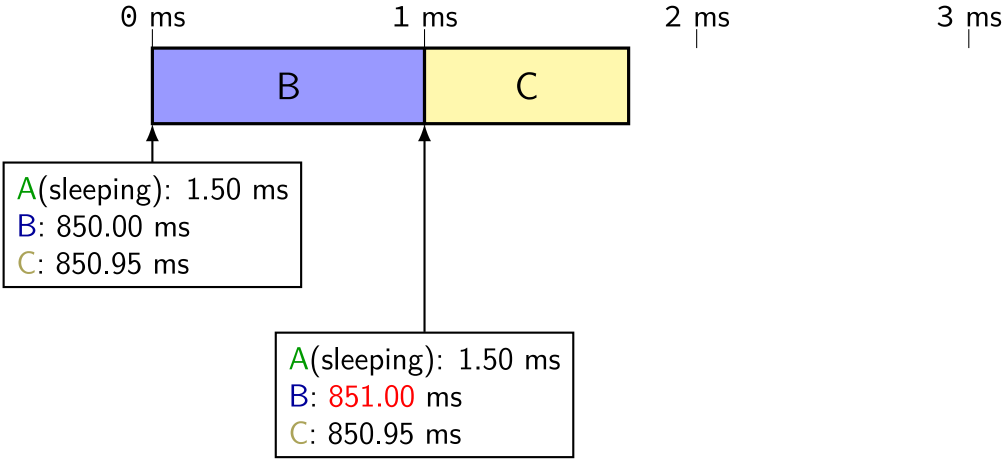
0 ms | 1 ms | 2 ms | 3 ms

A's long sleep...



scenario setup:
A started waiting for I/O a while ago
B, C been using CPU

A's long sleep...



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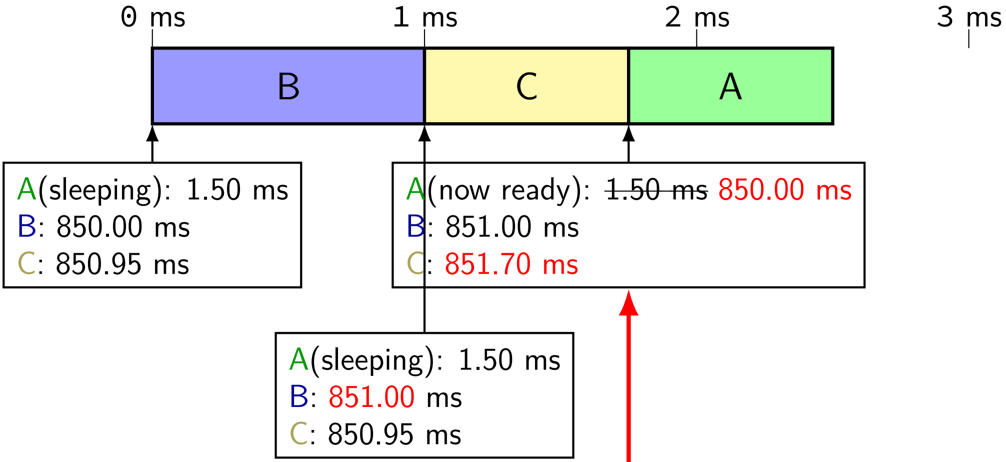
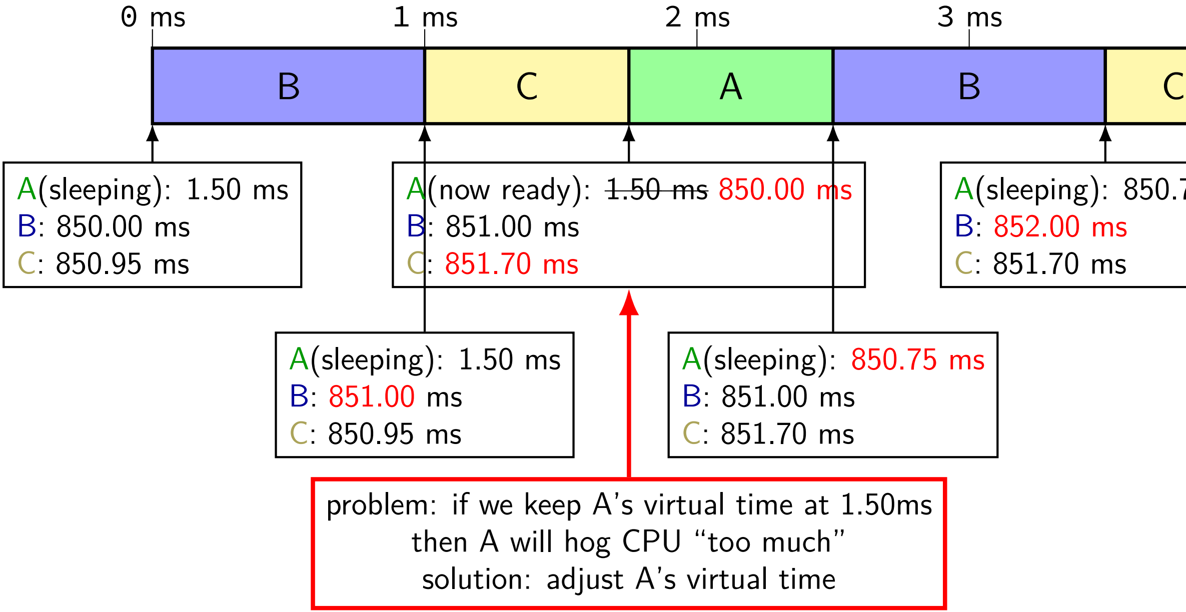


problem: if we keep A's virtual time at 1.50ms
then A will hog CPU "too much"
solution: adjust A's virtual time

A's long sleep...



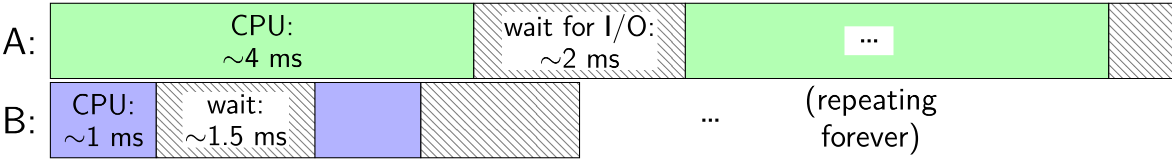
handling *proportional* sharing

solution: multiply used time by weight

e.g. 1 ms of CPU time costs process 2 ms of virtual time

higher weight $\implies$ process less favored to run

CFS exercise (0)



suppose programs A, B with alternating CPU + I/O as above

with CFS (and equal weights) and **no adjustments to virtual time for programs waking up from sleep**, **about** what portion of CPU does program A get?

exercise solution

if A, B, were running alone, could get at most 1/2 the CPU

B can't use that much time

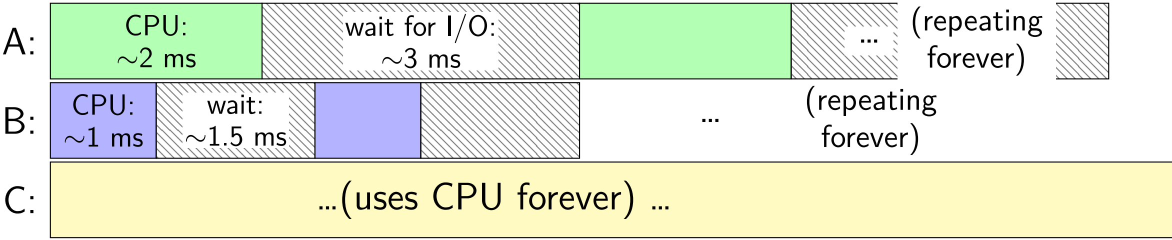
so B will run 2/5ths of the time (the most it can)

so B will almost always have lower virtual time than A

A will get the remaining about 3/5ths

exception: time both A and B are both doing I/O

CFS exercise (1)



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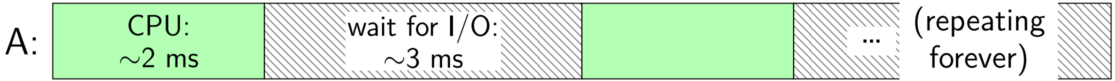
CFS exercise: maximum time for A



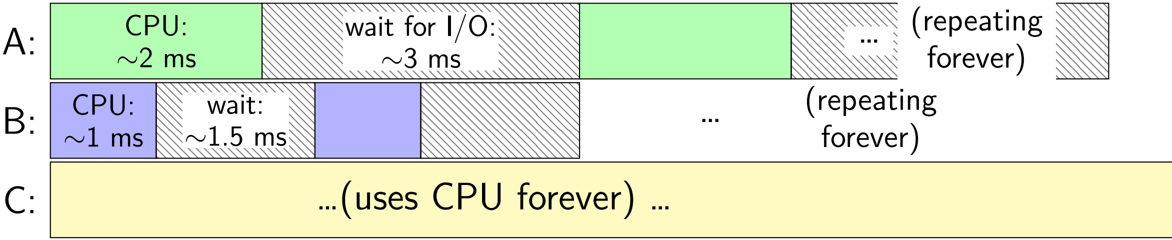
A running alone: A runs 2/5ths of the time

A, B, C sharing fairly: each runs 1/3rd of the time
- if A used more than 1/3rd of the time...
- then it would have a higher virtual time...
- and B and C would catch up
- (and same for B or C)

result: A runs at most 1/3rd of the time...

unless B can't use its full share because of I/O
- (because of being interrupted by A too much?)

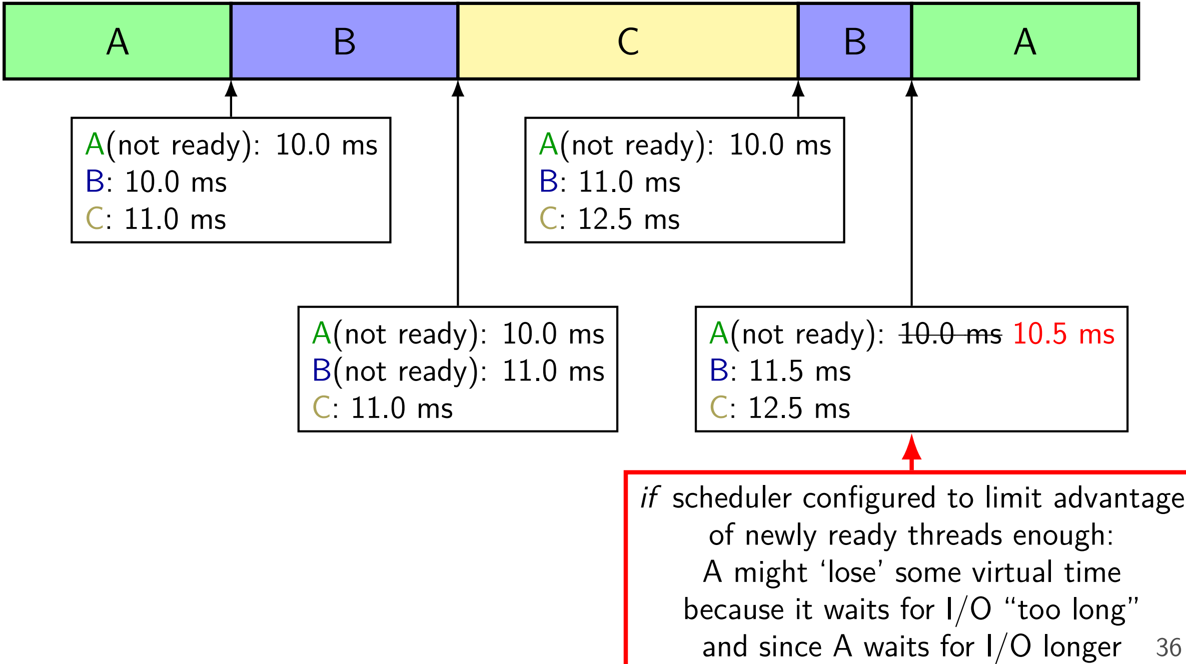
CFS exercise (2)



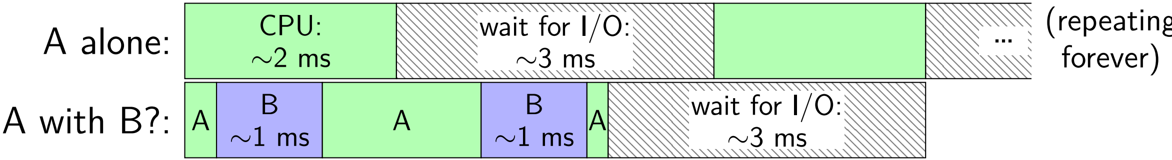
suppose we add adjustments to virtual time for waking up from sleep

expected direction of change in how much compute time A gets?

CFS exercise: A disadvantage from sleep



CFS exercise: A interrupted by B?



A interrupted by B a bunch sometimes...?

might not start I/O as often

might not be able to run 1/3rd of the time

e.g. sometimes $2/(2+2+3) \approx 28\%$ of CPU

which scheduler should I choose?

I care about...

CPU throughput: first-come first-serve

average response time: SRTF approximation

I/O throughput: SRTF approximation

fairness — medium-term CPU usage: something like Linux CFS

fairness — wait time: something like RR

real-world deadlines: earliest deadline first or similar

favoring certain users: strict priority

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a note on multiprocessors

what about multicore?

extra considerations:

want two processors to schedule without waiting for each other

want to keep process on same processor (better for cache)

what process to preempt when three+ choices?

4.4BSD scheduler

4.4BSD / FreeBSD pre-2003 scheduler was a variation on MLFQ

64 priority levels, 100 ms quantum

same quantum at every priority

priorities adjusted periodically

- in retrospect not good for performance — iterate through all threads
- part of why FreeBSD stopped using this scheduler

priority of threads that spent a lot of time waiting for I/O increased

priority of threads that used a lot of CPU time decreased

real-time

so far: “best effort” scheduling

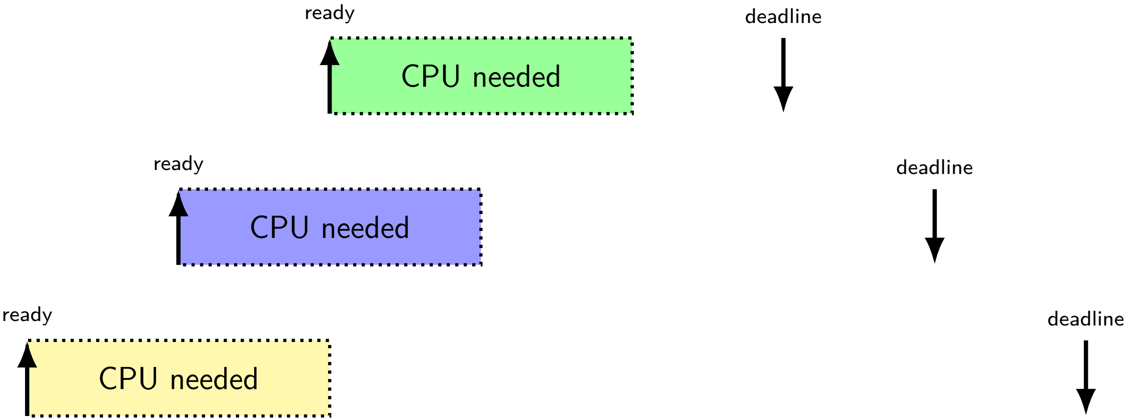
- best possible (by some metrics) given some work

alternate model: need gaurnetees

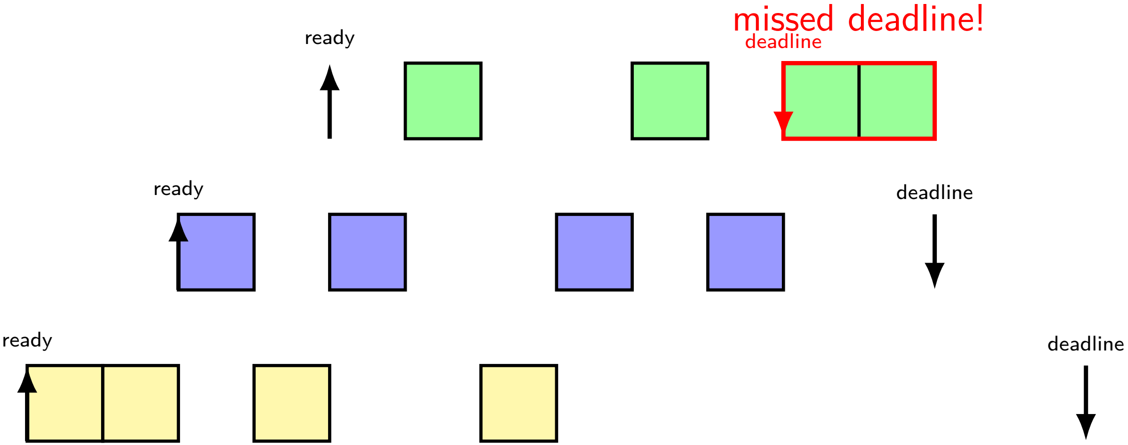
deadlines imposed by real-world

- process audio with 1ms delay
- computer-controlled cutting machines (stop motor at right time)
- car brake+engine control computer
- …

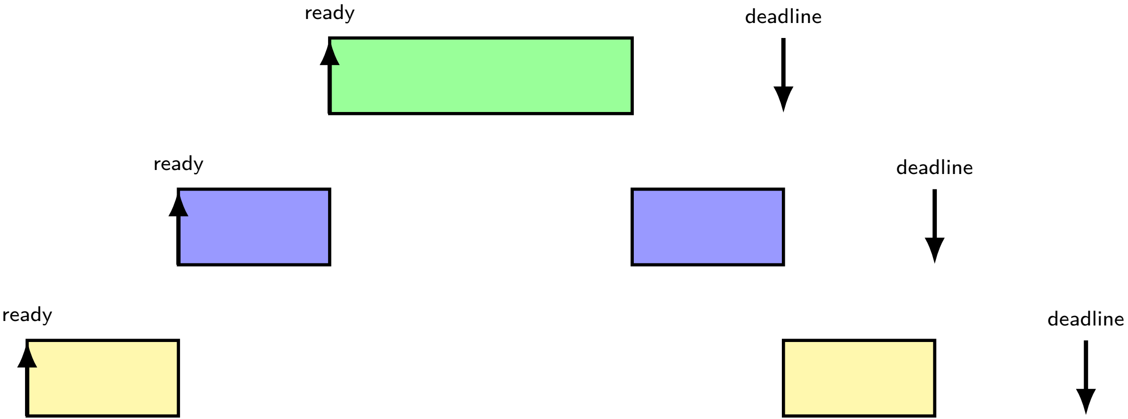
real time example: CPU + deadlines



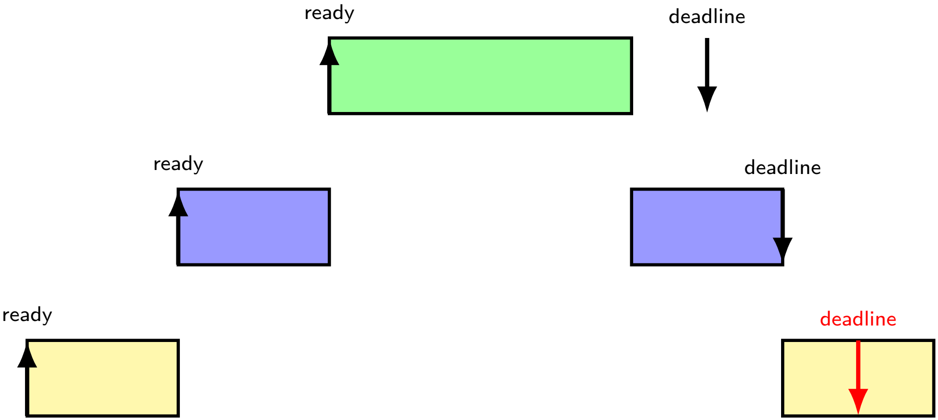
example with RR



earliest deadline first



impossible deadlines



no way to meet all deadlines!

admission control

given *worst-case* runtimes, start times, deadlines, scheduling algorithm,…

figure out whether it's possible to gaurentee meeting deadlines

- details on how — not this course (probably)

if not, then

- change something so they can?
- don't ship that device?
- tell someone at least?

earliest deadline first and...

earliest deadline first does *not* (even when deadlines met)

- minimize response time
- maximize throughput
- maximize fairness

exercise: give an example

other real-time schedulers

typical real time systems: *periodic tasks with deadlines*

"*rate monotonic*"

commonly approximate EDF with lower period = higher priority

easier to implement than true EDF

well-known method to determine if schedule is admissible

= won't exceed deadline (under some assumptions)

MLFQ variations

version of MLFQ I described is in Anderson-Dahlin

problems:

starvation

worse than with real SRTF — based on *guess*, not real remaining time

oscillation not great for predictability

variation to prevent starvation

Apraci-Dusseau presents version of MLFQ w/o starvation

two changes:

don't increase priority when whole quantum not used

- instead keep the same — more stable

periodically increase priority of *all threads*

- allow compute-heavy threads to run a little
- still deals with thread's behavior changing over time
- replaces finer-grained upward adjustments

FreeBSD scheduler

current default FreeBSD scheduler based on MLFQ idea

...but: time quantums don't depend on priority

computes *interactivity score* $\sim \dfrac{\text{I/O wait}}{\text{I/O wait} + \text{runtime}}$

note: deliberately not estimating remaining time

(using "recent" history of thread)

thread priorities set based on interactivity score

aside: measuring fairness (1)

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problem: what about programs waiting for I/O?

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don't consider what happens when program waiting for I/O

answer 2:
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most fair

least fair

CFS quantum lengths goals

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avoid too-frequent context switching

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quantum $\approx$ max(fixed window / num processes, minimum quantum)

CFS: avoiding excessive context switching

conflicting goals:

schedule newly ready tasks immediately

(assuming less virtual time than current task)

avoid excessive context switches

CFS rule:
if virtual time of new task $<$ current virtual time by threshold

default threshold: 1 ms

(otherwise, wait until quantum is done)