Scheduling 1: Concepts and Classic Policies

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CS 162: Operating Systems and System Programming

Lecture 11

https://inst.eecs.berkeley.edu/~cs162/su20

Read: A&D 7.1, OSTEP Ch 7

Recall: "Too Much Milk"

- Analogy between problems in OS and problems in real life
- Example: People need to coordinate:

Time	Person A	Person B
3:00	Look in Fridge. Out of milk	
3:05	Leave for store	
3:10	Arrive at store	Look in Fridge. Out of milk
3:15	Buy milk	Leave for store
3:20	Arrive home, put milk away	Arrive at store
3:25		Buy milk
3:30		Arrive home, put milk away

Recall: "Too Much Milk" Solution

This is a correct solution!

Thread A

```
leave note A
while (note B) {
  do nothing
}
if (noMilk) {
  buy milk
}
remove note A
```

Thread B

```
leave note B
if (noNote A) {
  if (noMilk) {
    buy milk
  }
}
remove note B
```

Recall: Single-Core Lock Implementation

- Key idea: maintain a lock variable (**`value`**) and disable interrupts only during operations on that variable

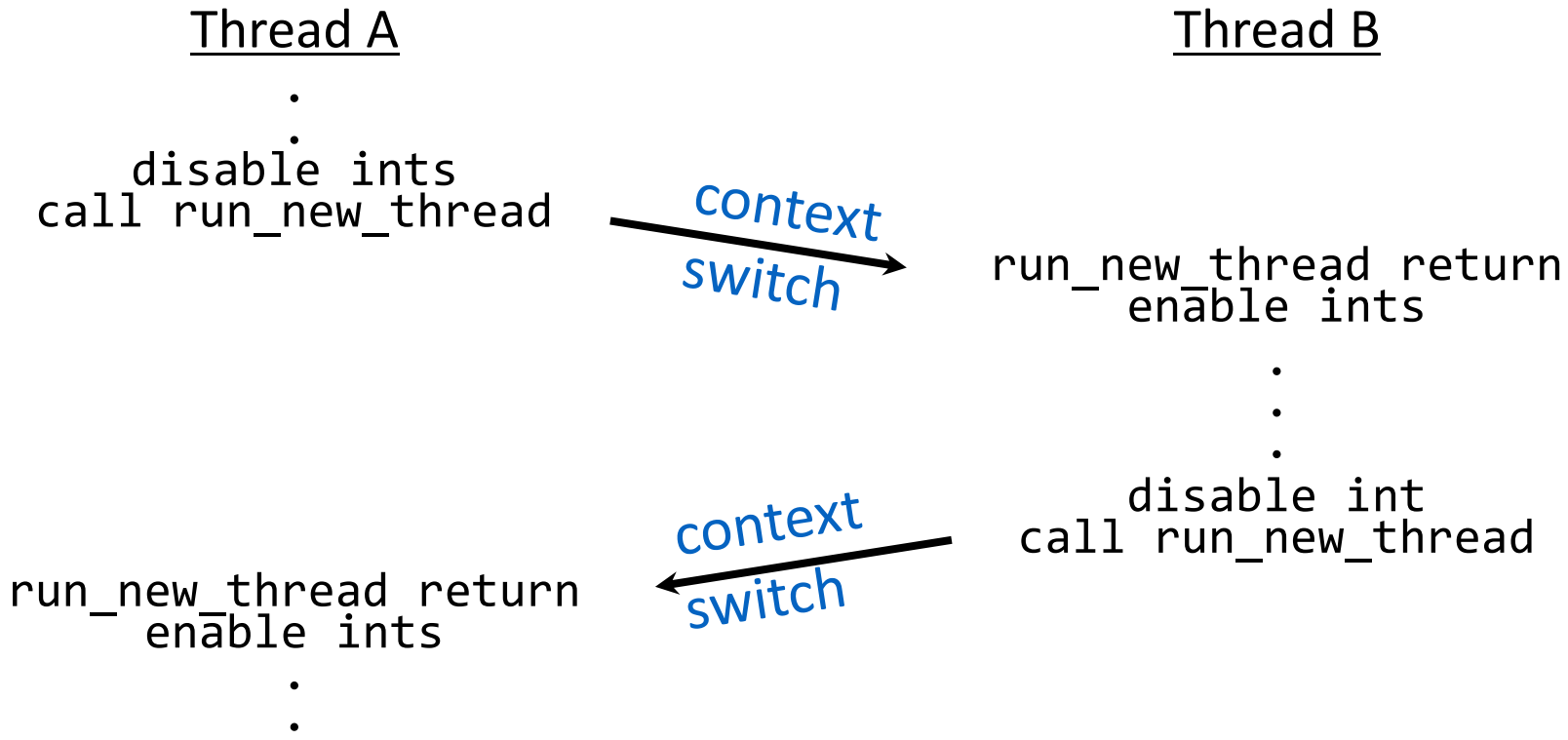
```
int value = FREE;

Acquire() {
  disable interrupts;
  if (value == BUSY) {
    put thread on wait queue;
    run_new_thread();
    // Enable interrupts?
  } else {
    value = BUSY;
  }
  enable interrupts;
}
```

```
Release() {
  disable interrupts;
  if (anyone on wait queue) {
    take thread off wait queue;
    Place on ready queue;
  } else {
    value = FREE;
  }
  enable interrupts;
}
```

Recall: Re-enable Interrupts when Waiting

- In scheduler, since interrupts are disabled when switching threads:
  - Responsibility of the next thread to re-enable interrupts
  - When the sleeping thread wakes up, returns to acquire and re-enables interrupts



Recall: Spinlock Implementation

- Spinlock implementation:

```
int value = 0; // Free

Acquire() {
   while (test&set(value)) {}; // spin while busy
}

Release() {
   value = 0;                  // atomic store
}
```

- Spinlock doesn't put the calling thread to sleep --- it just busy waits

Recall: Multi-Core Lock Implementation

- Can we build test&set locks without busy-waiting?
  - Can't entirely, but can minimize!
  - Idea: only busy-wait to atomically *check* lock value

```
int guard = 0;
int value = FREE;

Acquire() {
   // Short busy-wait time
   while (test&set(guard));
   if (value == BUSY) {
      put thread on wait queue;
      run_new_thread() & guard = 0;
   } else {
      value = BUSY;
      guard = 0;
   }
}
```

```
Release() {
   // Short busy-wait time
   while (test&set(guard));
   if anyone on wait queue {
      take thread off wait queue
      Place on ready queue;
   } else {
      value = FREE;
   }
   guard = 0;
```

- Note: sleep has to be sure to reset the guard variable
  - Why can't we do it just before or just after the sleep?

Recall: Bootstrapping a Spinlock

```
SpinLock guard = FREE;
int value = FREE;

Acquire() {
   // Short busy-wait time
   guard.Acquire();
   if (value == BUSY) {
      put thread on wait queue;
      run_new_thread() & guard.Release();
   } else {
      value = BUSY;
      guard.Release();
   }
}
```

```
Release() {
   // Short busy-wait time
   guard.Acquire();
   if anyone on wait queue {
      take thread off wait queue
      Place on ready queue;
   } else {
      value = FREE;
   }
   guard.Release();
```

Recall: `test&test&set`

- A better spinlock solution:

```
int mylock = 0; // Free

Acquire() {
   do {
     while(mylock);   // Wait until might be free
   } while(test&set(&mylock)); // exit if get lock
}


Release() {
   mylock = 0;
}
```

- Explanation:
  - Wait until lock might be free (only reading – stays in cache)
  - Then, try to grab lock with `test&set`
  - Repeat if fail to actually get lock
- Busy-Waiting: no longer impacts other processors!

Recall: Fast Userspace Mutex

```
#include <linux/futex.h>
#include <sys/time.h>

int futex(int *uaddr, int futex_op, int val,
      const struct timespec *timeout );
```

- `uaddr` points to a 32-bit value in user space
- `futex_op`
  - `FUTEX_WAIT` – if `val == *uaddr` sleep till `FUTEX_WAIT`
    - ***Atomic*** check that condition still holds
  - `FUTEX_WAKE` – wake up at most `val` waiting threads
  - `FUTEX_FD`, `FUTEX_WAKE_OP`, `FUTEX_CMP_REQUEUE`
- `timeout`
  - ptr to a *timespec* structure that specifies a timeout for the op

Recall: Userspace Locks with `futex`

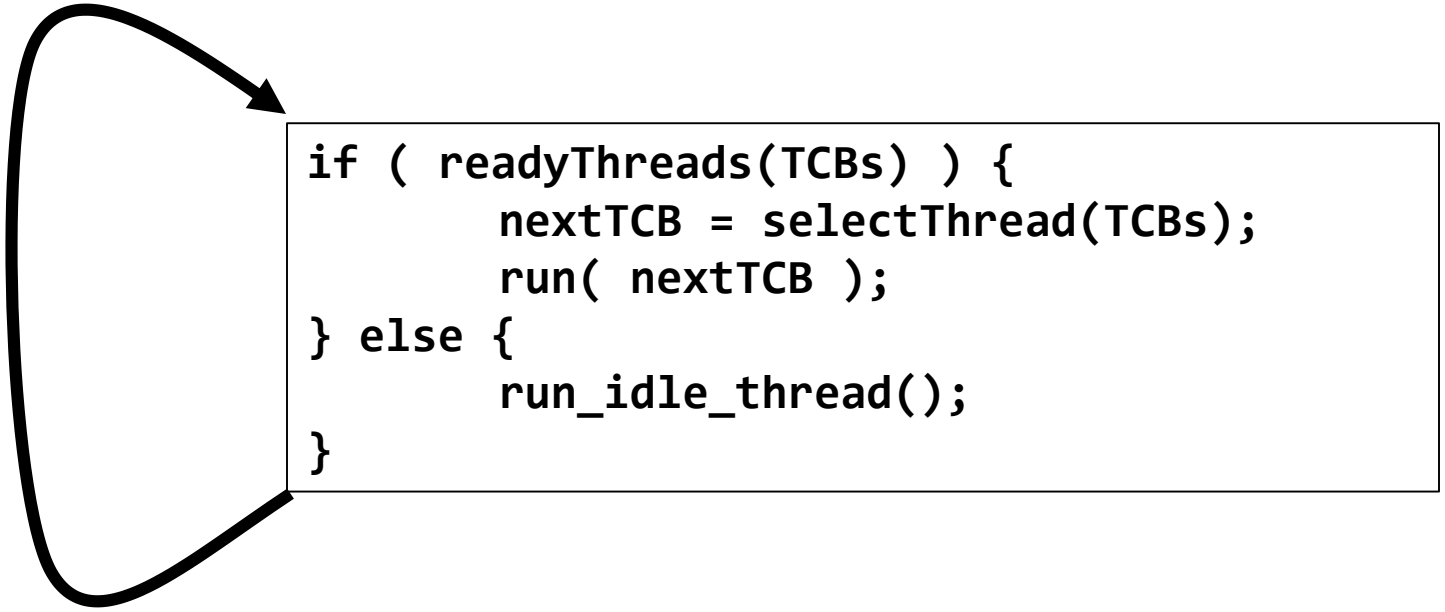
```
int value = 0; // free
bool maybe_waiters = false;

Acquire() {
   while (test&set(value)) {
      maybe_waiters = true;
      futex(&value, FUTEX_WAIT, 1);
      // futex: sleep if lock is acquired
      maybe_waiters = true;
   }
}
```

```
Release() {
   value = 0;
   if (maybe_waiters) {
      maybe_waiters = false;
      futex(&value, FUTEX_WAKE, 1);
      // futex: wake up a sleeping thread
   }
}
```

- This is syscall-free in the uncontended case
  - Temporarily falls back to syscalls if multiple waiters, or concurrent acquire/release
- But it can be considerably optimized!
  - See "Futexes are Tricky" by Ulrich Drepper

Today: CPU Scheduling



```
if ( readyThreads(TCBs) ) {
        nextTCB = selectThread(TCBs);
        run( nextTCB );
} else {
        run_idle_thread();
}
```

- Scheduler decides: Which thread should run on the CPU next?

Scheduling Opportunities

- Every “yield”
- Every timer tick (interrupt)

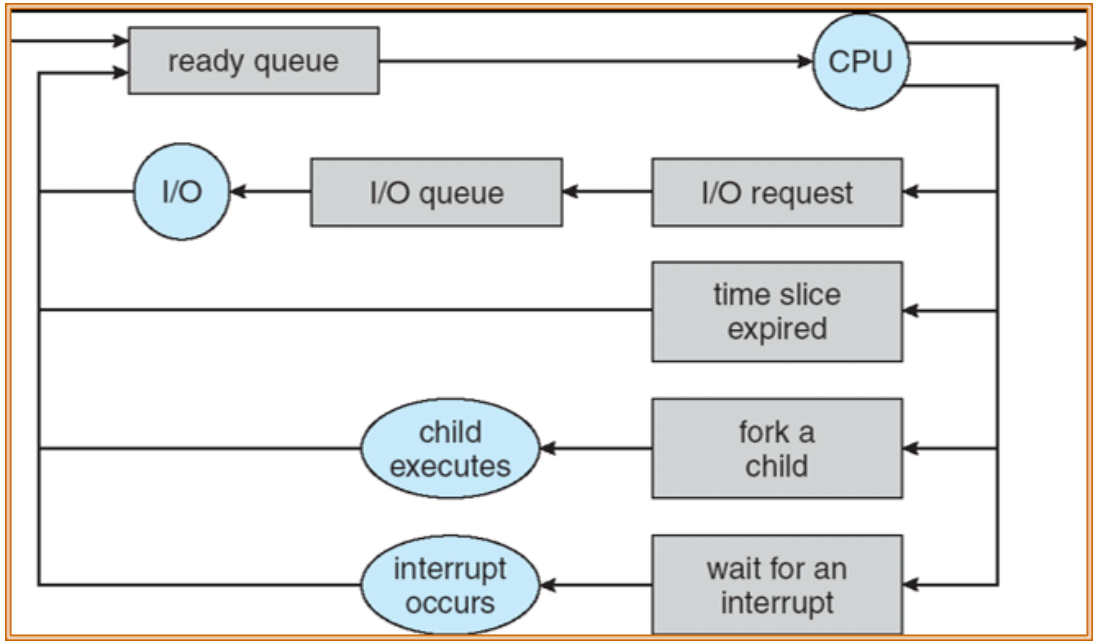
- But also:
  - Every syscall
  - Every interrupt (even if not due to timer)
  - Whenever you enter the kernel, for any reason…

- The kernel could switch the running thread at any of these times!

Broader Take on Scheduling

- Scheduling: deciding which threads are given access to resources from moment to moment
  - Often, we think in terms of CPU time, but could also think about access to resources like network BW or disk access

Scheduling: All About Queues



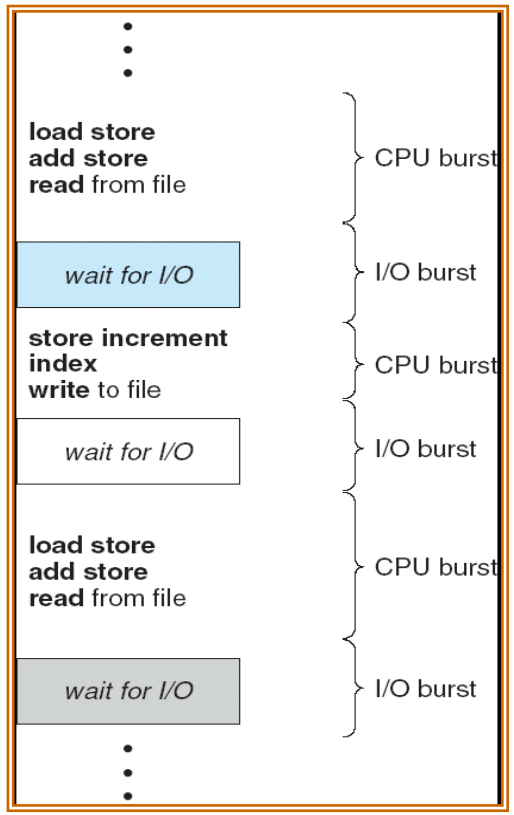
Useful formulation of scheduling: How is the OS to decide which of several tasks to take off a queue?

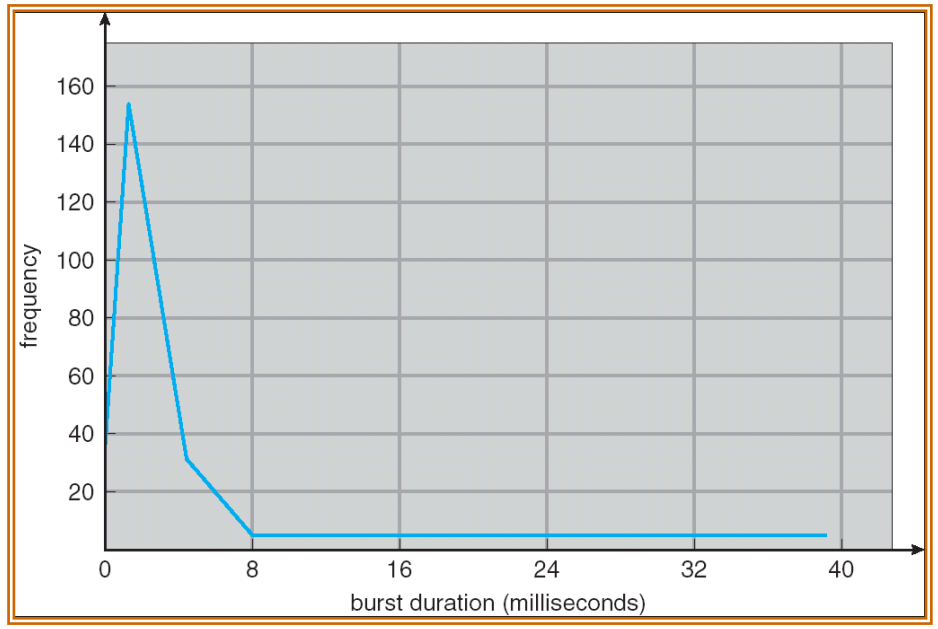
Scheduling: All About Trade-Offs

- Individuals care about getting their task done quickly
- System cares about overall efficiency
  - Utilize multiple HW resources well, low overhead, …
- Huge variation in job characteristics
- Fairness???

- What is our utility function?

CPU and I/O Bursts





- Programs alternate between bursts of CPU, I/O activity
- Scheduler: Which thread (CPU burst) to run next?
- **Interactive programs vs. Compute Bound vs. Streaming**

Evaluating Schedulers

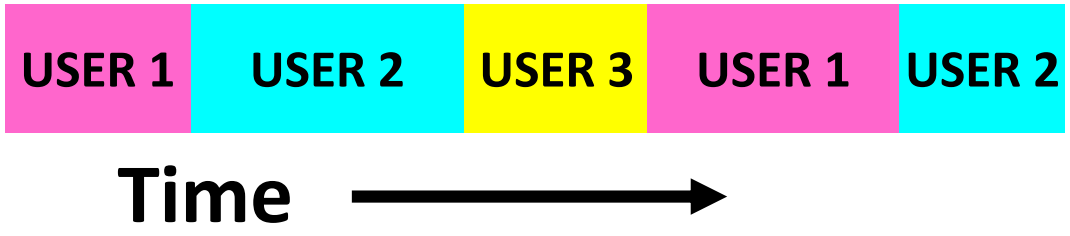
- **Response Time** (ideally *low*)
  - What user sees: from keypress to character on screen
  - Or completion time for non-interactive
- **Throughput** (ideally *high*)
  - Total operations (jobs) per second
  - Overhead (e.g. context switching), artificial blocks
- **Fairness**
  - Fraction of resources provided to each
  - May conflics with best avg. throughput, resp. time

Discussion: Scheduling Assumptions

- Equal or variable job length ?
- Run to completion vs preemption ?
- Arrival time (at once vs varied) ?
- Resources: CPU(s), I/O, Network, … ?
- Advanced Knowledge of Job characteristics or need
  - Off-line scheduling is given the entire collection of tasks and computes a schedule
  - On-line scheduling makes decisions as tasks arrive

Scheduling Assumptions

- Many implicit assumptions needed to make the problem solvable
- For instance: is “fair” about fairness among users or programs?
  - If I run one compilation job and you run five, you get five times as much CPU on many operating systems
- The high-level goal: Dole out CPU time to optimize some desired parameters of system



First-Come, First-Served Scheduling (FCFS)

- Also: “First In First Out” (FIFO)
- Example:

Process	Burst Time
T_1	24
T_2	3
T_3	3

- Arrival Order: T_1, T_2, then T_3 *(essentially at time 0)*

First-Come, First-Served Scheduling (FCFS)

- Response Times: T1 = 24, T2 = 27, T3 = 30
- Average Response Time = (24+27+30)/3 = 27

- Waiting times: T1 = 0, T2 = 24, T3 = 27
- Average Wait Time = (0 + 24 + 27)/3 = 17
- **Convoy Effect: Short processes stuck behind long processes**
  - If T2, T3 arrive any time < 24, they must wait

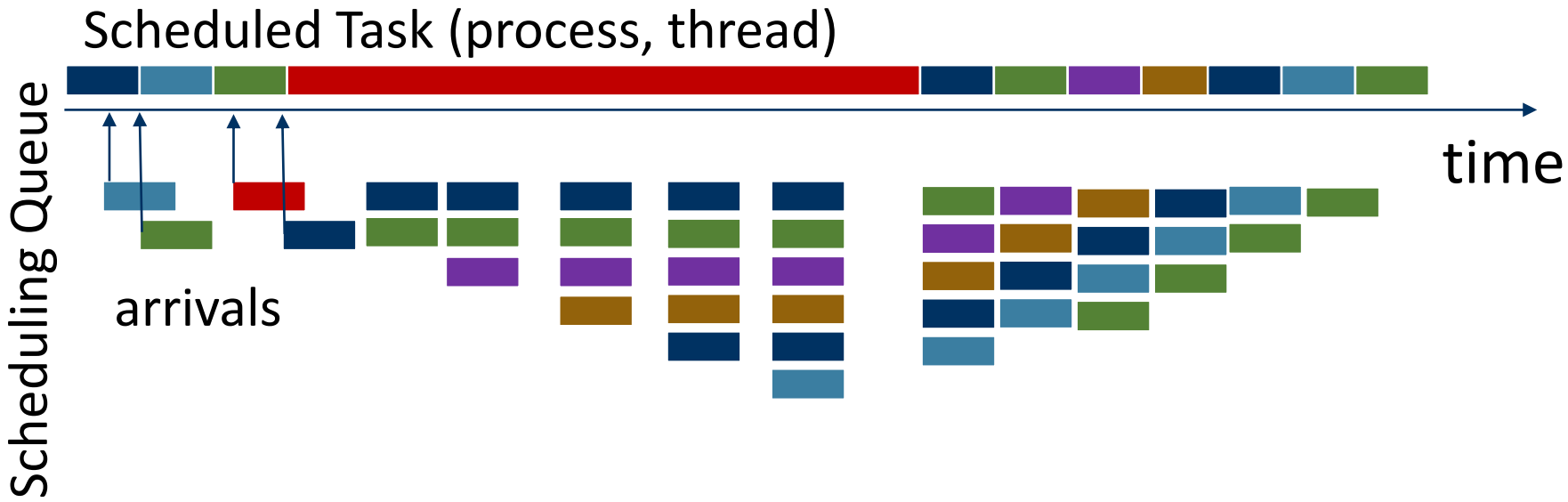
Slightly Different Arrival Order?

- T2 < T3 < T1
- Response Time: T1 = 30, T2 = 3, T3 = 6
- Average Response Time = (30 + 3 + 6)/3 = 13
  - versus 27 with T1 < T2 < T3
- Waiting Time: T1 = 6, T2 = 0, T3 = 3
- Average Waiting Time = (6+0+3)/3 = 3

How to Implement FCFS in the Kernel?

- Comes down to scheduling queue data structure
  - FIFO
  - E.g., `push_front`, `pop_back`

Convoy Effect



- With FCFS non-preemptive scheduling, convoys of small tasks tend to build up when a large one is running.

First-Come, First-Serve Scheduling

- FCFS Scheme: Potentially bad for short jobs!
  - Depends on submit order
  - If you are first in line at supermarket with milk, you don't care who is behind you, on the other hand…
- Idea: What if we preempt long-running jobs to give shorter jobs a chance to run?

Announcements

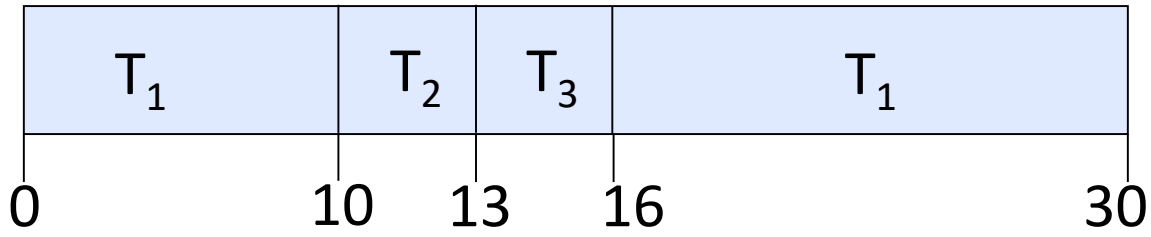
- Project 1 due Tuesday, July 14
  - Revised design doc due today
  - Checkpoint 1 is due today (optional)

- Homework 3 is due Friday next week (after the project)

Round-Robin Scheduling (RR)

- Give out *small* units of CPU time ("time quantum")
  - Typically 10 – 100 milliseconds
- When quantum expires, **preempt,** and schedule
  - Round Robin: add to end of the queue
- Each of *N* processes gets ~1/*N* of CPU (in window)
  - With quantum length *Q* ms, process waits at most *(N-1)*Q* ms to run again
- Downside: More context switches

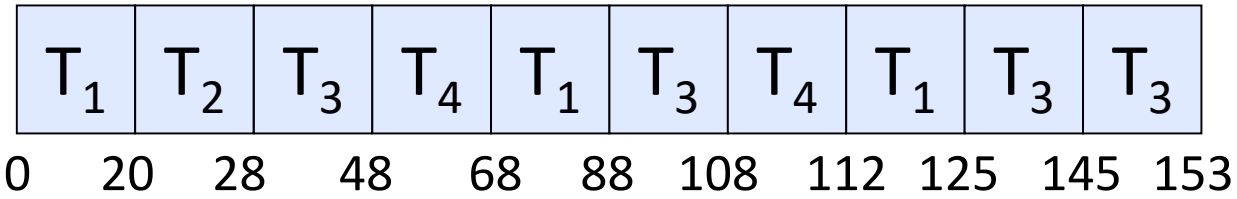
Example From Earlier ($Q = 10$)



- Regardless of arrival order, short jobs gets a chance early
- Much less sensitive to arrival order
- How much context switch overhead?

Another Example ($Q = 20$)

Task	Burst Time
T_1	53
T_2	8
T_3	68
T_4	24



- Avg. response time = (125+28+153+112)/4 = 104.5
- Waiting times:
  - T_1=(68-20)+(112-88)=72
  - T_2=(20-0)=20
  - T_3=(28-0)+(88-48)+(125-108)=85
  - T_4=(48-0)+(108-68)=88
- Average waiting time = (72+20+85+88)/4 = 66.25
- And don't forget context switch overhead!

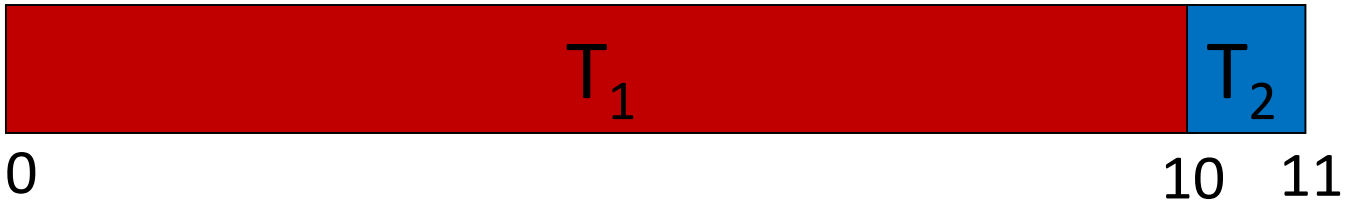
Round-Robin Quantum

- Assume that context switch overhead is 0
- What happens when we *decrease Q*?

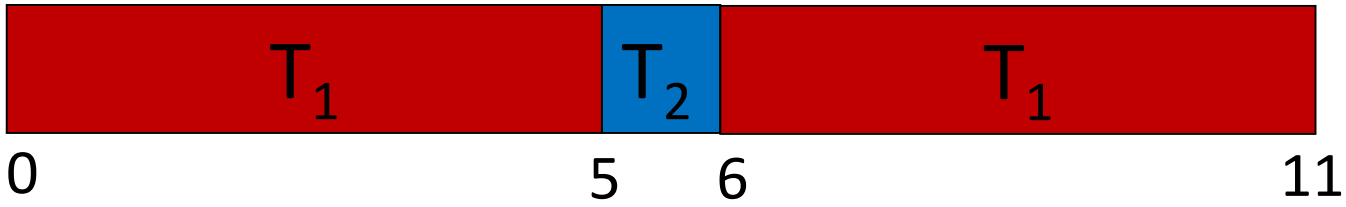
1. Avg. response time always **decreases** or **stays the same**
2. Avg. response time always **increases** or **stays the same**
3. Avg. response time can **increase**, **decrease**, or **stays the same**

Decrease Response Time

- T_1: Burst Length 10
- T_2: Burst Length 1
- Q = 10



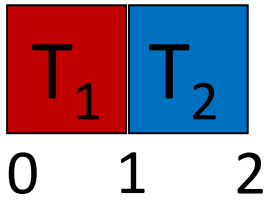
- Average Response Time = (10 + 11)/2 = 10.5
- Q = 5



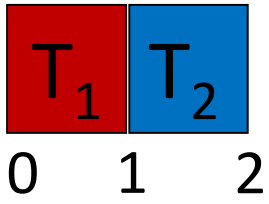
- Average Response Time = (6 + 11)/2 = 8.5

Same Response Time

- T_1: Burst Length 1
- T_2: Burst Length 1
- Q = 10



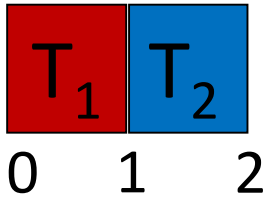
- Average Response Time = (1 + 2)/2 = 1.5
- Q = 1



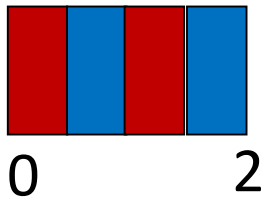
- Average Response Time = (1 + 2)/2 = 1.5

Increase Response Time

- T_1: Burst Length 1
- T_2: Burst Length 1
- $Q = 1$



- Average Response Time = (1 + 2)/2 = 1.5
- $Q = 0.5$

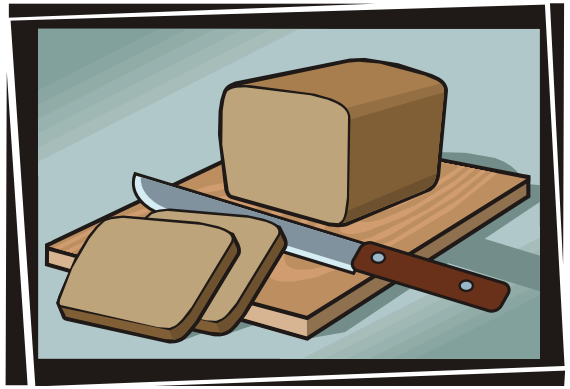


- Average Response Time = (1.5 + 2)/2 = 1.75

How to Implement RR in the Kernel?

- FIFO Queue, as in FCFS
- But preempt job after quantum expires, and send it to the back of the queue
  - How? Timer interrupt!
  - And, of course, careful synchronization

Discussion: Round-Robin Scheduling

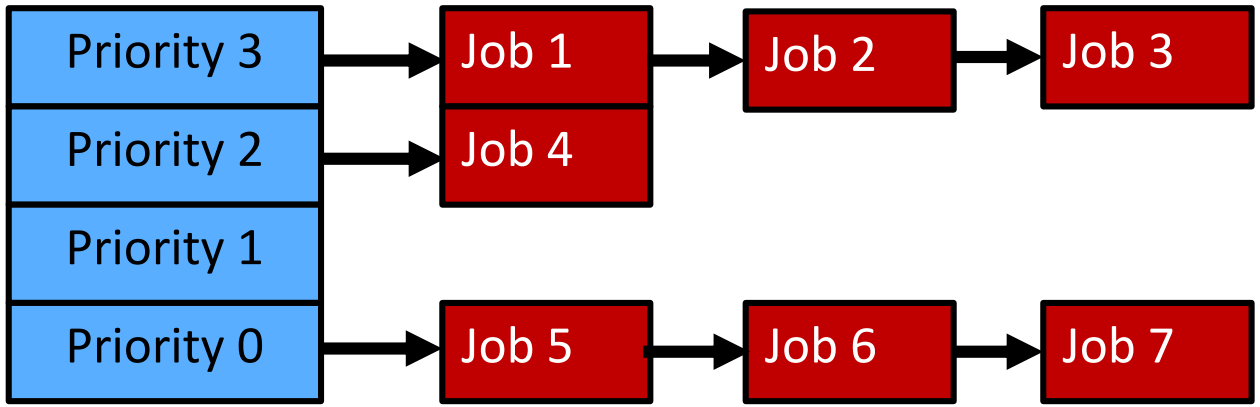


- How to choose the time quantum?
  - Too big? RR approaches FCFS
  - Too small? Throughput suffers (due to context switches)
- Actual choices of timeslice:
  - Initially, UNIX timeslice one second:
    - Worked ok when UNIX was used by one or two people.
    - When might this perform poorly?
  - Need to balance short-job performance and long-job throughput:
    - Typical time slice today is between 10ms – 100ms
    - Typical context-switching overhead is 0.1ms – 1ms
    - Roughly 1% overhead due to context-switching

Priority

- Interactive vs. compute bound

Priority Scheduler



- Something gives jobs (processes) priority
  - Usually the user sets it explicitly, perhaps based on $ rate
- Always run the **ready** thread with *highest priority*
  - Low priority thread might never run!
  - **Starvation**

How to Implement Priority Scheduling in the Kernel?

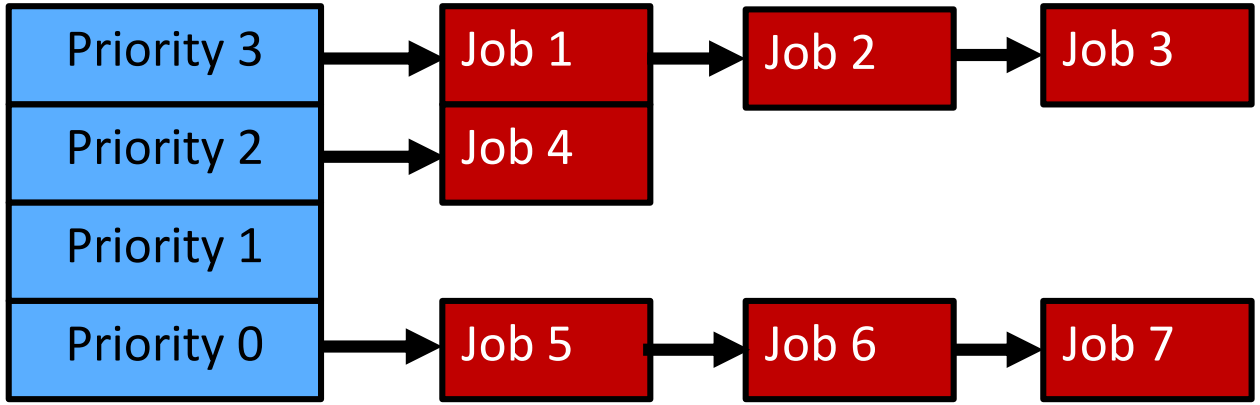
- Scheduling queue data structure determines next thread **of those in the ready queue**
  - Kernel prefers threads with more urgent priority
- Why might a thread not be in the ready queue?
  - Waiting on I/O
  - Locks?

Break

Adaptive Scheduling

- Modern schedulers use knowledge about program to make better scheduling decisions
- Provided by the user (servers vs. background)
- Estimate future based on the past

Policy Based on Priority Scheduling



- Systems may try to set priorities according to some **policy goal**
- Example: Give interactive higher priority than long calculation
  - 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 overload)

Adaptive Scheduling

- How can we adapt the scheduling algorithm based on threads' past behavior?

- Two steps:
  1. Based on past observations, predict what threads will do in the future.
  2. Make scheduling decisions based on those predictions.

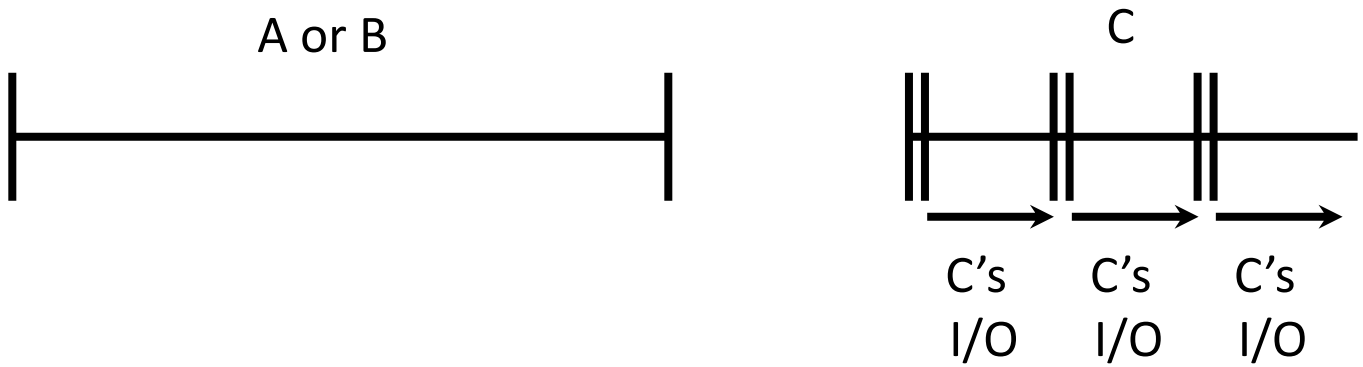
- Start with the second step. Suppose we knew the workload in advance. What should the scheduler do?

What if we know how long each CPU burst will be, in advance?

- Key Idea: remove convoy effect
  - Short jobs always stay ahead of long ones
- Non-preemptive: **Shortest Job First**
  - Like FCFS if we always chose the best possible ordering
- Preemptive Version: **Shortest Remaining Time First**
  - If a job arrives and has shorter time to completion than current job, immediately preempt CPU
  - Sometimes called “Shortest Remaining Time to Completion First”

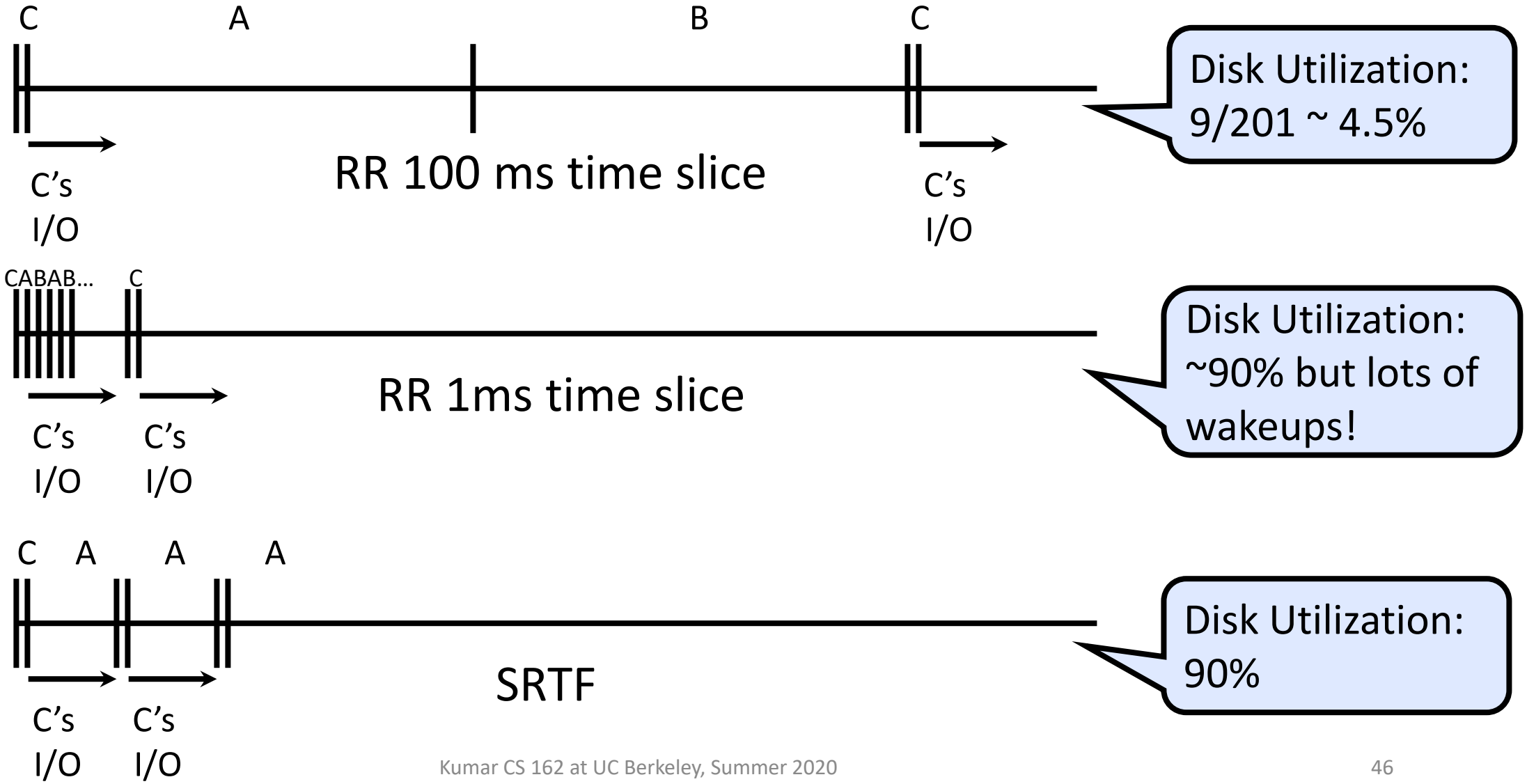
SRTF Example

- Three jobs in system
  - *A* and *B* are CPU calculations that take a week to run
  - *C*: Continuous loop of 1ms CPU time, 9ms of I/O time



- FCFS? *A* or *B* starve *C*
  - I/O throughput problem: lose opportunity to do work for *C* while CPU runs *A* or *B*

SRTF Example



Discussion: SJF and SRTF

- **Provably Optimal** with respect to Response Time
- But Starvation is possible
  - What if new short jobs keep arriving?

- But: Need to predict the future!
  - Ask the user when they submit the job? How to prevent cheating?
  - SRTF useful as a benchmark to measure other policies?

Adaptive Scheduling

- How can we adapt the scheduling algorithm based on threads' past behavior?

- Two steps:
  1. Based on past observations, predict what threads will do in the future.
  2. Make scheduling decisions based on those predictions.

- Now, let's look at the first step. How can we predict future behavior from past behavior?

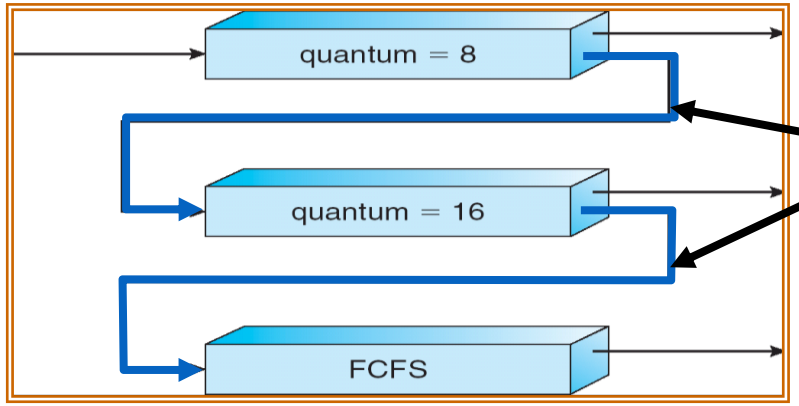
Predicting Future Behavior

- Consider Round-Robin Scheduling

- If process exhausts quantum, has to be preempted
  - Consuming all of the CPU time it can: “CPU-Bound”
  - **Likely to remain CPU-Bound**

- If process blocks on I/O before quantum exhausted
  - Short CPU bursts, just to initiate I/O: “I/O-Bound”
  - Often interactive tasks
  - **Likely to remain I/O-Bound and/or Interactive**

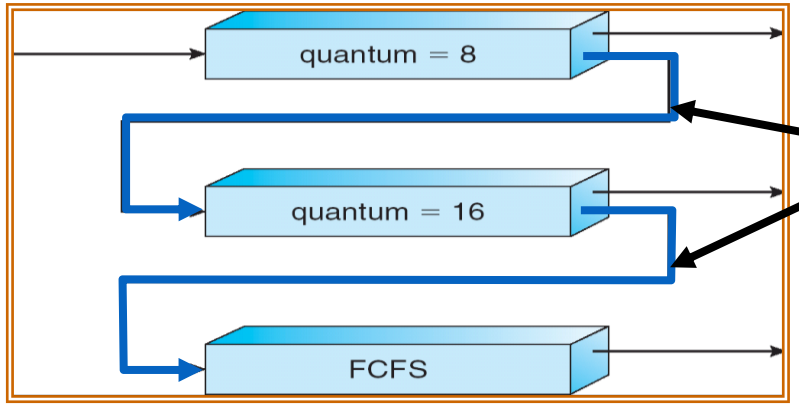
Multi-Level Feedback Queue (MLFQ)



Long-Running Compute Tasks Demoted to Low Priority

- Multiple queues, each of different priority
  - Round Robin within each queue
  - Different quantum length for each queue
- Favor I/O-bound jobs for interactivity
  - Get click or kick off I/O transfer
- Low overhead for CPU bound

Multi-Level Feedback Queue (MLFQ)



Long-Running Compute Tasks Demoted to Low Priority

- Intuition: approximate SRTF by setting priority level proportional to burst length
- Job Exceeds Quantum: Drop to lower queue
- Job Doesn't Exceed Quantum: Raise to higher queue

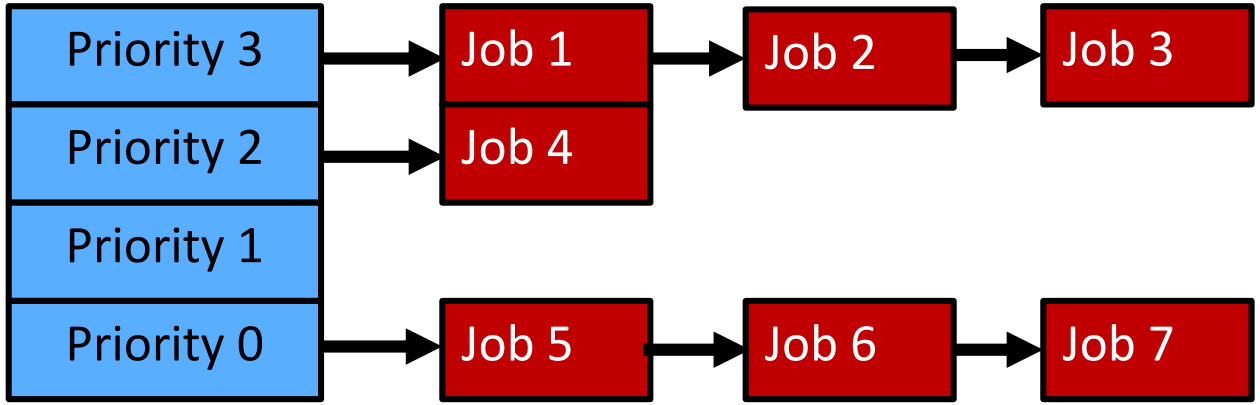
Multi-Level Feedback Queue

- Approximates Shortest Remaining Time First
  - CPU-bound have lowest priority (run last)
  - I/O-bound (short CPU bursts) have highest priority (run first)
- Low overhead
  - Easy to update priority of a job
  - Easy to find next ready task to run
- Can a process cheat?
  - Yes, add meaningless I/O operations (but has a cost)

How to Implement MLFQ in the Kernel?

- We could explicitly build the queue data structures
- Or, we can leverage priority-based scheduling!

Recall: Policy Based on Priority Scheduling



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- Example: Give interactive higher priority than long calculation
  - 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 overload)

Conclusion

- **First-Come First-Served**: Simple, vulnerable to convoy effect
- **Round-Robin**: Fixed CPU time quantum, cycle between ready threads
- **Priority:** Respect differences in importance
- **Shortest Job/Remaining Time First:** Optimal for average response time, but unrealistic
- **Multi-Level Feedback Queue:** Use past behavior to approximate SRTF and mitigate overhead