

# CS111, Lecture 19

## Preemption and Implementing Locks



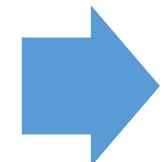
masks recommended

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# Topic 3: Multithreading - How can we have concurrency within a single process? How does the operating system support this?

# CS111 Topic 3: Multithreading, Part 2

Scheduling and  
Dispatching



**Lecture 17**

Scheduling and  
Preemption,  
Continued



**Lecture 18**

Preemption and  
Implementing  
Locks

**This Lecture**

**assign5:** implement your own version of **thread**, **mutex** and **condition\_variable**!

# Learning Goals

- Compare tradeoffs between various approaches to scheduling
- Learn about the assign5 infrastructure and how to implement a dispatcher with *preemption*
- See how our understanding of thread dispatching/scheduling allows us to implement locks

# Plan For Today

- **Recap and continuing:** Scheduling
- Preemption and Interrupts
- Implementing Locks

```
cp -r /afs/ir/class/cs111/lecture-code/lect19 .
```

# Plan For Today

- **Recap and continuing: Scheduling**
  - Preemption and Interrupts
  - Implementing Locks

```
cp -r /afs/ir/class/cs111/lecture-code/lect19 .
```

# Scheduling

**Key Question:** How does the operating system decide which thread to run next? (e.g. many **ready** threads). Assume just 1 core.

We discussed 2 main designs so far:

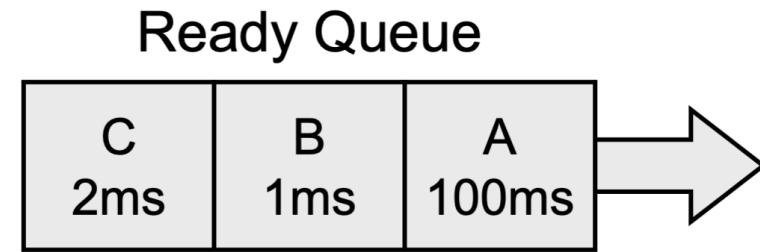
1. **First-come-first-serve (FIFO / FCFS):** keep threads in ready queue, add threads to the back, run thread from front until completion or blocking.
2. **Round Robin:** run thread for one time slice, then add to back of queue if wants more time

# Scheduling Algorithms

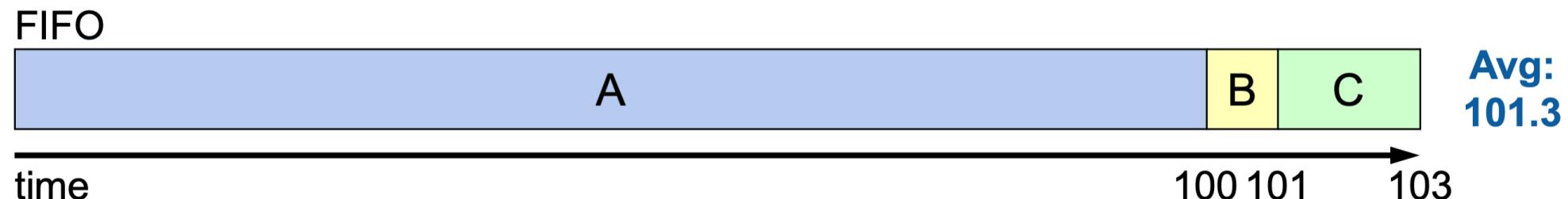
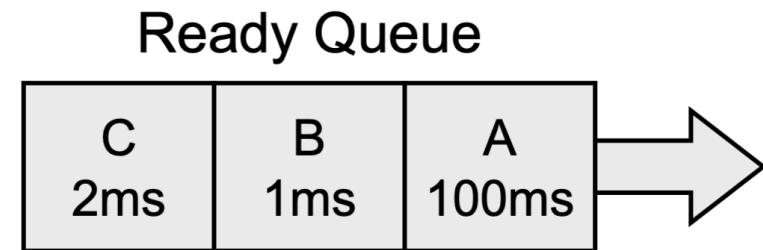
How do we decide whether a scheduling algorithm is good?

- Minimize response time (time to useful result)
  - e.g. keystroke -> key appearing, or “make” -> program compiled
  - Assume useful result is when the thread blocks or completes
- Use resources efficiently
  - keep cores + disks busy
  - low overhead (minimize context switches)
- Fairness (e.g. with many users, or even many jobs for one user)

# Comparing FCFS/RR: Scenario 1

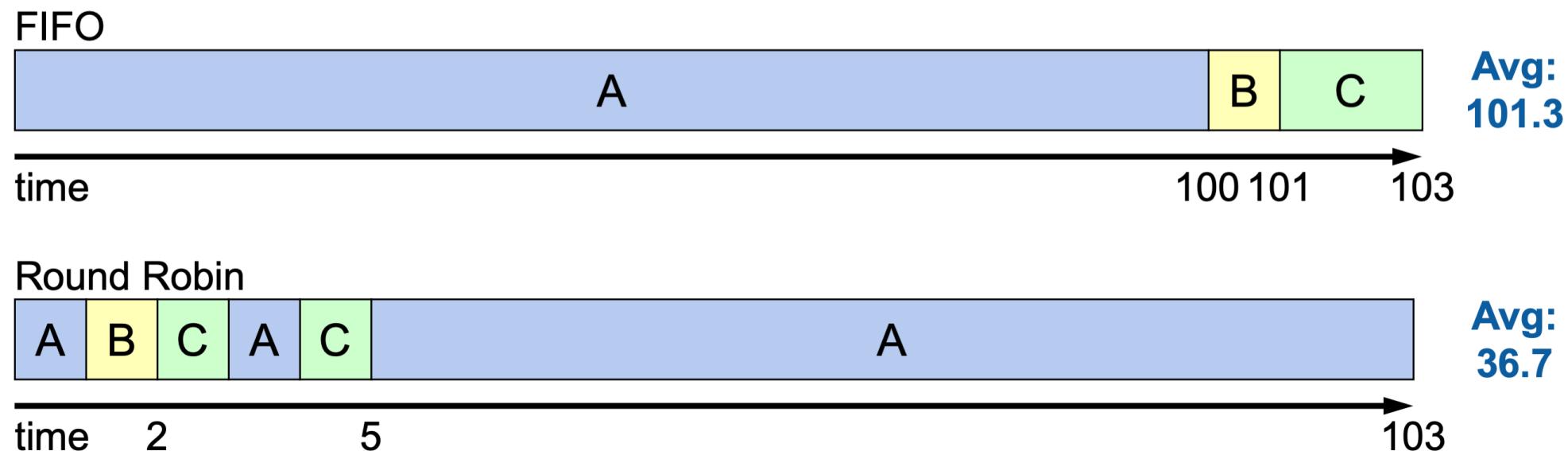
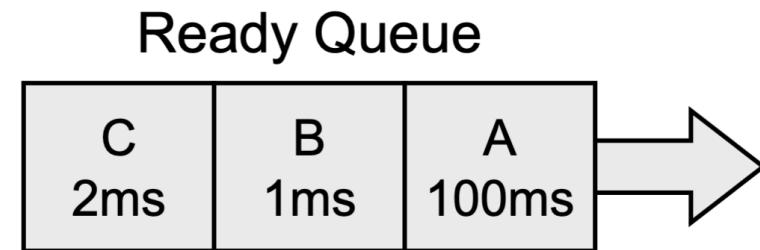


# Comparing FCFS/RR: Scenario 1

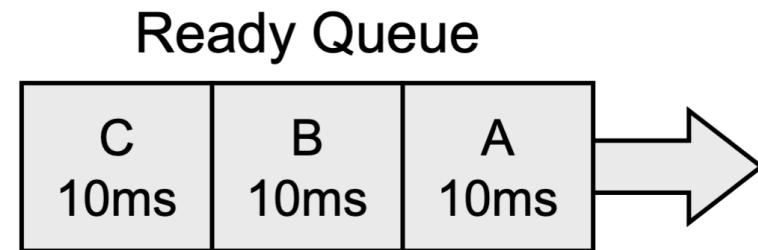


# Comparing FCFS/RR: Scenario 1

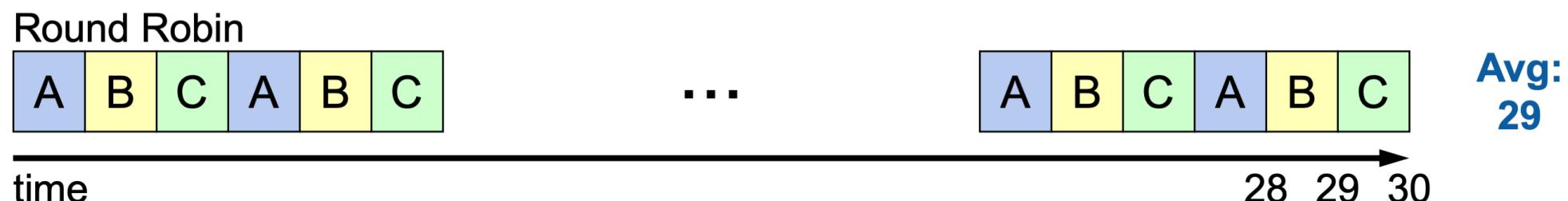
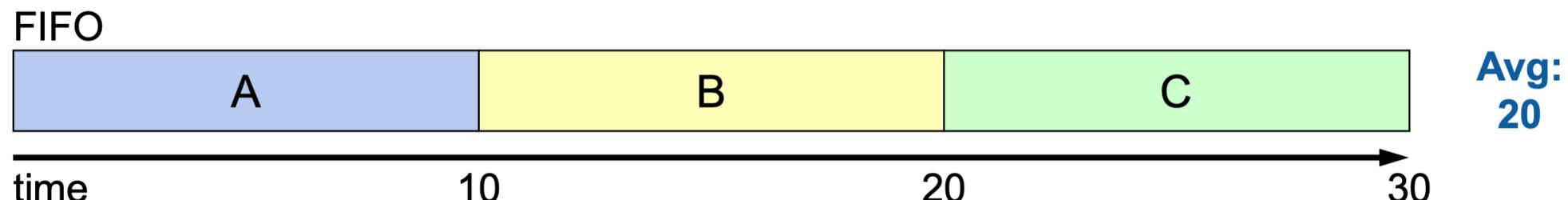
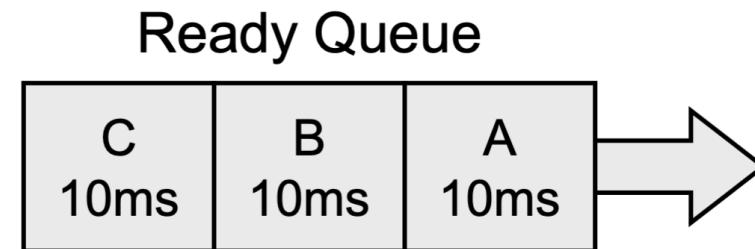
Is RR *always*  
better than FCFS?



# Comparing FCFS/RR: Scenario 2



# Comparing FCFS/RR: Scenario 2



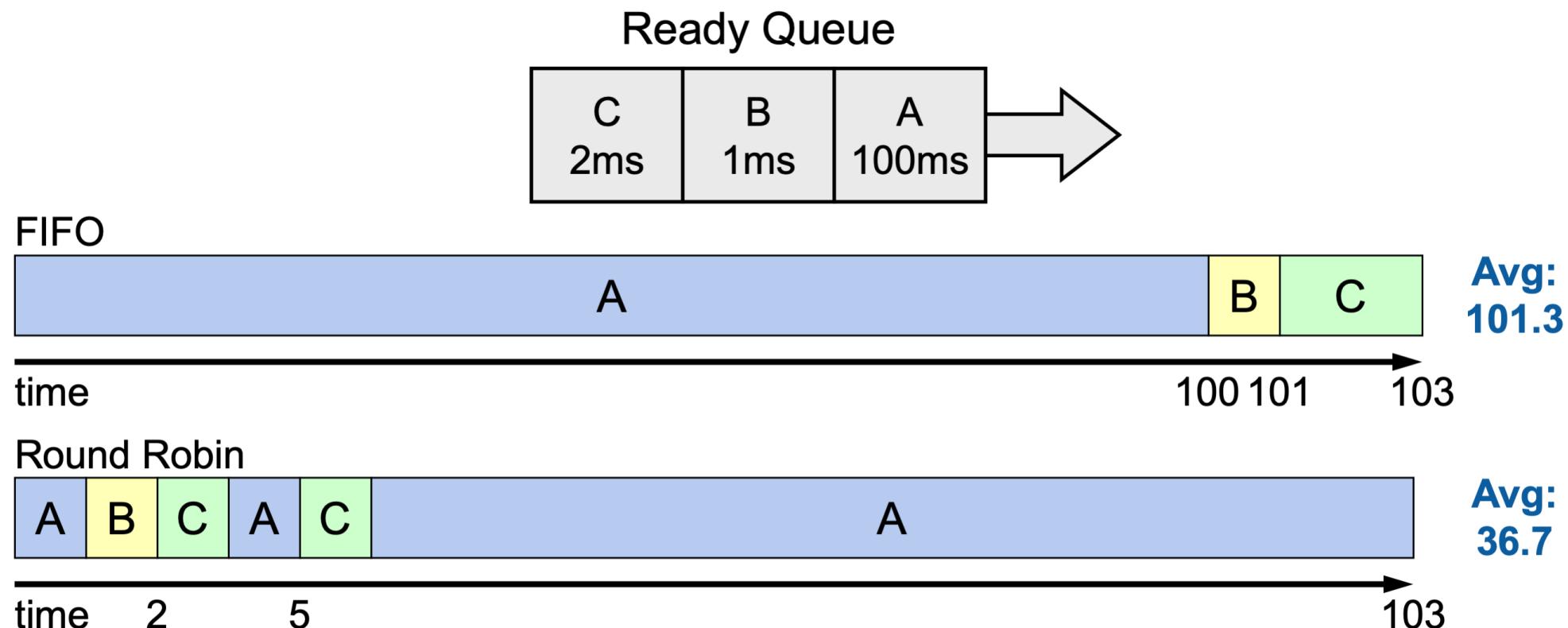
**What's the optimal  
approach if we want to  
minimize average  
response time?**

# Shortest Remaining Processing Time

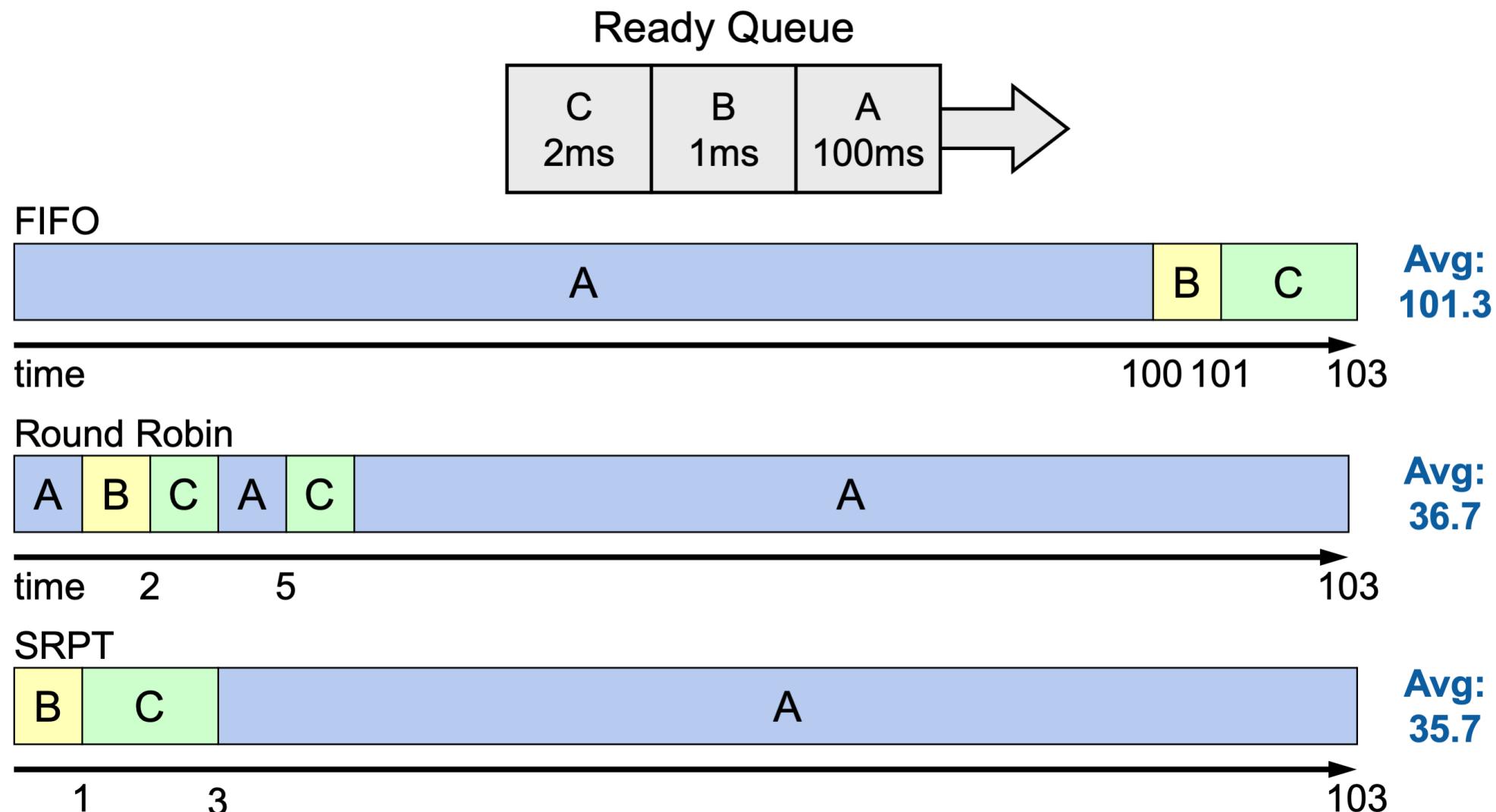
What would it look like if we optimized for completion time? (time to finish, or time to block).

**Idea - SRPT:** pick the thread that will finish the most quickly and run it to completion. This is the optimal solution for minimizing average response time.

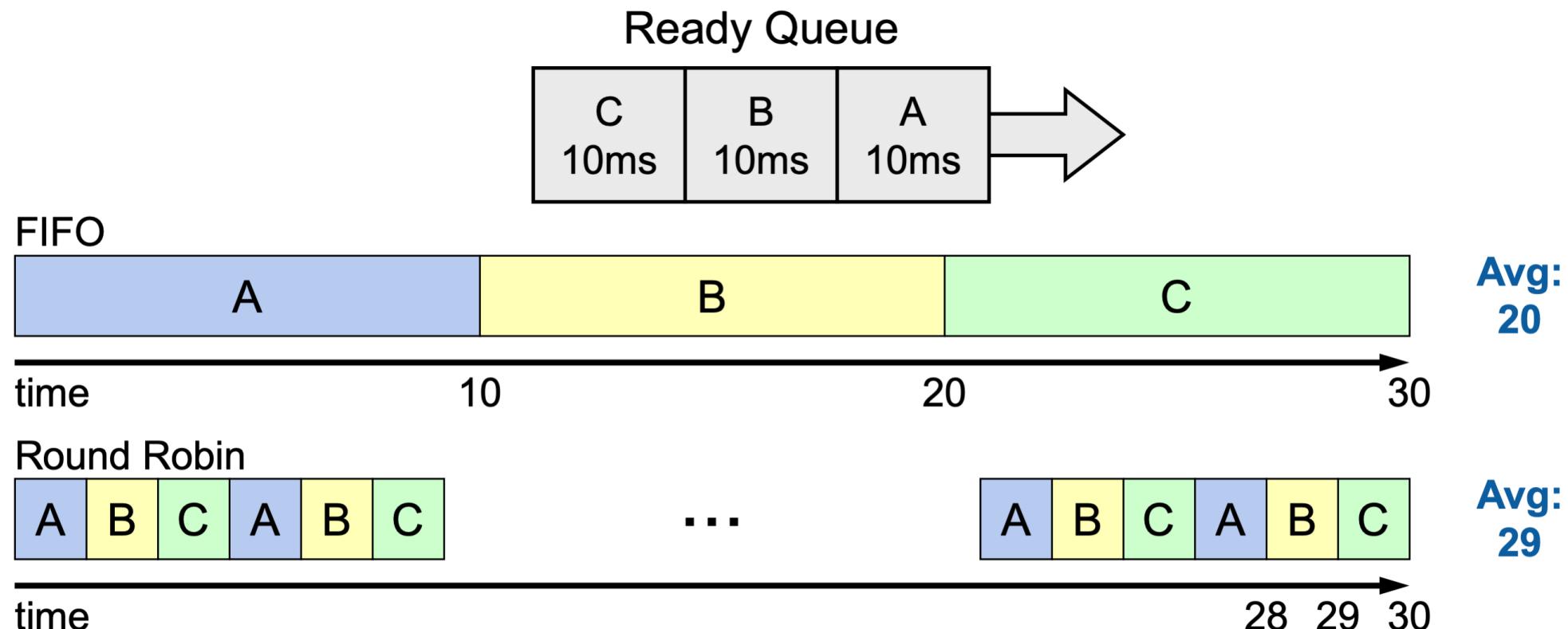
# Evaluating SRPT



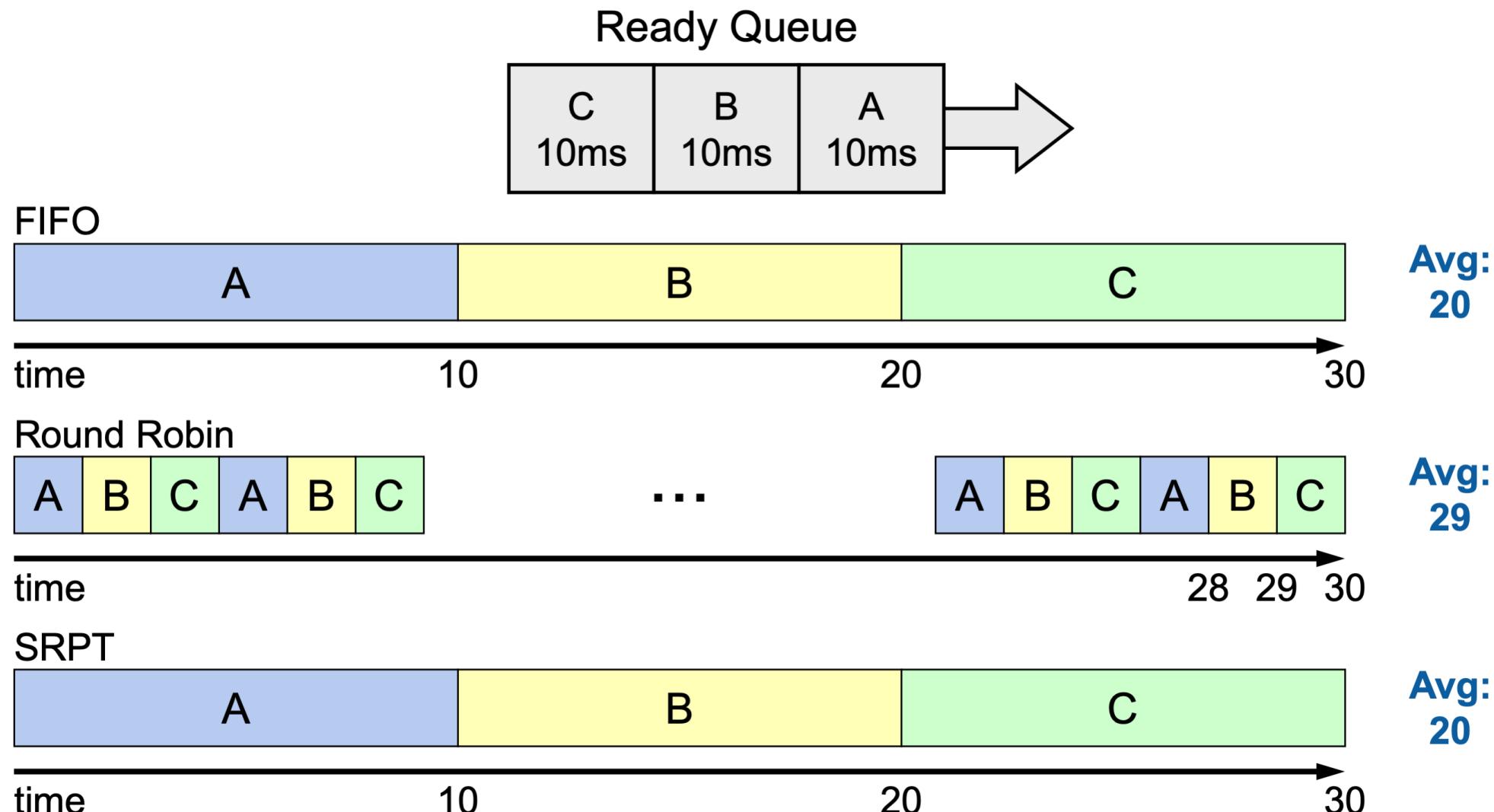
# Evaluating SRPT



# Evaluating SRPT



# Evaluating SRPT



# Shortest Remaining Processing Time

**SRPT:** pick the thread that will finish the most quickly and run it to completion. This is the optimal solution for minimizing average response time.

What are some problems/challenges with the SRPT approach?

**Problem #1:** how do we know which one will finish most quickly? (we must be able to predict the future...)

**Problem #2:** if we have many short-running threads and one long-running one, the long one will not get to run (“starvation”)

**How can we get close to SRPT but without having to predict the future or neglect certain threads?**

# Priority-Based Scheduling

**Goal:** we want to get close to SRPT, but without having to predict the future, and without neglecting certain threads.

**Key Idea:** can use past performance to predict future performance.

- Behavior tends to be consistent
- If a thread runs for a long time without blocking, it's likely to continue running

# Priority-Based Scheduling

**Goal:** we want to get close to SRPT, but without having to predict the future, and without neglecting certain threads.

**Idea:** let's make threads have priorities that adjust over time as they run. We'll have 1 ready queue for each priority, and always run highest-priority threads.

- Overall idea: threads that aren't using much CPU time stay in the higher-priority queues, threads that are migrate to lower-priority queues.
- After blocking, thread starts in highest priority queue
- If a thread reaches the end of its time slice without blocking it moves to the next lower queue.

**Problem:** could still neglect long-running threads!

# Priority-Based Scheduling

**Idea:** let's make threads have priorities that adjust over time as they run. We'll have 1 ready queue for each priority, and always run highest-priority threads.

**Problem:** could still neglect long-running threads!

Let's keep track of *recent CPU usage per thread*. If a thread hasn't run in a long time, its priority goes up. And if it has run a lot recently, priority goes down.  
(4.4 BSD Unix used this, ideas carried forward)

- No more neglecting threads: a thread that hasn't run in a long time will get its priority increased
- If there are many equally-long threads that want to run, the priorities even out over time, at a kind of “equilibrium”

# Scheduling

**Key Question:** How does the operating system decide which thread to run next? (e.g. many **ready** threads). Assume just 1 core.

We discussed 4 main designs:

1. **First-come-first-serve (FIFO / FCFS):** keep threads in ready queue, add threads to the back, run thread from front until completion or blocking.
2. **Round Robin:** run thread for one time slice, then add to back of queue if wants more time
3. **Shortest Remaining Processing Time (SRPT):** pick the thread that will complete or block the soonest and run it to completion.
4. **Priority-Based Scheduling:** threads have priorities, and we have one ready queue per priority. Threads adjust priorities based on time slice usage, or based on recent CPU usage (4.4 BSD Unix)

# Plan For Today

- Recap and continuing: Scheduling
- **Preemption and Interrupts**
- Implementing Locks

```
cp -r /afs/ir/class/cs111/lecture-code/lect19 .
```

# Preemption and Interrupts

On assign5, you'll implement a **dispatcher and scheduler** using the Round Robin approach.

- *Preemptive*: threads can be kicked off in favor of others (after time slice)

To implement this, we've provided a **timer** implementation that lets you run code every X microseconds.

- Fires a timer interrupt at specified interval

**Idea:** we can use the timer handler to trigger a context switch!

(For simplicity, on assign5 we'll always do a context switch when the timer fires)

# Timer Demo

```
// this program runs timer_interrupt_handler every 0.5 seconds

void timer_interrupt_handler() {
    cout << "Timer interrupt occurred!" << endl;
}

int main(int argc, char *argv[]) {
    // specify microsecond interval and function to call
    timer_init(50000, timer_interrupt_handler);
    while(true) {}
}
```



interrupt.cc

**Demo:** context-switch-preemption-buggy.cc

# Interrupts

When the timer handler is called, it's called with (all) interrupts **disabled**. Why?  
To avoid a timer handler interrupting a timer handler.

When the timer handler finishes, interrupts are **re-enabled**.

```
// within timer code  
  
// (omitted) timer disables interrupts here  
your_timer_handler();  
// (omitted) timer re-enables interrupts here
```

Interrupt state is shared (not per-thread).

# Interrupts

When the timer handler is called, it's called with (all) interrupts **disabled**. Why?  
To avoid a timer handler interrupting a timer handler.

When the timer handler finishes, interrupts are **re-enabled**.

```
// within timer code  
  
// (omitted) timer disables interrupts here  
your_timer_handler();  
// (omitted) timer re-enables interrupts here
```

**Problem:** because we context switch in the middle of the timer handler, when we start executing another thread **for the first time**, we will have interrupts **disabled** and the timer won't be heard anymore!

# Enabling Interrupts

**Solution:** manually enable interrupts when a thread is first run.

```
void other_func() {  
    intr_enable(true);  
    while (true) {  
        cout << "Other thread here!  Hello." << endl;  
    }  
}
```

On assign5: when a program creates a thread and gives you the function that thread should run, you will run that thread initially by **enabling interrupts first** and *then* running their specified function.

# Disabling/Enabling Interrupts

The assignment starter code provides the following to enable or disable interrupts:

```
void intr_enable(bool on);
```

# Interrupts

What about when we switch to a thread that we've already run before? Do we need to enable interrupts there too?

**No** – if a thread is paused that means when it was previously running, the timer handler was called and it context-switched to another thread. Therefore, when that thread resumes, **it will resume at the end of the timer handler**, where interrupts are re-enabled.

# Interrupts

On assign5, there are other places where interrupts can cause complications.

- E.g. we could be in the middle of adding to the ready queue, but then the timer fires and we go to remove something from the ready queue!
- This sounds like a race condition problem we can solve with **mutexes!**...right?
- **Not in this case** – because we are the OS, and we implement mutexes! And they rely on the thread dispatching code in this assignment.
- Therefore, the mechanism for avoiding race conditions is to enable/disable interrupts when we don't want to be interrupted (e.g. by timer).
- Interrupts are a shared state – not per-thread.
- We're assuming a single-core machine, where disabling interrupts is sufficient to guarantee no other thread will run.

# Plan For Today

- Recap and continuing: Scheduling
- Preemption and Interrupts
- **Implementing Locks**

```
cp -r /afs/ir/class/cs111/lecture-code/lect19 .
```

# Implementing Locks

Now that we understand how thread dispatching/scheduling works, we can write our own **mutex** implementation! Mutexes need to block threads (functionality the dispatcher / scheduler provides).

What does the design of a lock look like? What state does it need?

- Track whether it is locked / unlocked
- The lock “owner” (if any) – perhaps combine with first bullet
- A list of threads waiting to get this lock

# Implementing Locks

Now that we understand how thread dispatching/scheduling works, we can write our own **mutex** implementation! Mutexes need to block threads (functionality the dispatcher / scheduler provides).

What does the design of a lock look like? What state does it need?

- Track whether it is locked / unlocked
- The lock “owner” (if any) – perhaps combine with first bullet
- **A list of threads waiting to get this lock**

We can keep a queue of threads (for fairness). (Hint: C++ has a built-in **queue** data structure)

# Lock

1. If this lock is unlocked, mark it as locked by the current thread
2. Otherwise, add the current thread to the back of the waiting queue

```
// Instance variables
int locked = 0;
ThreadQueue q;

void Lock::lock() {
    if (!locked) {
        locked = 1;
    } else {
        q.add(currentThread);
        blockThread(); // block/switch to next ready thread
    }
}
```

# Unlock

1. If no-one is waiting for this lock, mark it as unlocked
2. Otherwise, keep it locked, but unblock the next waiting thread

```
// Instance variables
int locked = 0;
ThreadQueue q;

void Lock::unlock() {
    if (q.empty()) {
        locked = 0;
    } else {
        unblockThread(q.remove()); // add to ready queue
    }
}
```

# Mutex

```
// Instance variables
int locked = 0;
ThreadQueue q;

void Lock::lock() {
    if (!locked) {
        locked = 1;
    } else {
        q.add(currentThread);

        // block/switch to next
        // ready thread
        blockThread();
    }
}
```

```
void Lock::unlock() {
    if (q.empty()) {
        locked = 0;
    } else {
        // add to ready queue
        unblockThread(q.remove());
    }
}
```

Can you think of an example race condition that could occur if we do not disable interrupts here and two threads lock a single mutex at the same time?

# Mutex

```
// Instance variables
int locked = 0;
ThreadQueue q;

void Lock::lock() {
    if (!locked) {
        locked = 1;
    } else {
        q.add(currentThread);

        // block/switch to next
        // ready thread
        blockThread();
    }
}
```

```
void Lock::unlock() {
    if (q.empty()) {
        locked = 0;
    } else {
        // add to ready queue
        unblockThread(q.remove());
    }
}
```

Can you think of an example race condition that could occur if we do not disable interrupts here and two threads lock a single mutex at the same time?

Example: thread 1 is in the middle of getting ownership, but then the timer fires, we switch to thread 2, and it locks the mutex. Then thread 1 resumes and *also* gets the mutex.

# Lock

```
// Instance variables
int locked = 0;
ThreadQueue q;

void Lock::lock() {
    intr_enable(false);
    if (!locked) {
        locked = 1;
    } else {
        q.add(currentThread);
        intr_enable(true); // ???
        blockThread();    // block/switch
    }
}
```

## Possible scenario (2 threads):

1. Thread #1 locks mutex
2. Thread #2 locks mutex, adds itself to the queue, enables interrupts
3. *Right before thread #2 blocks, thread #1 unlocks the mutex and unblocks thread #2*
4. Thread #2 then proceeds to block.
5. Nobody unblocks thread #2 ☹

# Lock

```
// Instance variables
int locked = 0;
ThreadQueue q;

void Lock::lock() {
    IntrGuard guard;
    if (!locked) {
        locked = 1;
    } else {
        q.add(currentThread);
        blockThread(); // block/switch to next ready thread
    }
}
```

Instead, we must re-enable interrupts at the end of **lock()**. This means that once a thread *unblocks* to acquire the lock, it wakes up after **blockThread()** and re-enables interrupts.

# Lock

```
// Instance variables
int locked = 0;
ThreadQueue q;

void Lock::lock() {
    IntrGuard guard;
    if (!locked) {
        locked = 1;
    } else {
        q.add(currentThread);
        blockThread(); // block/switch
    }
}
```

IntrGuard is like unique\_lock but for interrupts. It saves the current interrupt state (enabled/disabled) when it's created and turns interrupts off. When it is deleted, it restores interrupts to the saved state.

**Key idea:** if interrupts are already disabled when an IntrGuard is created, it keeps them disabled.

# Unlock

1. If no-one is waiting for this lock, mark it as unlocked
2. Otherwise, keep it locked, but unblock the next waiting thread

```
// Instance variables
int locked = 0;
ThreadQueue q;

void Lock::unlock() {
    IntrGuard guard;
    if (q.empty()) {
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# Lock

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// Instance variables
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}
```

**Problem:** what happens when we switch to the next ready thread?  
Interrupts will be disabled!

# Lock

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// Instance variables
int locked = 0;
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void Lock::lock() {
    IntrGuard guard;
    if (!locked) {
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        q.add(currentThread);
        blockThread(); // block/switch
    }
}
```

**Problem:** what happens when we switch to the next ready thread?  
Interrupts will be disabled!

**Key Idea:** we know that every possible way a thread resumes (e.g. timer), it will re-enable interrupts. Therefore, this isn't a problem.



# Enabling/Disabling Interrupts

Interrupts  
ON

## Thread #1

```
void Lock::lock() {  
    IntrGuard guard;  
    if (!locked) {  
        locked = 1;  
    } else {  
        q.add(currentThread);  
        blockThread();  
    }  
}
```

## Thread #2

```
void Lock::lock() {  
    IntrGuard guard;  
    if (!locked) {  
        locked = 1;  
    } else {  
        q.add(currentThread);  
        blockThread();  
    }  
}
```



# Enabling/Disabling Interrupts

Interrupts  
OFF

## Thread #1

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void Lock::lock() {  
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## Thread #2

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void Lock::lock() {  
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```
void Lock::lock() {  
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# Enabling/Disabling Interrupts

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        blockThread();  
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## Thread #2

```
void Lock::lock() {  
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}
```



# Enabling/Disabling Interrupts

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void Lock::lock() {  
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# Enabling/Disabling Interrupts

Interrupts  
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        blockThread();  
    }  
}
```



## Thread #2

```
void Lock::lock() {  
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    if (!locked) {  
        locked = 1;  
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        blockThread();  
    }  
}
```



# Enabling/Disabling Interrupts

Interrupts  
OFF

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## Thread #2

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# Enabling/Disabling Interrupts

Interrupts  
OFF

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    }  
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```

## Thread #2

```
void Lock::lock() {  
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    ➔ if (!locked) {  
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```



# Enabling/Disabling Interrupts

Interrupts  
OFF

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void Lock::lock() {  
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# Enabling/Disabling Interrupts

Interrupts  
OFF

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}
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## Thread #2

```
void Lock::lock() {  
    IntrGuard guard;  
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        locked = 1;  
    } else {  
        q.add(currentThread);  
        blockThread();  
    }  
}
```



# Enabling/Disabling Interrupts

Interrupts  
ON

## Thread #1

```
void Lock::lock() {  
    IntrGuard guard;  
    if (!locked) {  
        locked = 1;  
    } else {  
        q.add(currentThread);  
        blockThread();  
    }  
}
```

## Thread #2 (blocked)

```
void Lock::lock() {  
    IntrGuard guard;  
    if (!locked) {  
        locked = 1;  
    } else {  
        q.add(currentThread);  
        blockThread();  
    }  
}
```

→ (assume thread 1 reenables  
interrupts when resumed and  
disables them when paused)



# Enabling/Disabling Interrupts

Interrupts  
ON

## Thread #1

```
void Lock::unlock() {  
    IntrGuard guard;  
    if (q.empty()) {  
        locked = 0;  
    } else {  
        unblockThread(q.remove());  
    }  
}
```

(assume thread 1 reenables  
interrupts when resumed and  
disables them when paused)

## Thread #2 (blocked)

```
void Lock::lock() {  
    IntrGuard guard;  
    if (!locked) {  
        locked = 1;  
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    }  
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```



# Enabling/Disabling Interrupts

Interrupts  
OFF

## Thread #1

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void Lock::unlock() {  
    IntrGuard guard;  
    if (q.empty()) {  
        locked = 0;  
    } else {  
        unblockThread(q.remove());  
    }  
}
```

(assume thread 1 reenables  
interrupts when resumed and  
disables them when paused)

## Thread #2 (blocked)

```
void Lock::lock() {  
    IntrGuard guard;  
    if (!locked) {  
        locked = 1;  
    } else {  
        q.add(currentThread);  
        blockThread();  
    }  
}
```



# Enabling/Disabling Interrupts

Interrupts  
OFF

## Thread #1

```
void Lock::unlock() {  
    IntrGuard guard;  
    if (q.empty()) {  
        locked = 0;  
    } else {  
        unblockThread(q.remove());  
    }  
}
```



(assume thread 1 reenables  
interrupts when resumed and  
disables them when paused)

## Thread #2

```
void Lock::lock() {  
    IntrGuard guard;  
    if (!locked) {  
        locked = 1;  
    } else {  
        q.add(currentThread);  
        blockThread();  
    }  
}
```



# Enabling/Disabling Interrupts

Interrupts  
ON

## Thread #1

```
void Lock::unlock() {  
    IntrGuard guard;  
    if (q.empty()) {  
        locked = 0;  
    } else {  
        unblockThread(q.remove());  
    }  
}
```



(assume thread 1 reenables  
interrupts when resumed and  
disables them when paused)

## Thread #2

```
void Lock::lock() {  
    IntrGuard guard;  
    if (!locked) {  
        locked = 1;  
    } else {  
        q.add(currentThread);  
        blockThread();  
    }  
}
```



# Enabling/Disabling Interrupts

Interrupts  
OFF

## Thread #1

```
void Lock::unlock() {  
    IntrGuard guard;  
    if (q.empty()) {  
        locked = 0;  
    } else {  
        unblockThread(q.remove());  
    }  
}
```

## Thread #2

```
void Lock::lock() {  
    IntrGuard guard;  
    if (!locked) {  
        locked = 1;  
    } else {  
        q.add(currentThread);  
        blockThread();  
    }  
}
```

→ (assume thread 1 reenables  
interrupts when resumed and  
disables them when paused)



# Enabling/Disabling Interrupts

Interrupts  
OFF

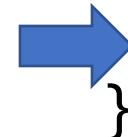
## Thread #1

```
void Lock::unlock() {  
    IntrGuard guard;  
    if (q.empty()) {  
        locked = 0;  
    } else {  
        unblockThread(q.remove());  
    }  
}
```

(assume thread 1 reenables  
interrupts when resumed and  
disables them when paused)

## Thread #2

```
void Lock::lock() {  
    IntrGuard guard;  
    if (!locked) {  
        locked = 1;  
    } else {  
        q.add(currentThread);  
        blockThread();  
    }  
}
```





# Enabling/Disabling Interrupts

Interrupts  
ON

## Thread #1

```
void Lock::unlock() {  
    IntrGuard guard;  
    if (q.empty()) {  
        locked = 0;  
    } else {  
        unblockThread(q.remove());  
    }  
}
```

(assume thread 1 reenables  
interrupts when resumed and  
disables them when paused)

## Thread #2

```
void Lock::lock() {  
    IntrGuard guard;  
    if (!locked) {  
        locked = 1;  
    } else {  
        q.add(currentThread);  
        blockThread();  
    }  
}
```



# Plan For Today

- Recap and continuing: Scheduling
- Preemption and Interrupts
- Implementing Locks

**Next time:** Virtual Memory

**Lecture 19 takeaway:** To implement preemption and locks, we must make sure to correctly enable and disable interrupts. Locks consist of a waiting queue and redispatching to make threads sleep.