Multitasking and Real-Time Systems

Today

Multitasking

Scheduling

RTOS

Imperative programs

(using book definition)

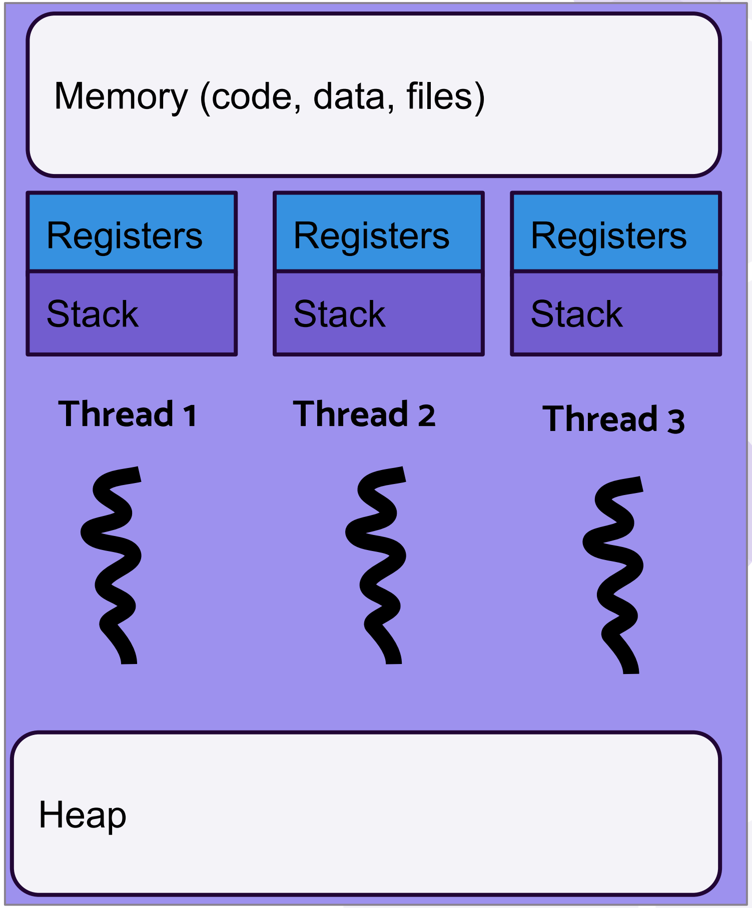
Computation is expressed as a sequence of operations

Each step changes the state of memory on the machine

Threads

Individual imperative programs that run concurrently and share a memory space

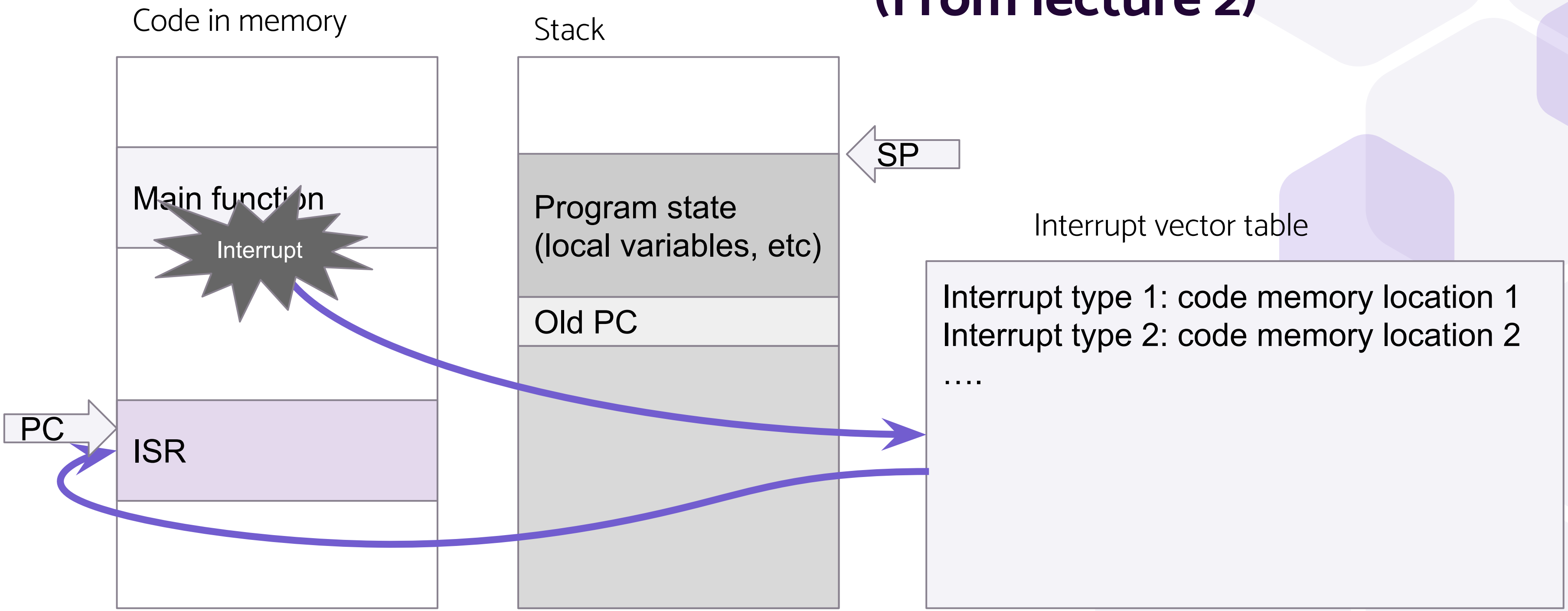
On single-CPU systems, technically only one thread is executing at a given time, but multiple may be "active" (pending computation)



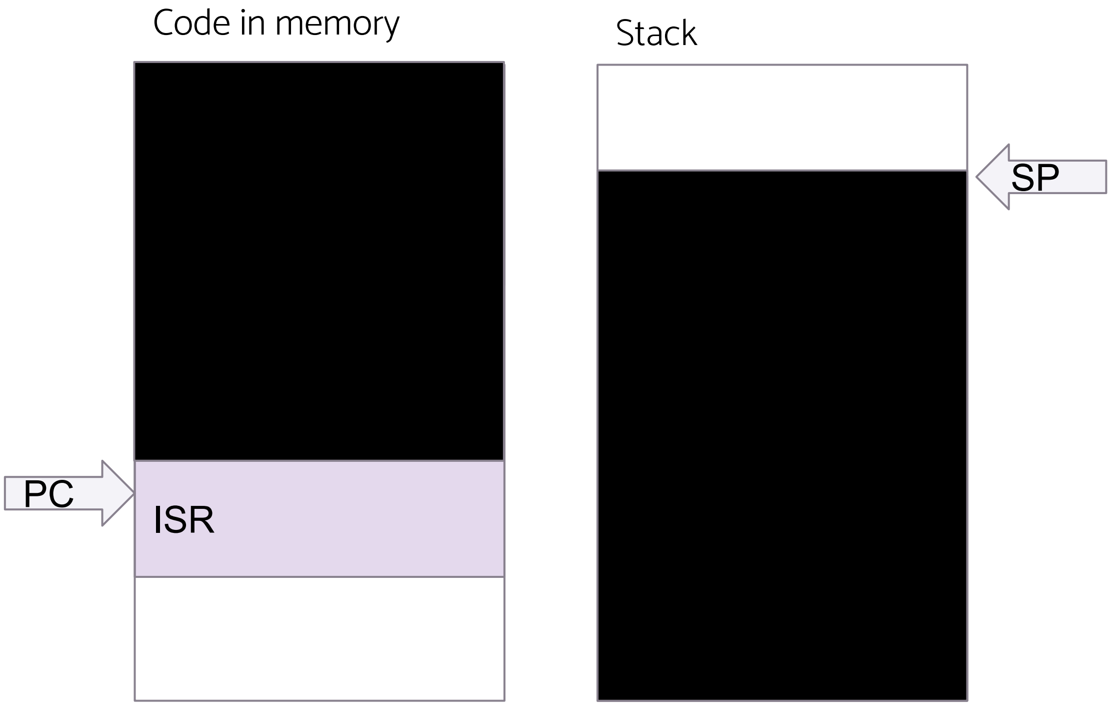
What example of thread-like behavior have we seen so far in this class?

Interrupts as threads

(From lecture 2)

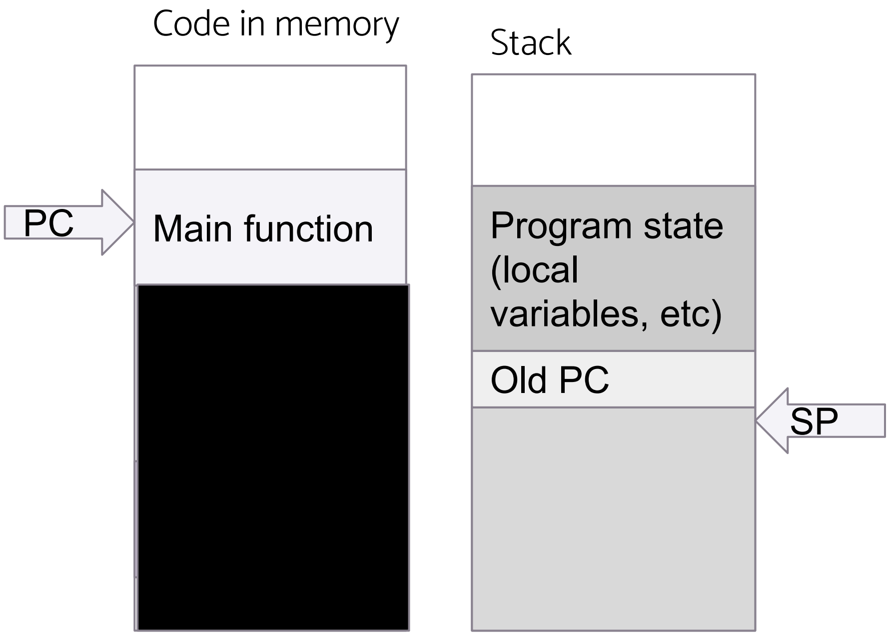


Interrupt’s view of execution

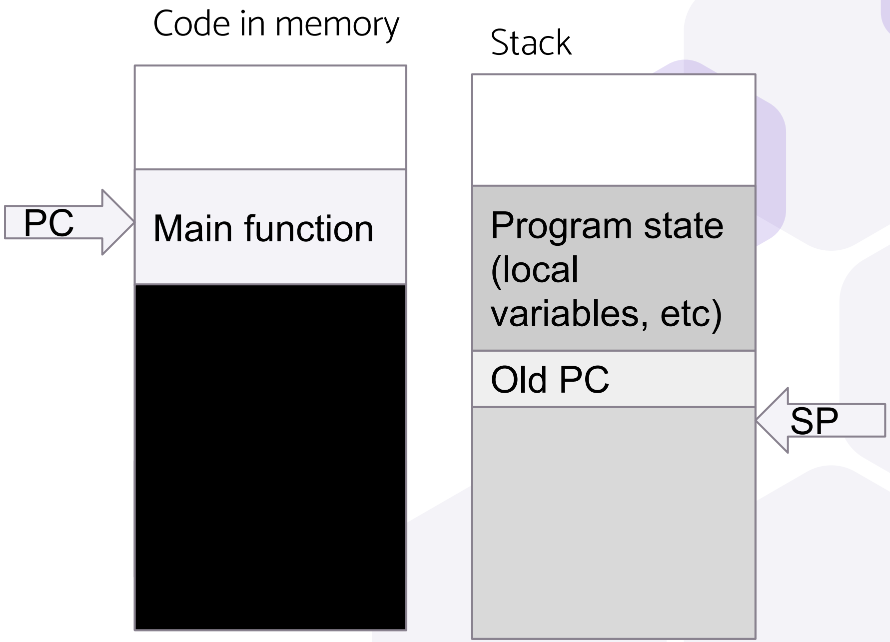


Main process' view of execution

Before interrupt



After interrupt



What are the limitations of having interrupts as the only source of concurrency in embedded programming?

Cyclic Execution

Threading-like behavior without library/os/scheduler

“DIY concurrency”

Each task keeps track of the state it needs

```
void loop() {
  poll_inputs();
  task1();
  task2();
  task3();
}
```

Pros/cons to cyclic execution?

Cyclic Execution timing analysis

```
void loop() {
  poll_inputs();
  task1();
  task2();
  task3();
}
```

Worst-case time:

$$T_{loop} = T_{poll\_inputs} + T_{task1} + T_{task2} + T_{task3}$$

(as long as worst-case time of tasks is known)

Latency

Time that a task has to wait to start executing

Cyclic tasks - time between execution of task

- Basically: main loop time

Interrupts - time between stimulus and ISR entry

Threads - time between arrival and start

Multi-rate cyclic execution

```
void loop() {
  poll_inputs();
  task1();
  poll_inputs();
  task2();
  poll_inputs();
  task3();
}
```

Or even…

```
void loop() {
  poll_inputs();
  task1_step1();
  poll_inputs();
  task1_step2();
  poll_inputs();
  task2_step1();
  poll_inputs();
  task3_step1();
  …
}
```

Timing analysis + interrupts

```
void loop() {
  task1();
  task2();
  task3();
}
```

```
void input_isr() {
  ...
}
```

Assume $T_{task1} + T_{task2} + T_{task3} = 200$ ms

Assume interrupt takes 2 ms and happens at most every 20 ms

Worst case execution time of loop + interrupts = ?

Timing analysis + multiple interrupts

Loop time without interrupts = 200ms

Interrupt 1: 2ms, at most every 20ms

Interrupt 2: 1ms, at most every 10ms ← Highest possible latency of this interrupt?

Compute the limit:

In 200 ms, 11x interrupt1, 21x interrupt2: 200 + 22 + 21 = 243ms

In 243 ms, 13x interrupt1, 25x interrupt2: 200 + 26 + 25 = 251ms

In 251 ms, 13x interrupt1, 26x interrupt2: 200 + 26 + 26 = 252ms

In 252 ms, 13x interrupt1, 26xinterrupt2: 200 + 26 + 26 = **252ms**

More general multithreading

OS exposes an API for control

(...what OS?!)

Library (like pthreads in C) takes care of things

```
pthread_create(&threads[i], NULL, perform_work, &thread_args[i]);
```

Scheduler schedules threads

We'll talk scheduling strategies soon

More open to control/data pitfalls

For now: we are talking about single-processor systems

Race condition - circular buffer

Race condition: order in which two threads access a resource affects outcome of the program

Recall from lab:

Check that a circular buffer is empty (assume we know it isn't full):

```
start_i == end_i
```

Check that a circular buffer is not about to be full:

```
(end_i + 1) % n != start_i
```

n = 4 , start_i = 2, end_i = 1

main loop:

```
// if not empty, take from buffer
if(start_i != end_i) {
  Serial.println(buffer[start_i]);
  start_i = (start_i + 1) % n
}
```

interrupt:

```
// if still room, store in buffer
if((end_i + 1) % n != start_i) {
  buffer[end_i] = something;
  end_i = (end_i + 1) % n
}
```

Mutual exclusion (mutex/lock)

Mechanism that can only be owned by one thread at a time

- Commonly: blocks execution of thread until lock is acquired
- Acquire lock before accessing shared resource, then release it

```
pthread_mutex_lock(&x_lock); // blocks until lock is free
//access x
pthread_mutex_unlock(&x_lock);
```

Deadlock

```
pthread_mutex_lock(&lock1);
pthread_mutex_lock(&lock2);
// thread A task
pthread_mutex_unlock(&lock2);
pthread_mutex_unlock(&lock1);
```

```
pthread_mutex_lock(&lock2);
pthread_mutex_lock(&lock1);
// thread B task
pthread_mutex_unlock(&lock1);
pthread_mutex_unlock(&lock2);
```

Memory consistency

```
w = 1;                  y = 1;
x = y;                  z = w;
```

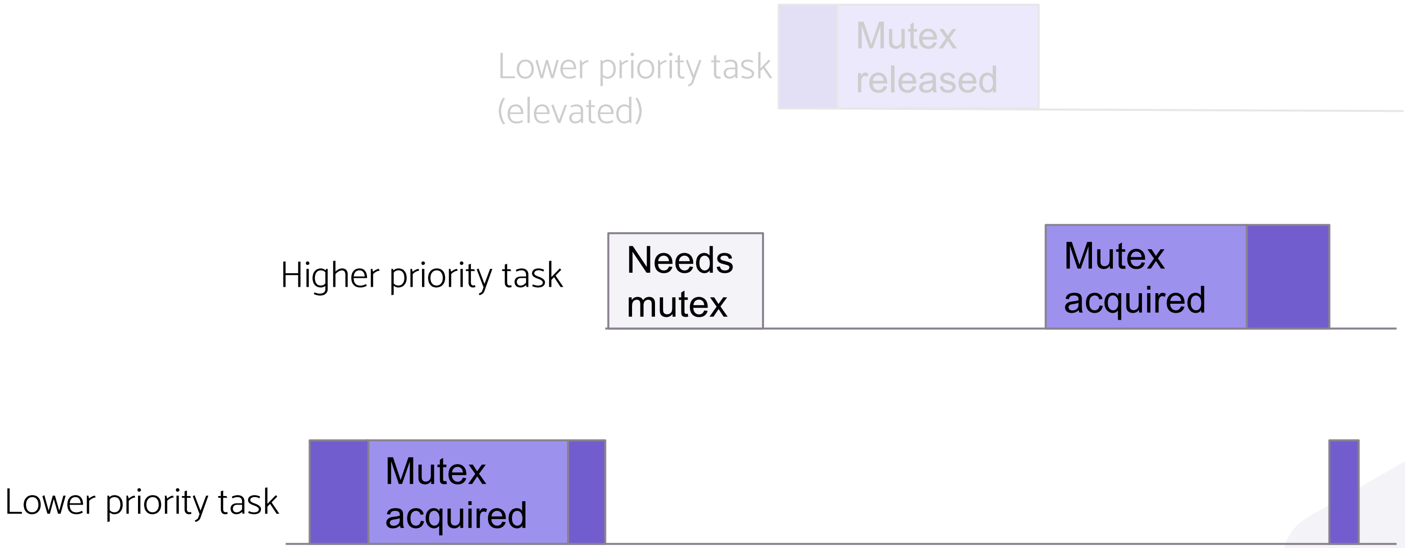
Can we guarantee that at least one of {x, z} will be 1 by the time both threads finish executing?

Depending on compiler optimization, "independent" operations may be rearranged within a thread!!

Priority

- Remember interrupt priorities?
  - Higher-priority interrupt can interrupt lower-priority interrupt but not the other way around
- Task/thread priorities are the same idea
  - In preemptive system, higher-priority tasks can start executing before lower-priority tasks are done
- Various configuration of # of supported priorities, dynamic vs static priorities, etc

Priority inversion



Latency and priority

High priority interrupt: A (4 ms every 10 ms)

Lower priority interrupts: B (7 ms every 100ms),
C (1ms every 15 ms)

Can C fail to execute within 15 ms?

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

C arrives

A arrives

Questions on threading?

Real-time systems

Correctness depends on the *time* an answer is delivered, not just the answer

```
float const_mult(float x, float y) {
   return x * y * C;
}
```

(on your computer, it's probably fine if this takes more time than anticipated)

Same function, different context

```
float determine_speed(float rpm,
                      float radius) {
   return rpm * radius * CONVERSION_FACTOR;
}
…
void safety_critical_loop() {
   …
   if (determine_speed(rpm, r) >= SPEED_LIMIT) {
     brake = ON;
   }
   …
}
```

Scheduling

Decide when CPU runs what task so that deadlines are met

Soft: correctness "degrades" if deadlines aren't met

vs

Hard: correctness fails if deadlines aren't met

Dynamic: done at run-time

vs

Static: done at compile-time

Preemptive: task can interrupt lower-priority task

vs

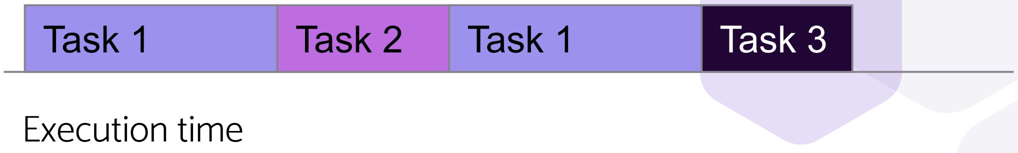
Non-preemptive: tasks can't interrupt each other

Threads and scheduling

Instead of this

```
void loop() {
  task1();
  task2();
  task3();
}
```

CPU schedules each task as its own thread



One approach: cooperative multitasking

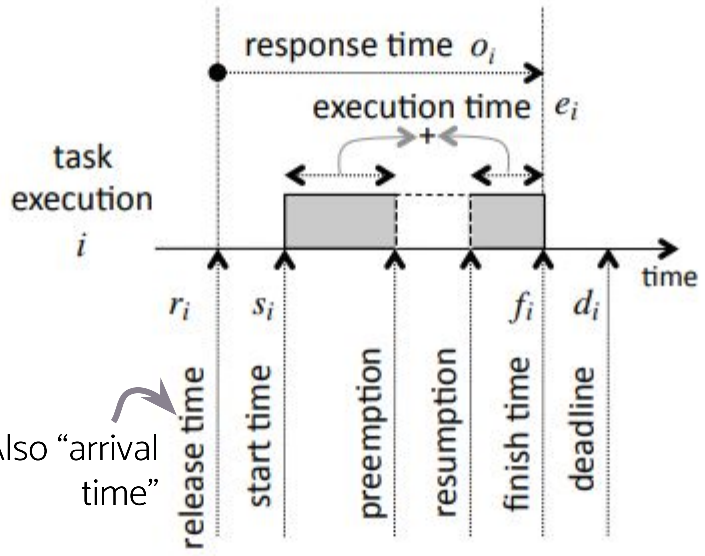
Thread is not interrupted unless it calls a procedure saying it's done

- Then other thread starts

Fairness concern - can lead to **starvation** of some threads

How can we enforce fairness?

Terminology



Also "arrival time"

Figure 12.1: Summary of times associated with a task execution.

For periodic tasks: release time = period offset from start of execution
Deadline = period p_i (an assumption)

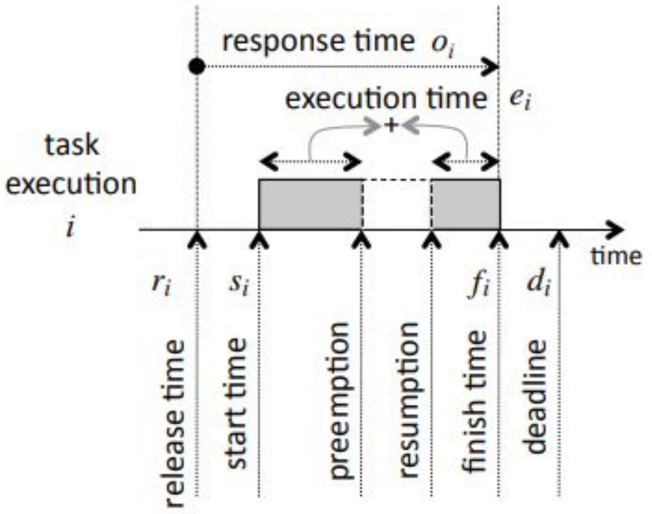
[Lee/Seshia chapter 12]

Criteria for comparing schedulers

Feasibility: feasible if $f_i \leq d_i$ *for all i*

Utilization: % of time CPU spends executing tasks (vs idle)

Maximum Lateness:



Feasibility of scheduling periodic tasks

1) Sum of e_i/p_i for all i is at most 1

   Aka utilization <= 100%

   Necessary but not **Sufficient**

2) Can you figure out a way to schedule all tasks during the LCM of all task periods? Then you can always schedule the tasks

Types of schedulers

Static - figure it out ahead of time, CPU follows the set schedule

Dynamic:

- Earliest deadline first (EDF)
- Least laxity first (LLF) (**laxity** = $d_i - e_i$)

Exercise: statically schedule the following tasks

Board exercise

Periodic scheduling

Utilization <=100% → are there cases where a scheduler does not achieve feasibility (non-preemptive vs preemptive EDF)

Rate Monotonic Scheduling (RMS)

Fixed-priority, determined ahead of time

- Each task has its own priority
- Task with smallest period = highest priority
- Pre-emptive (higher priority tasks interrupt lower-priority tasks)

Guarantee of scheduling when utilization < 69.3%

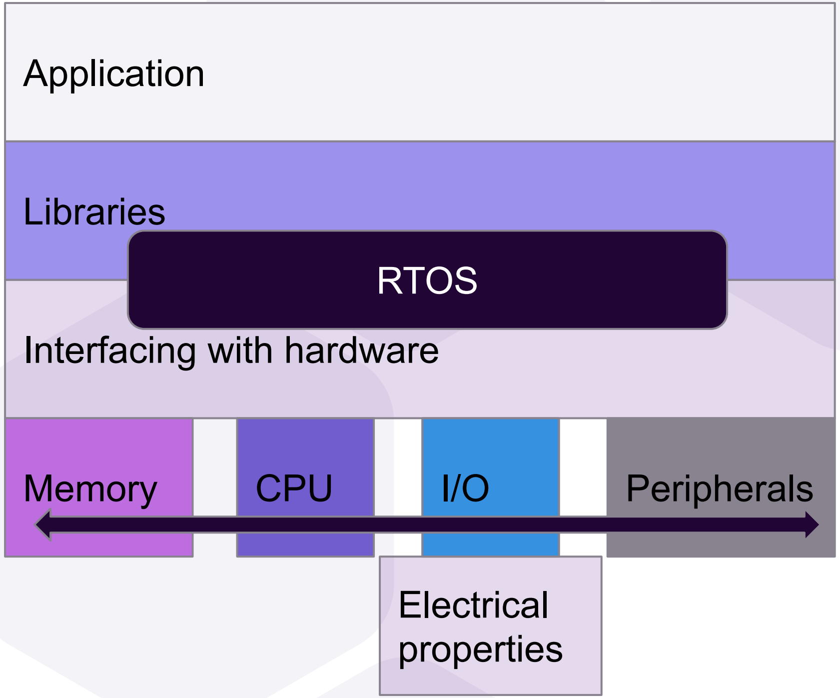
$$\mu \leq n(2^{1/n} - 1), \qquad (12.2)$$

Real-Time Operating Systems

OS - manages system resources and provides services to programs/processes/threads

RTOS - an OS with real-time constraints

- Scheduling policies
- Often support for prioritization
- Libraries for mutexes/semaphores
- Memory management


Application
Libraries
RTOS
Interfacing with hardware
Memory
CPU
I/O
Peripherals
Electrical properties

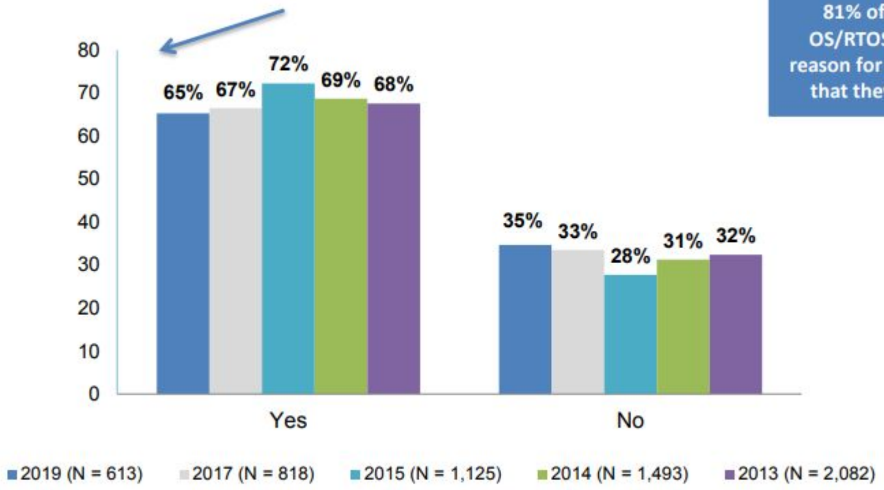
Pros/cons to using an RTOS?

Would you want to write your own RTOS?

“Free” RTOS considerations

- Expertise for being versed in RTOS use isn’t free
    - Usually when you buy software you also buy support
- Patching in updates isn’t free
- Industry use of open-source is tricky
    - License may require release of code

Does your current embedded project use an operating system, RTOS, kernel, software executive, or scheduler of any kind?



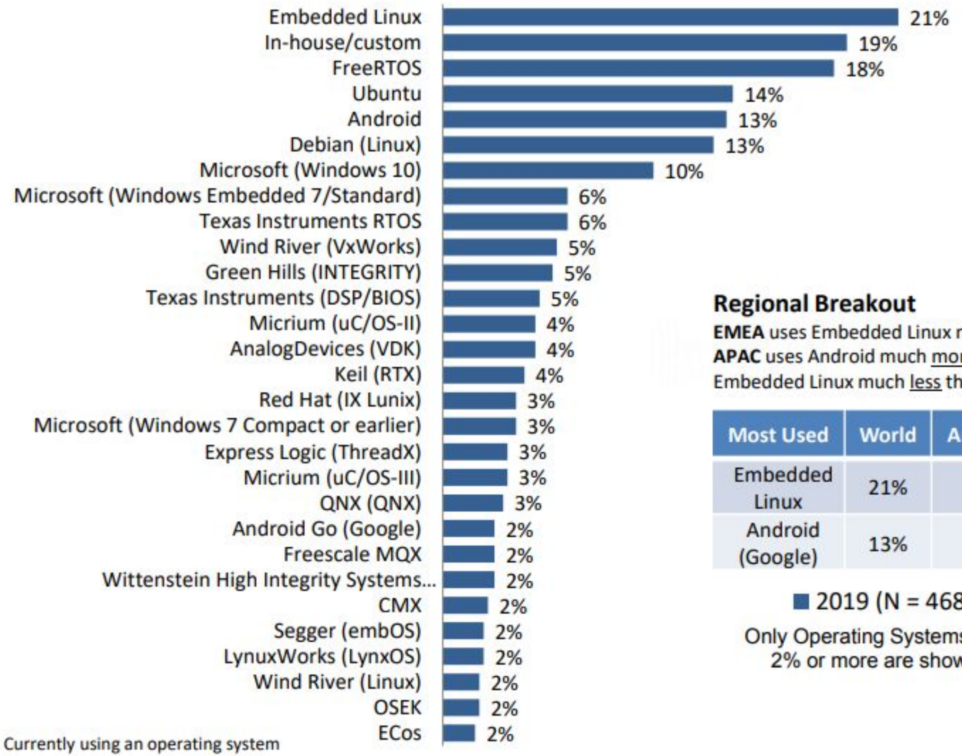
81% of those not using OS/RTOSes, said the main reason for NOT using is simply that they are not needed.

EETimes embedded

2019 Embedded Markets Study

Image source

Please select ALL of the operating systems you are currently using.



Regional Breakout

EMEA uses Embedded Linux much more than other regions.
APAC uses Android much more than other regions and uses Embedded Linux much less that others.

Most Used	World	Americas	EMEA	APAC
Embedded Linux	21%	21%	30%	15%
Android (Google)	13%	9%	14%	27%

■ 2019 (N = 468)

Only Operating Systems with 2% or more are shown.

Base: Currently using an operating system

EETimes embedded 2019 Embedded Markets Study

Image source

Summary

Multitasking introduces complexity

- Data/control dependencies
- Scheduling

RTOS is a layer to manage scheduling