TI RTOS - Introduction

RTOS Concepts & TI RTOS Introduction

Agenda

- Bare metal example
- TI RTOS Concepts
- Sharing resources
- Common challenges

Prerequisites

- Basic embedded firmware experience
  - Interrupts
  - Memory
    - Data
    - Stack
    - Heap

Bare metal vs. RTOS

Example – Smart Thermostat

Example – Smart Thermostat

Super loops, interrupts and how we would really want it to work

Example – Smart Thermostat

- Requirements – Version 1
  - User interface
    - LCD
    - Buttons
  - Remote control to change temperature
    - RF Transceiver
  - Sensor inputs
    - Temperature
  - Schedule operation based on time

Bare Metal – Smart Thermostat

- Bare metal system design – No OS
- Super loop:

```
void main() {
  /* Initialize hardware */

  while(1) {
    checkButtons();
    updateLcd();
    checkTemperature();
    checkTimeSchedule();
    checkRadioReceive();
    doRadioTransmit();
  }
}
```

Example – Smart Thermostat

- **Updated** Requirements – Version 2
  - User interface
    Smooth user experience, < X ms from button press to LCD updated
    - LCD
    - Buttons
  - Remote control to change temperature
    Needs to send an ACK within Y ms from receiving a packet
    - RF Transceiver
  - Sensor inputs
    Sensor readings every second
    - Temperature
    - Humidity
  - Schedule operation based on time

Bare Metal – Smart Thermostat

- Bare metal system design – No OS
- **Interrupt driven**

```c
void main() {
  /* Initialize hardware and setup interrupts */
  while(1);
}
```

Interrupt service routines

```c
void buttonIsr() {
  /* Read buttons */
  /* Update LCD */
  /* Do logic */
}
```

```c
void scheduleTimerIsr() {
  /* Check schedule */
  /* Update target temp. */
}
```

```c
void sensorTimerIsr() {
  /* Save current temp. */
}
```

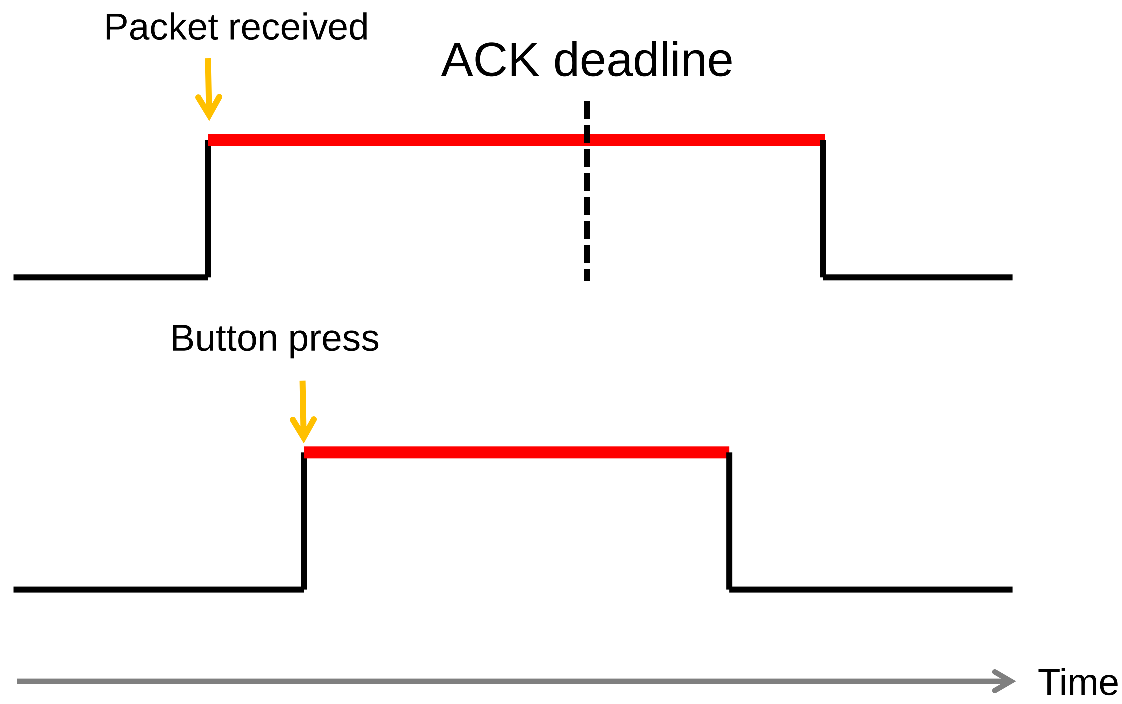
```c
void radioRxIsr() {
  /* Check packet*/
  /* Transmit ACK*/
}
```

Bare Metal – Smart Thermostat

Interrupt service routines – No nesting

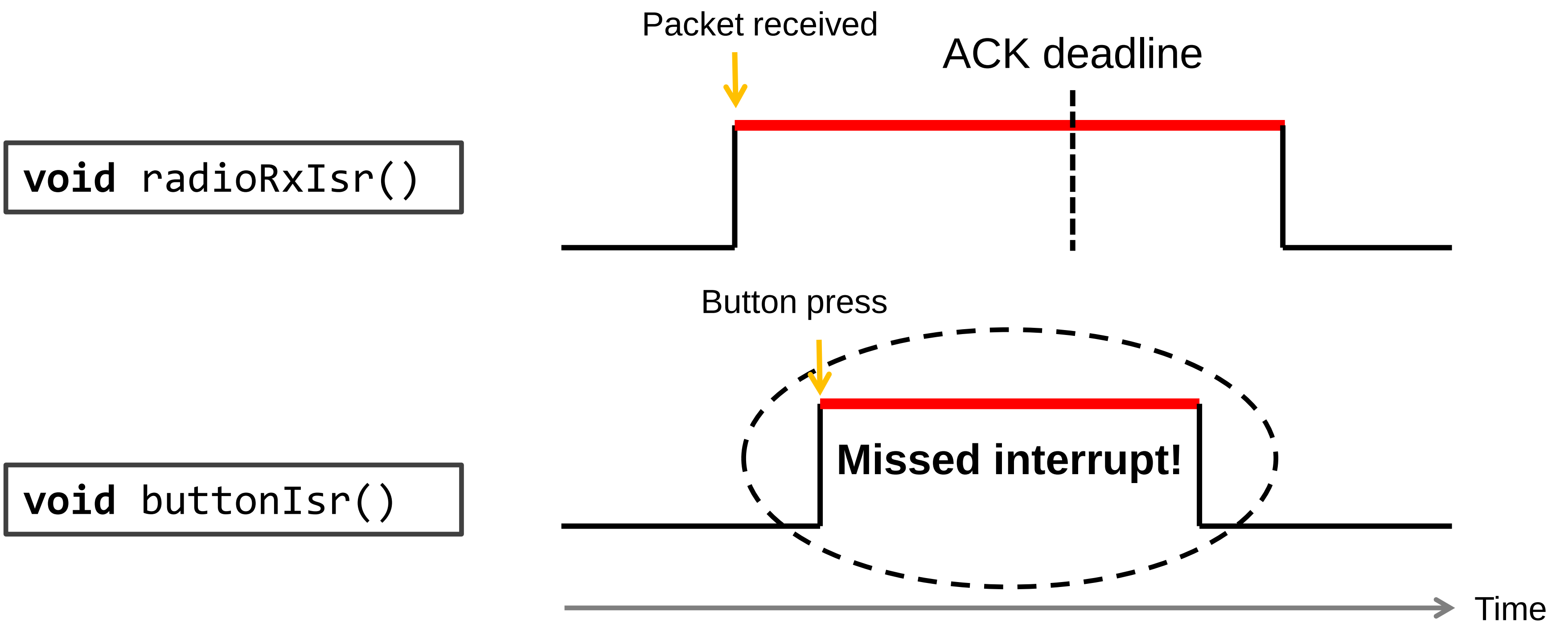
`void radioRxIsr()`

`void buttonIsr()`



Bare Metal – Smart Thermostat

Interrupt service routines – No nesting



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Bare Metal – Smart Thermostat

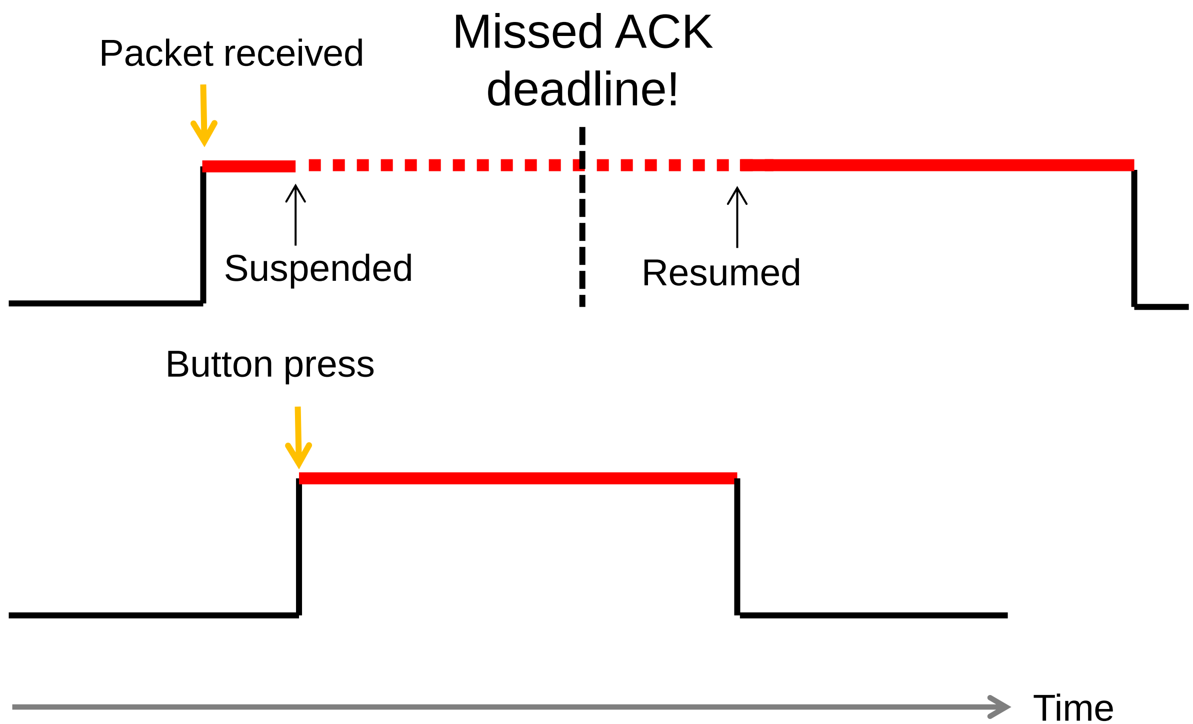
Solution: <u>Nested</u> Interrupt service routines

`void radioRxIsr()`

Lower priority

Higher priority

`void buttonIsr()`



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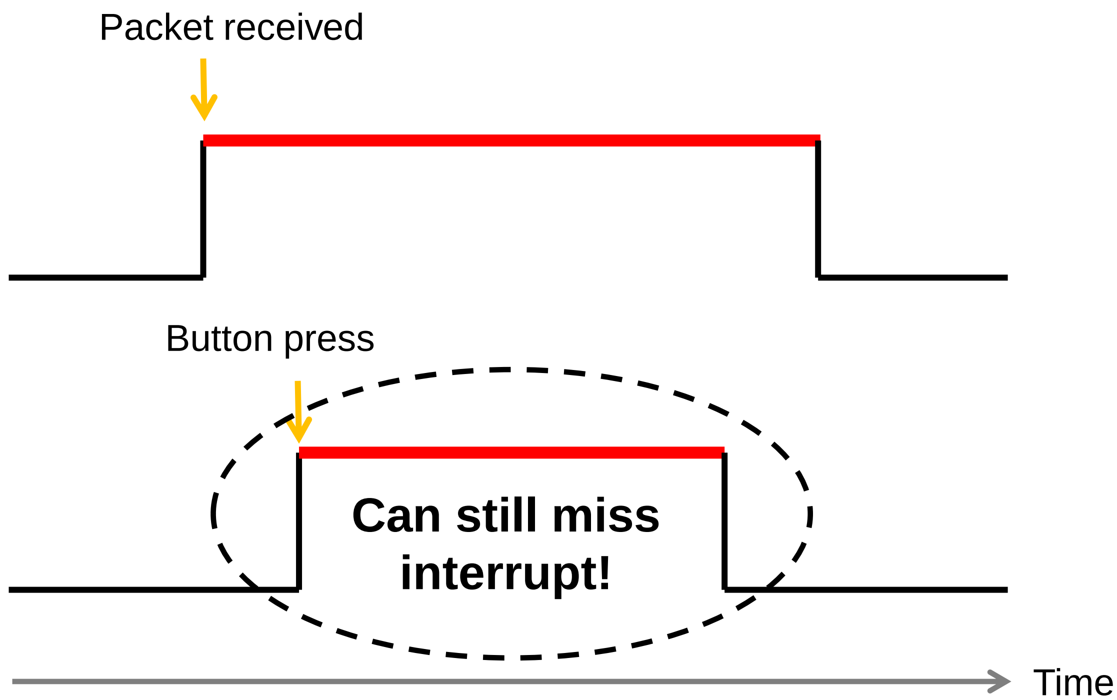
Solution: <u>Nested</u> Interrupt service routines

`void radioRxIsr()`

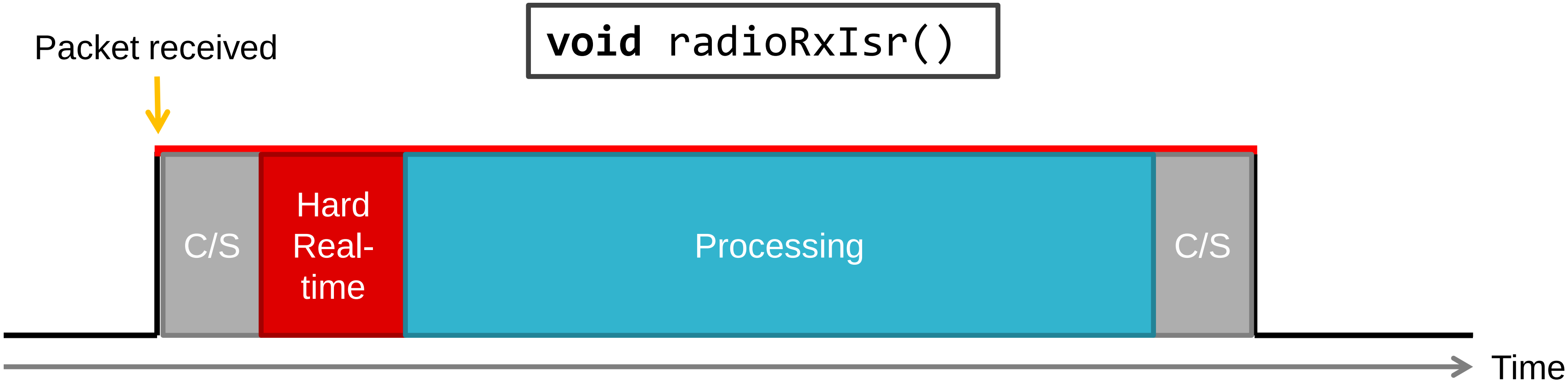
Higher priority

Lower priority

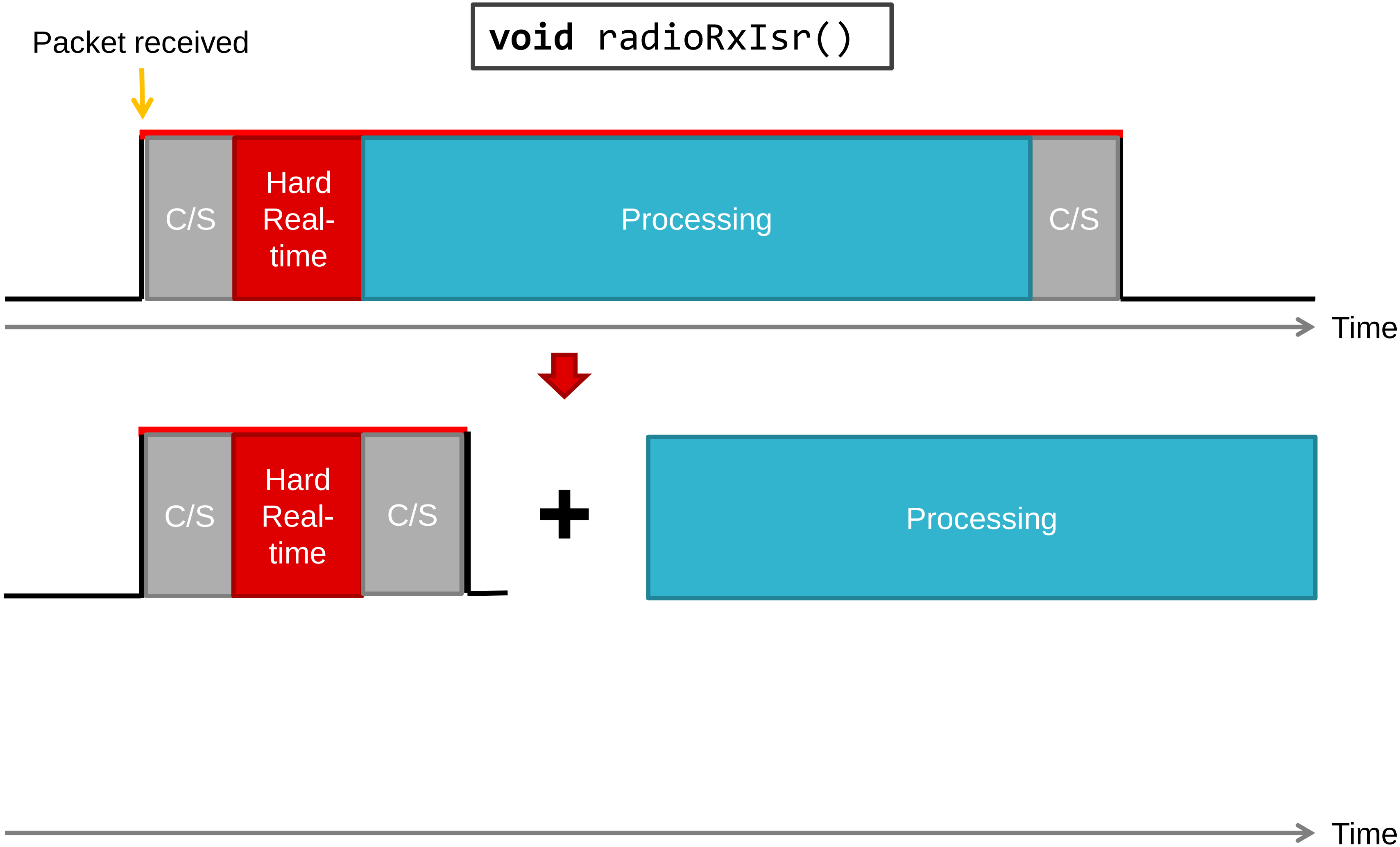
`void buttonIsr()`



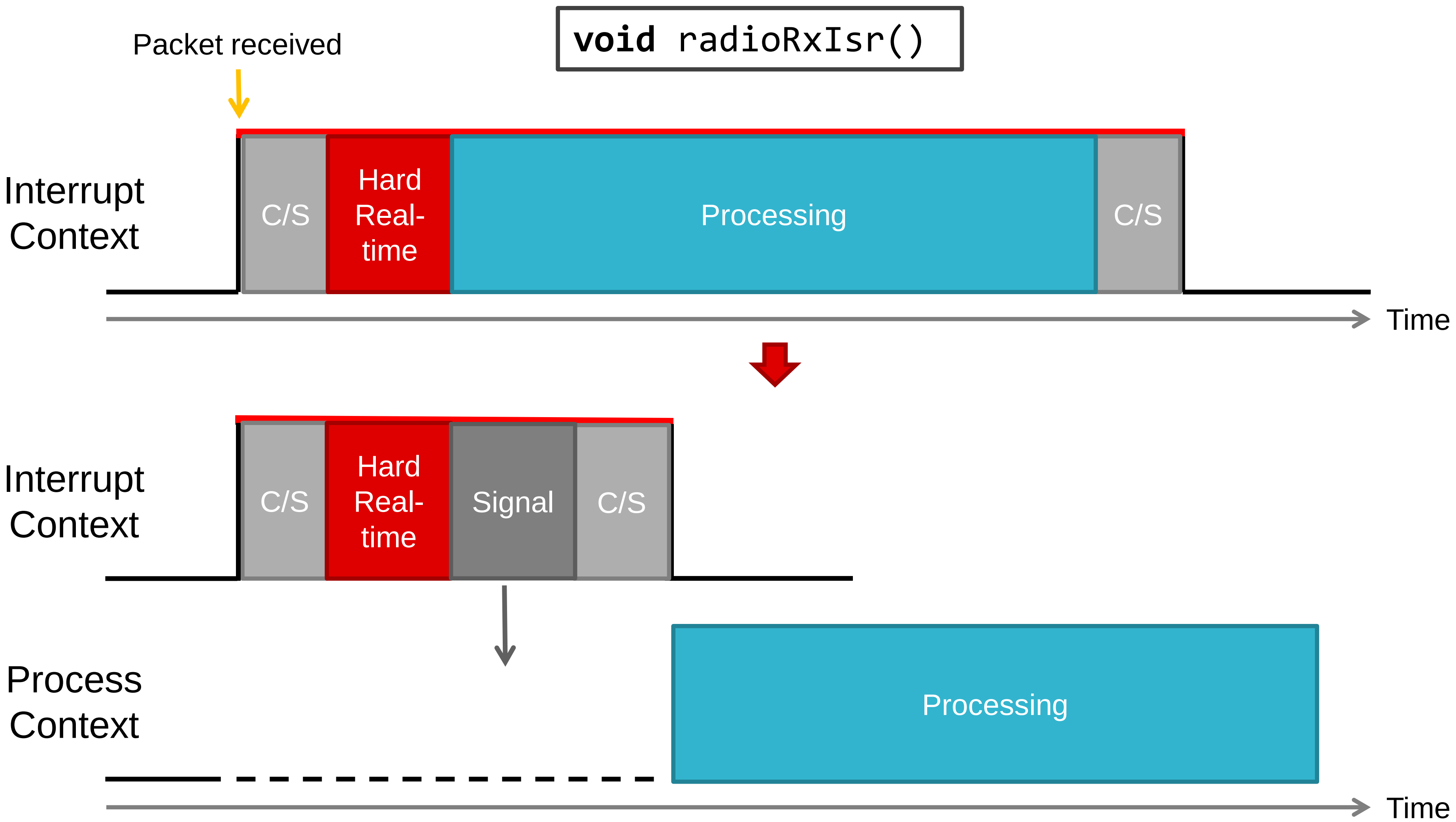
Bare Metal – Smart Thermostat



Bare Metal – Smart Thermostat



Bare Metal – Smart Thermostat



Bare Metal – Smart Thermostat

- **Interrupt driven with processing in main**

```c
void main() {
  /* Initialize hardware and setup interrupts */
  while(1) {
    if(buttonSemaphore)
      processButtonPress();     // Takes time
    if(radioRxSemaphore)
      processPacketReceived(); // Takes time
  }
}
```

Interrupt service routines

```c
void buttonIsr() {
  /* Read buttons */
  buttonSemaphore = 1;
}
```

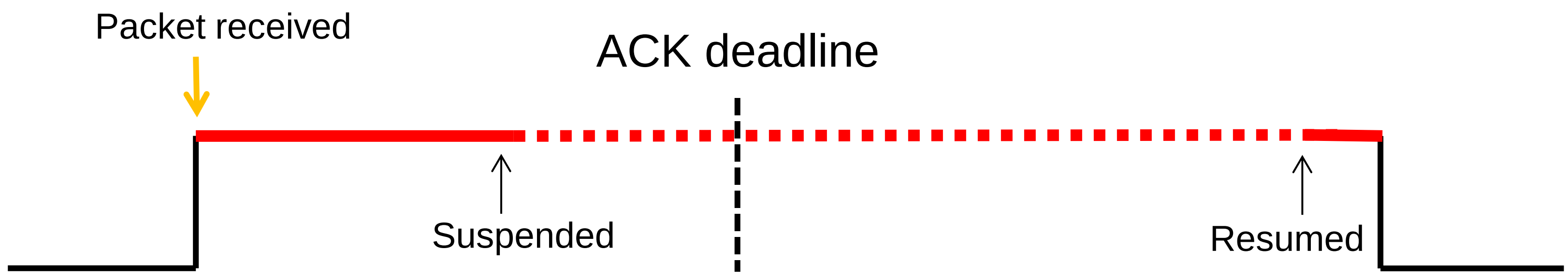
```c
void radioRxIsr() {
  /* Read packet*/
  radioRxSemaphore = 1;
}
```

Bare Metal – Smart Thermostat

Nested Interrupt service routines

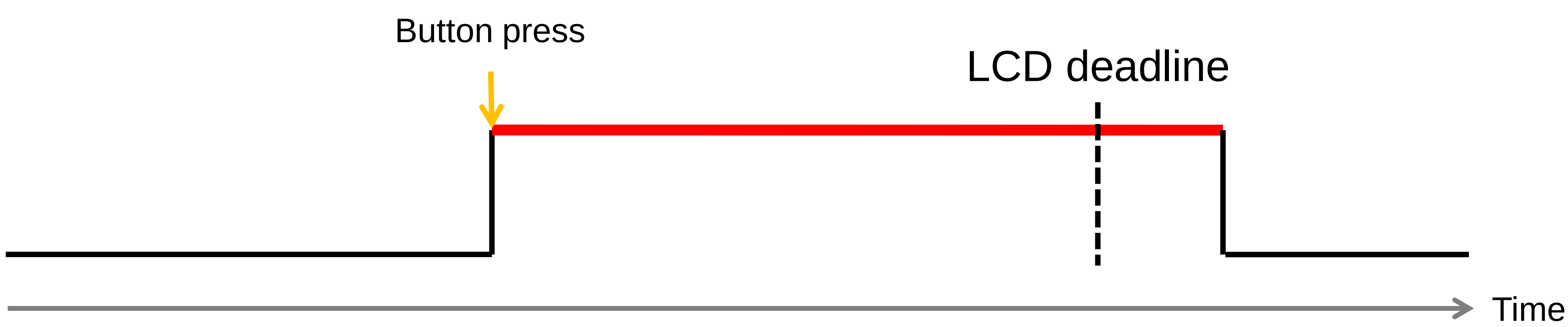
```
void radioRxIsr()
```

Lower priority

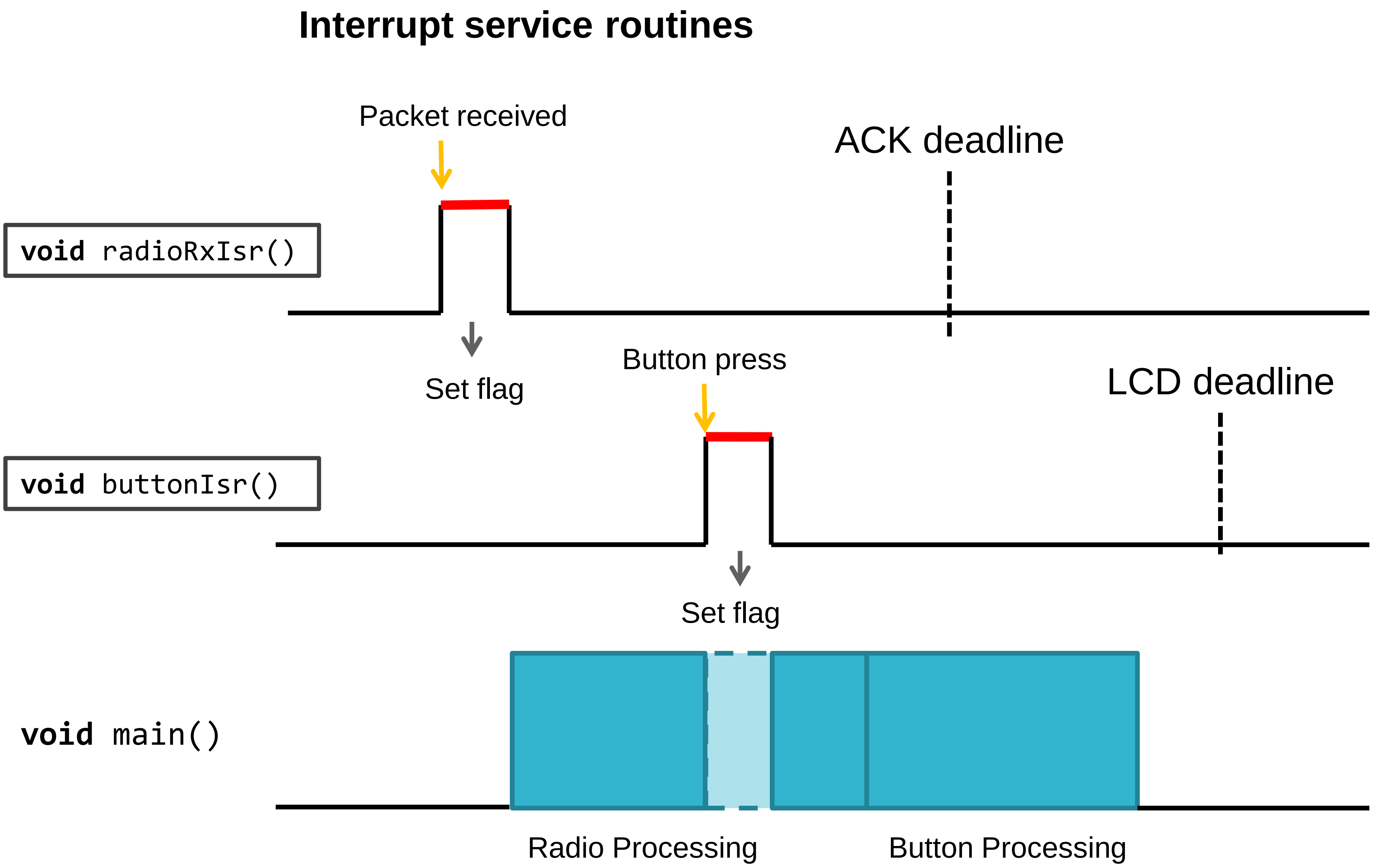



```
void buttonIsr()
```

Higher priority

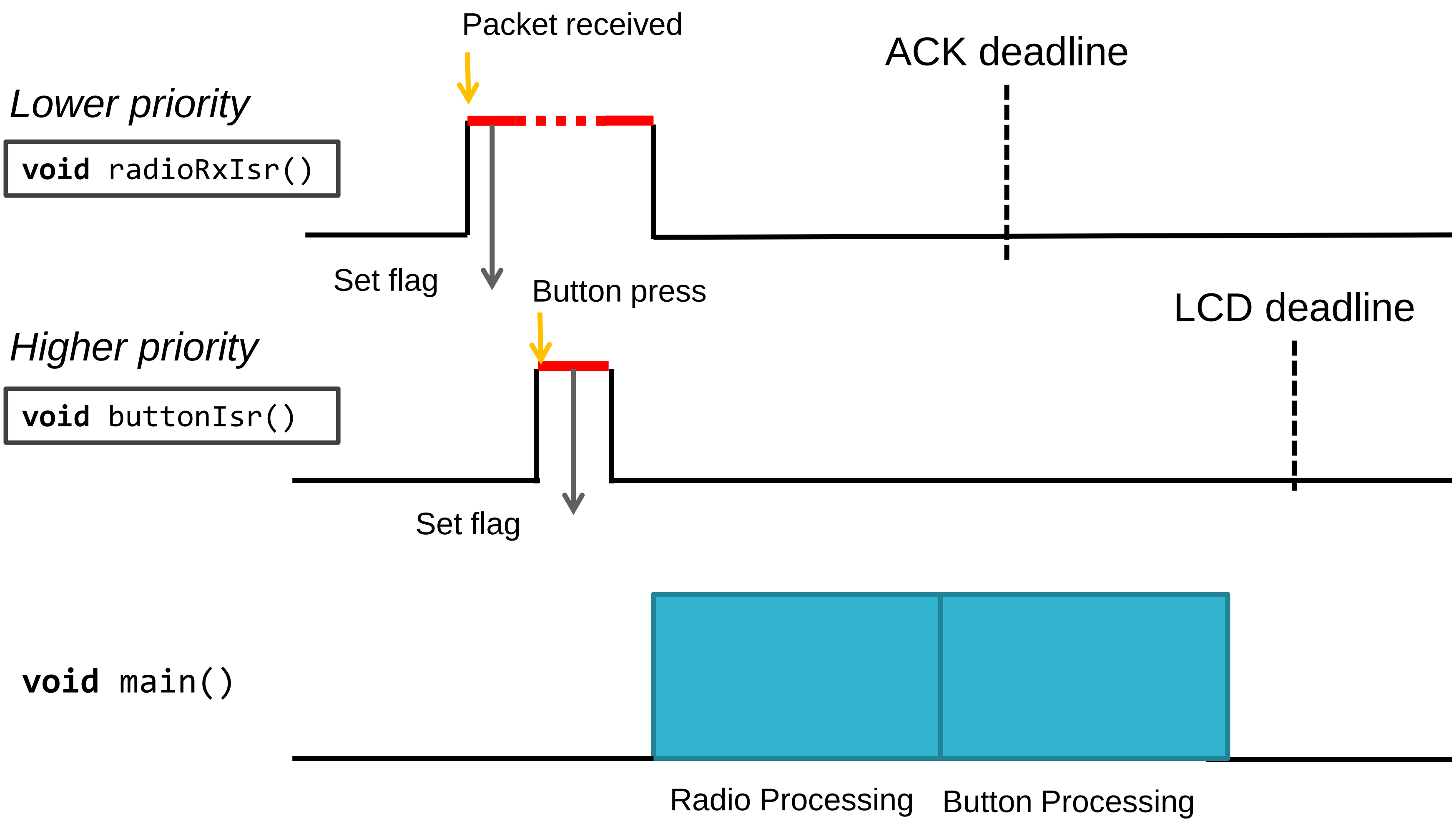


Bare Metal – Smart Thermostat



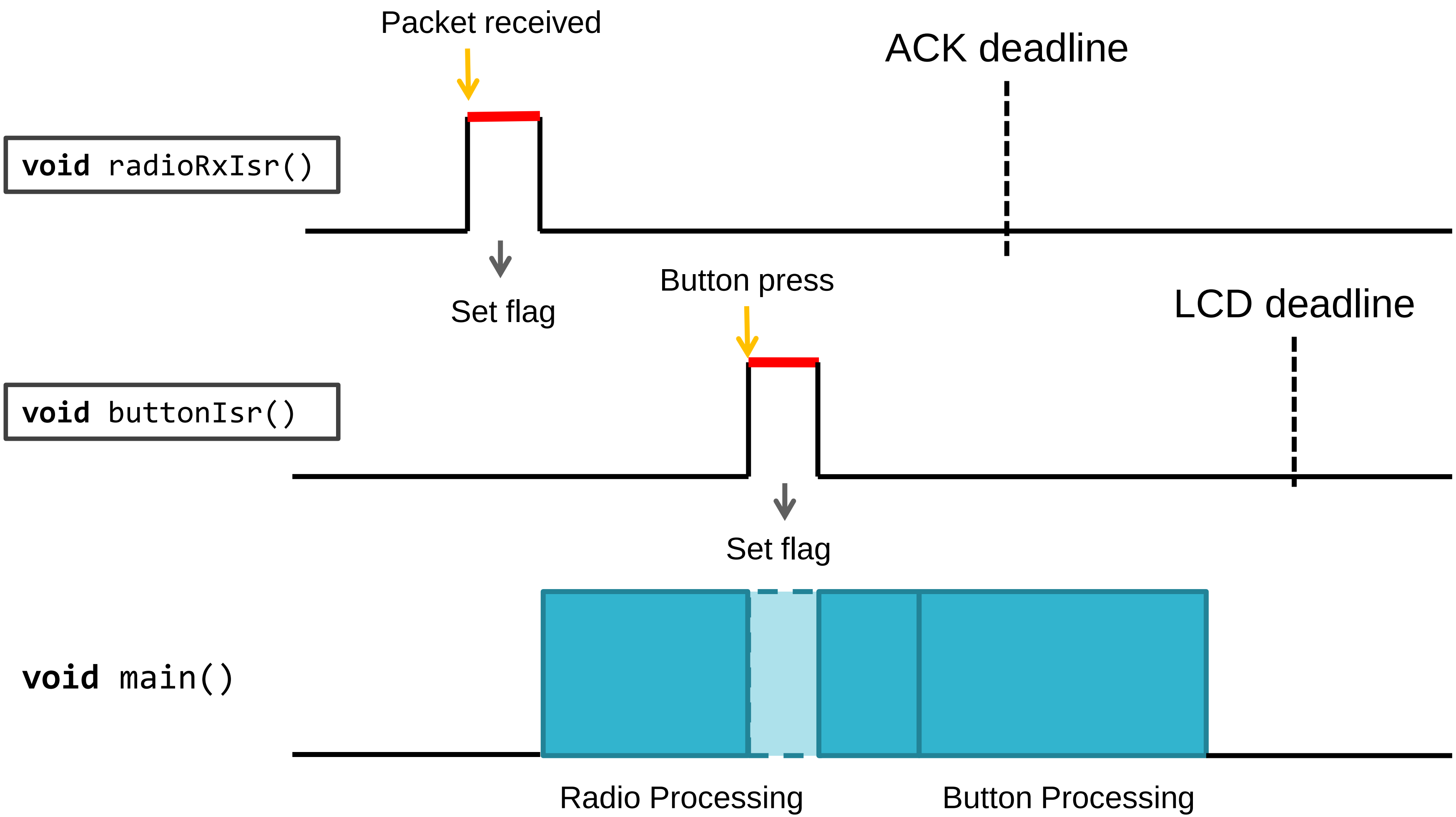
Bare Metal – Smart Thermostat

Nested Interrupt service routines



Bare Metal – Smart Thermostat

What is one of the major problems with this approach?



Example – Smart Thermostat

- **Updated** Requirements – Version 3
  A smooth user experience is most important. If necessary, it's okay to miss the ACK deadline to improve the user experience.

  – User interface
    Smooth user experience, <200ms from button press to LCD updated
    - LCD
    - Buttons

  – Remote control to change temperature
    Needs to send an ACK within 1ms from receiving a packet
    - RF Transceiver

  – Sensor inputs
    Sensor readings every second
    - Temperature
    - Humidity

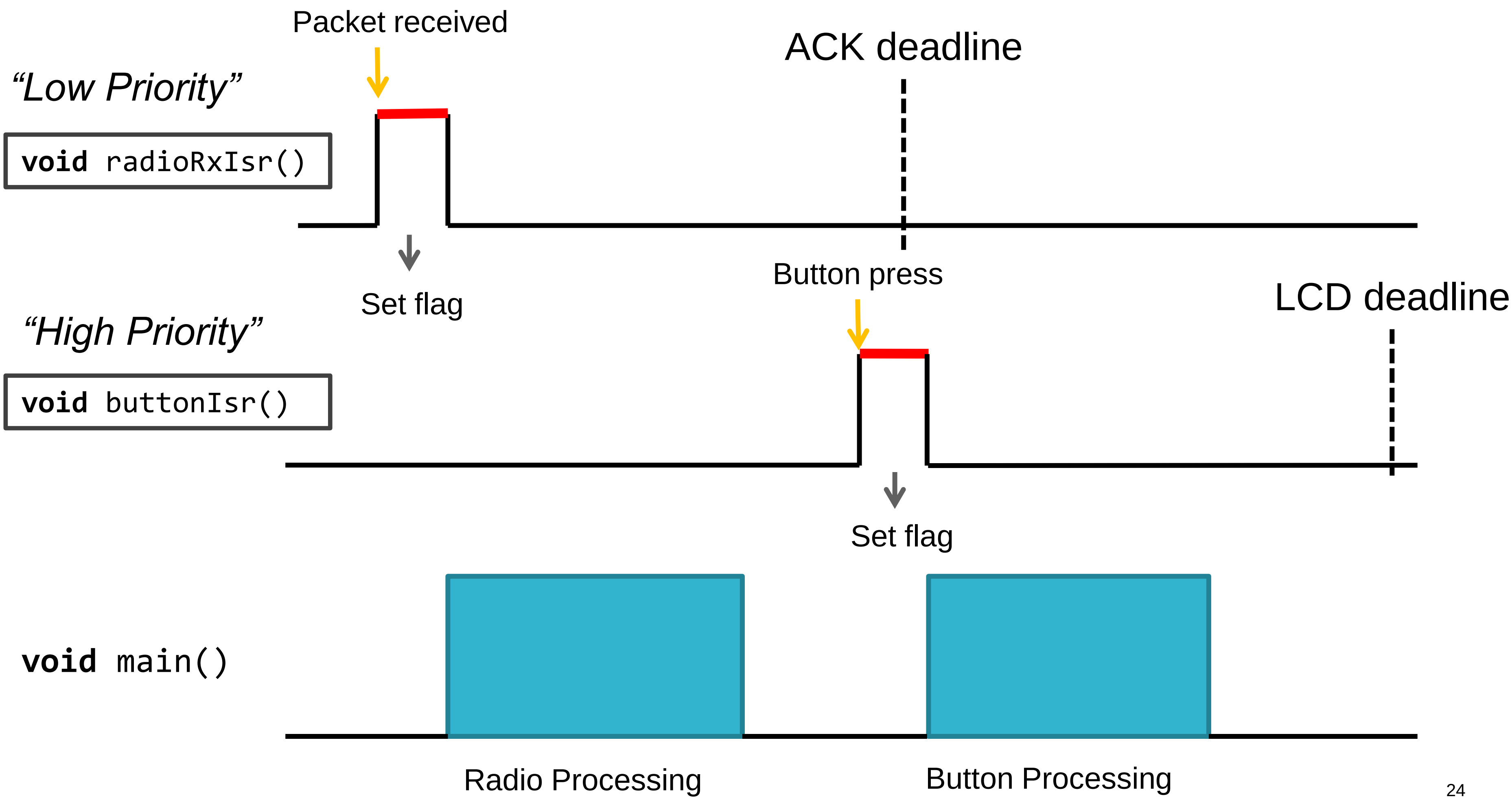
  – Schedule operation based on time

Example – Smart Thermostat

- **Updated** Requirements – Version 3
  A smooth user experience is most important. If necessary, it's okay to miss the ACK deadline to improve the user experience.
  - User interface – **"High Priority"**
    Smooth user experience, <200ms from button press to LCD updated
    - LCD
    - Buttons
  - Remote control to change temperature – **"Low Priority"**
    Needs to send an ACK within 1ms from receiving a packet
    - RF Transceiver
  - Sensor inputs
    Sensor readings every second
    - Temperature
    - Humidity
  - Schedule operation based on time

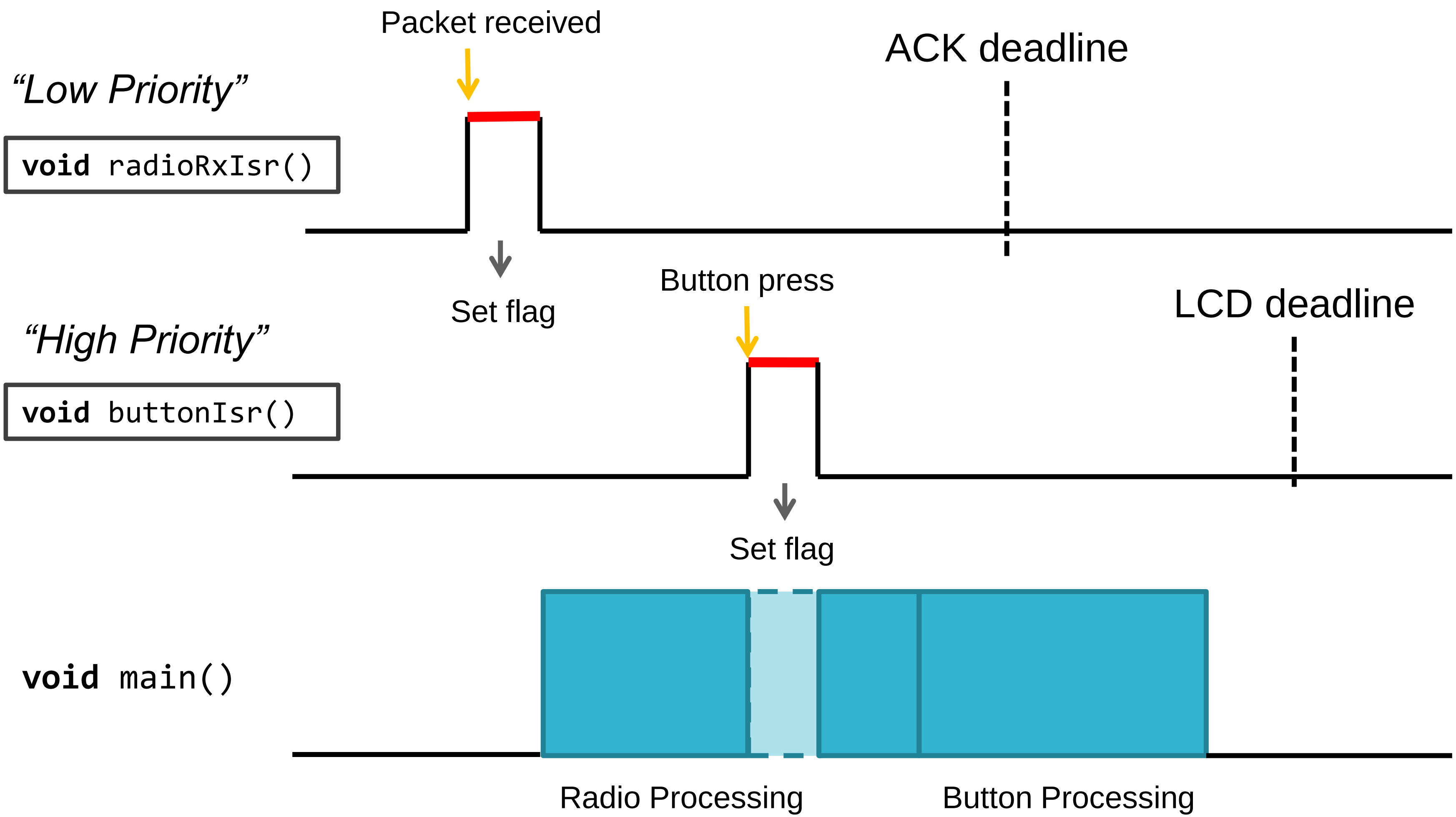
Bare Metal – Smart Thermostat

Case one: Interrupts so far apart that all process is done before next interrupt



Bare Metal – Smart Thermostat

Case two: Process interrupted, but still time for all processing to finish



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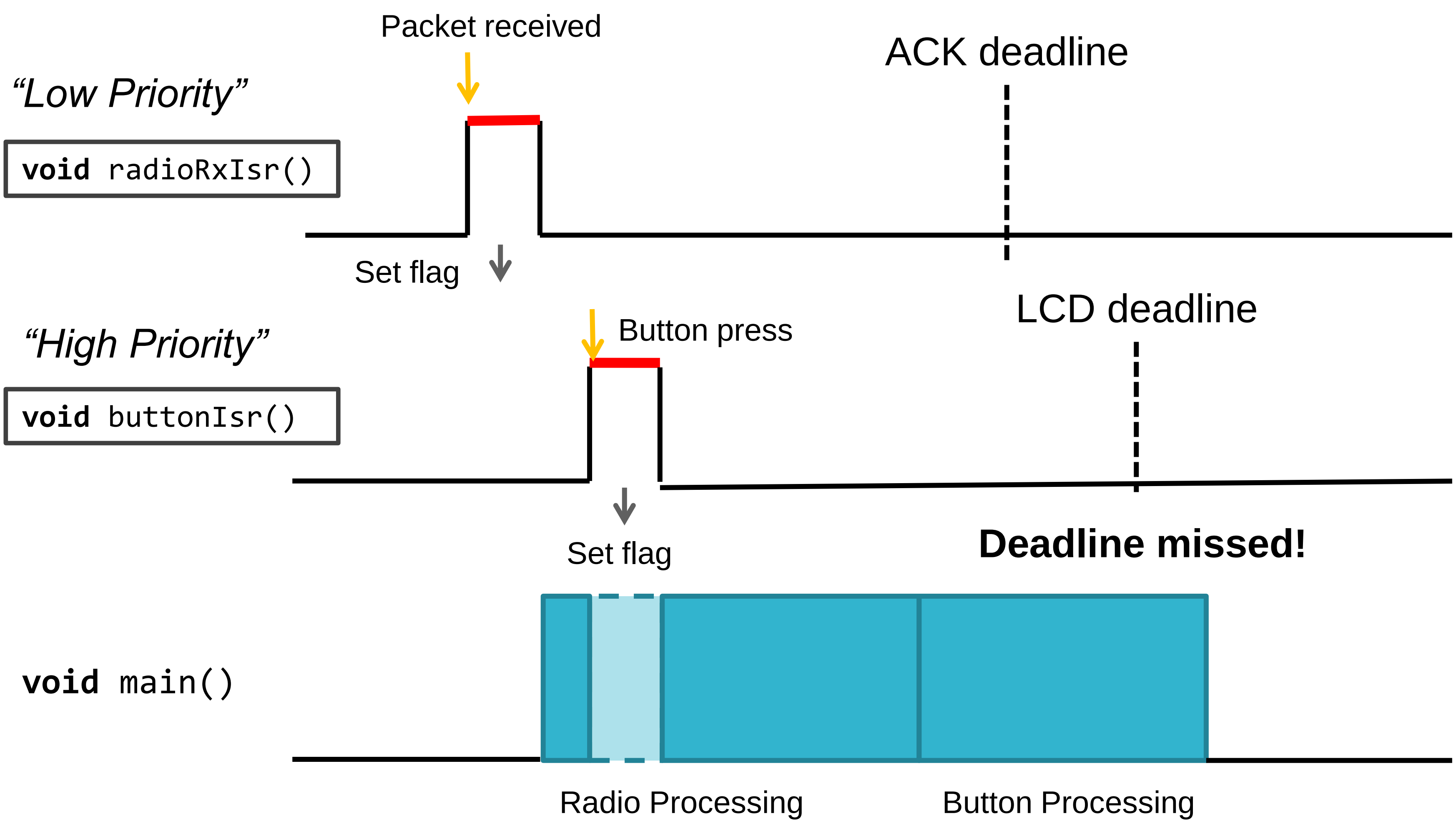
Case three: Low priority task makes higher priority task miss deadline!



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Why did this happen?

```
void main() {
  /* Initialize hardware and setup interrupts */
  while(1) {
    if(buttonSemaphore)
      processButtonPress();       // Takes time
    if(radioRxSemaphore)
      processPacketReceived();    // Takes time
  }
}
```

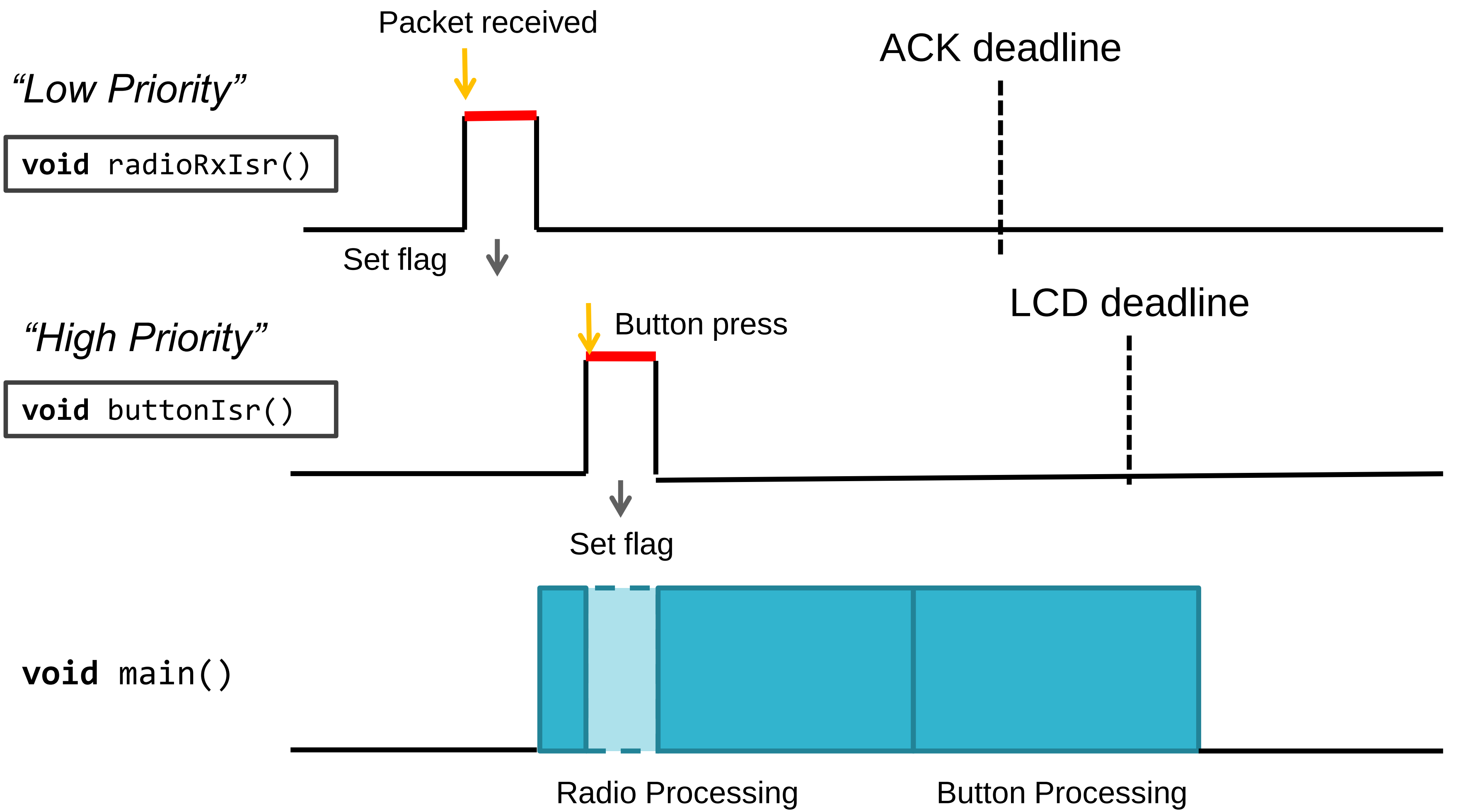
Interrupt service routines

```
void buttonIsr() {
  /* Read buttons */
  buttonSemaphore = 1;
}
```

```
void radioRxIsr() {
  /* Read packet*/
  radioRxSemaphore = 1;
}
```

Bare Metal – Smart Thermostat

How would we have wanted this to work?



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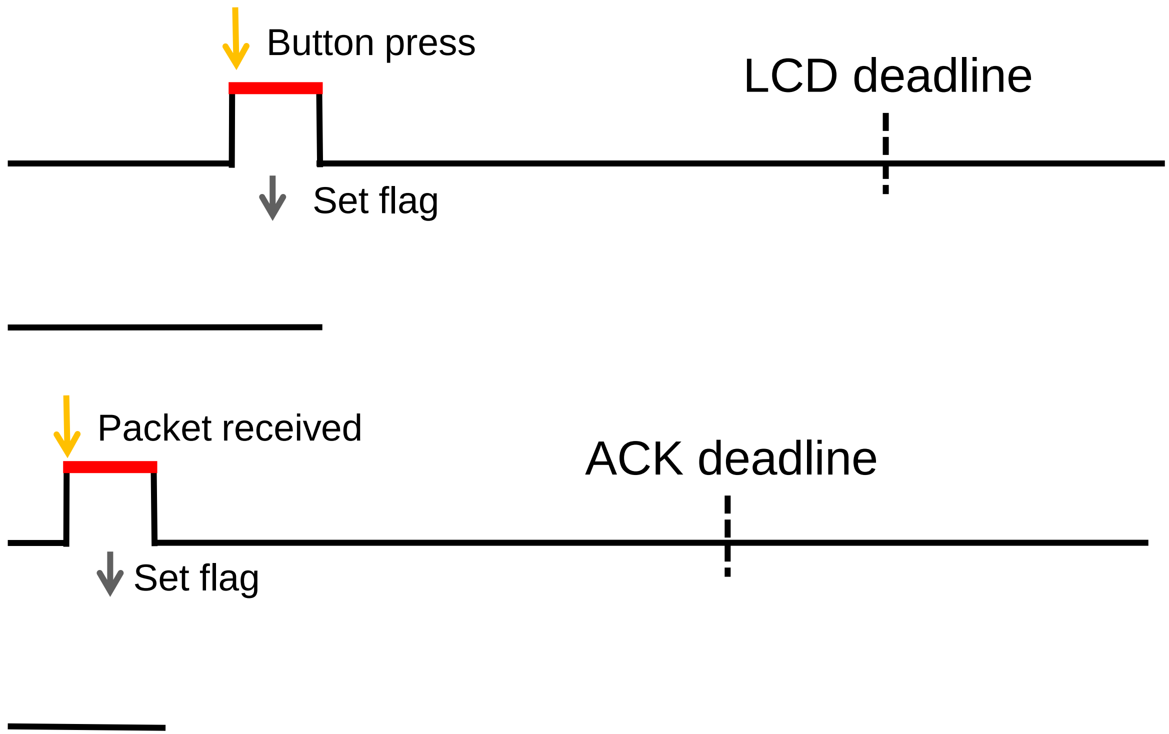
How would we have wanted this to work?

`void buttonIsr()`

“High Priority”
`void processButton()`

`void radioRxIsr()`

“Low Priority”
`void processPacketRx()`



Deadline missed!

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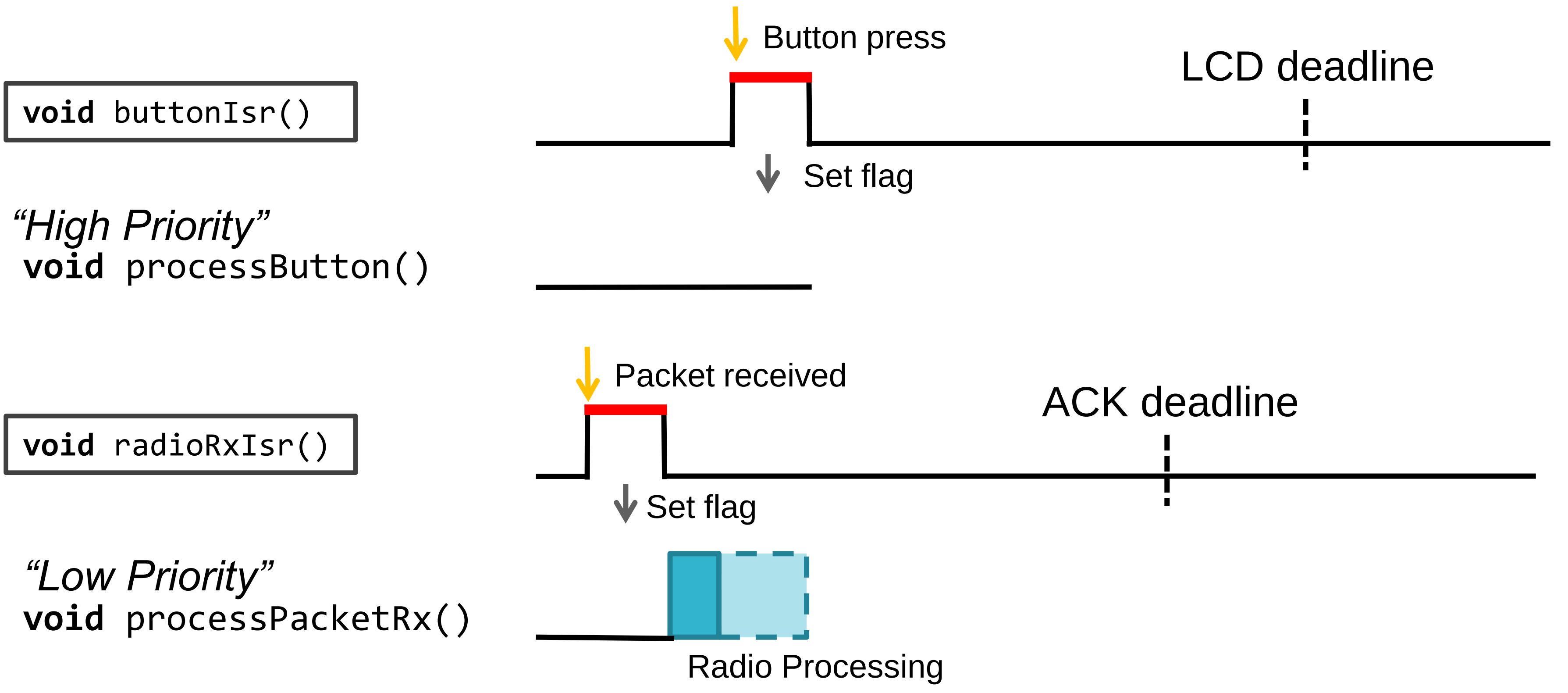
How would we have wanted this to work?



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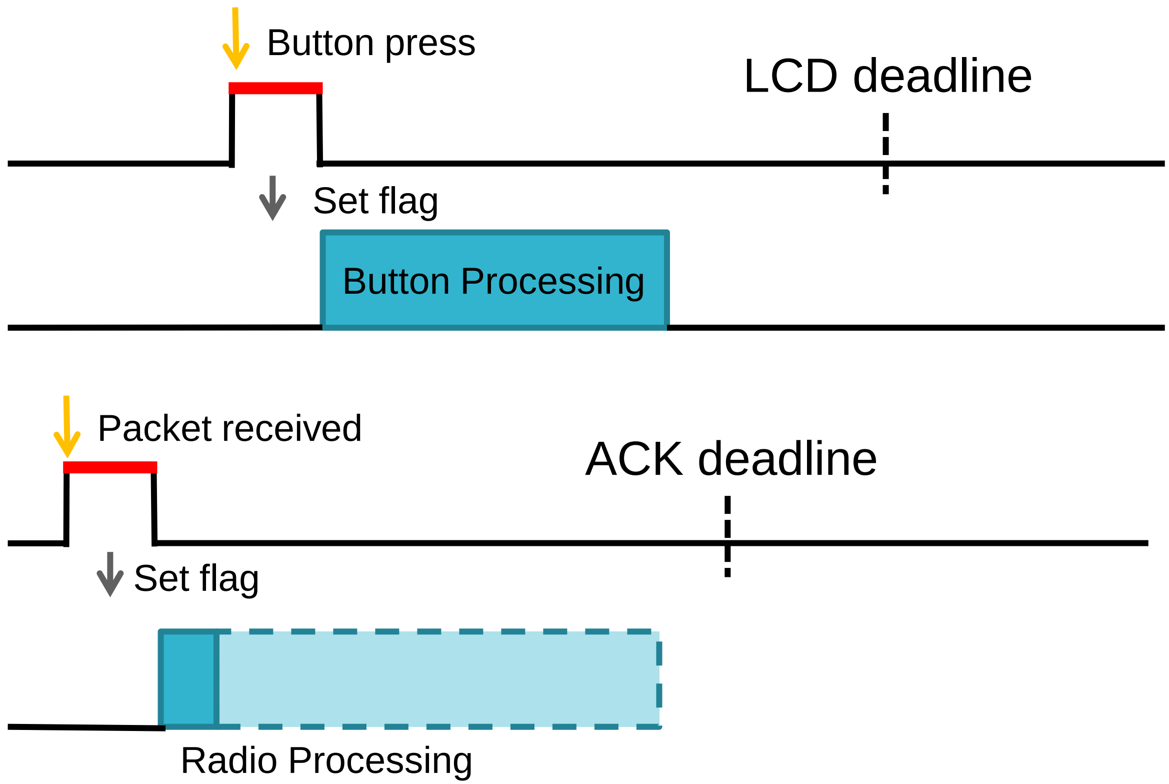
How would we have wanted this to work?

`void buttonIsr()`

“High Priority”
`void processButton()`

`void radioRxIsr()`

“Low Priority”
`void processPacketRx()`



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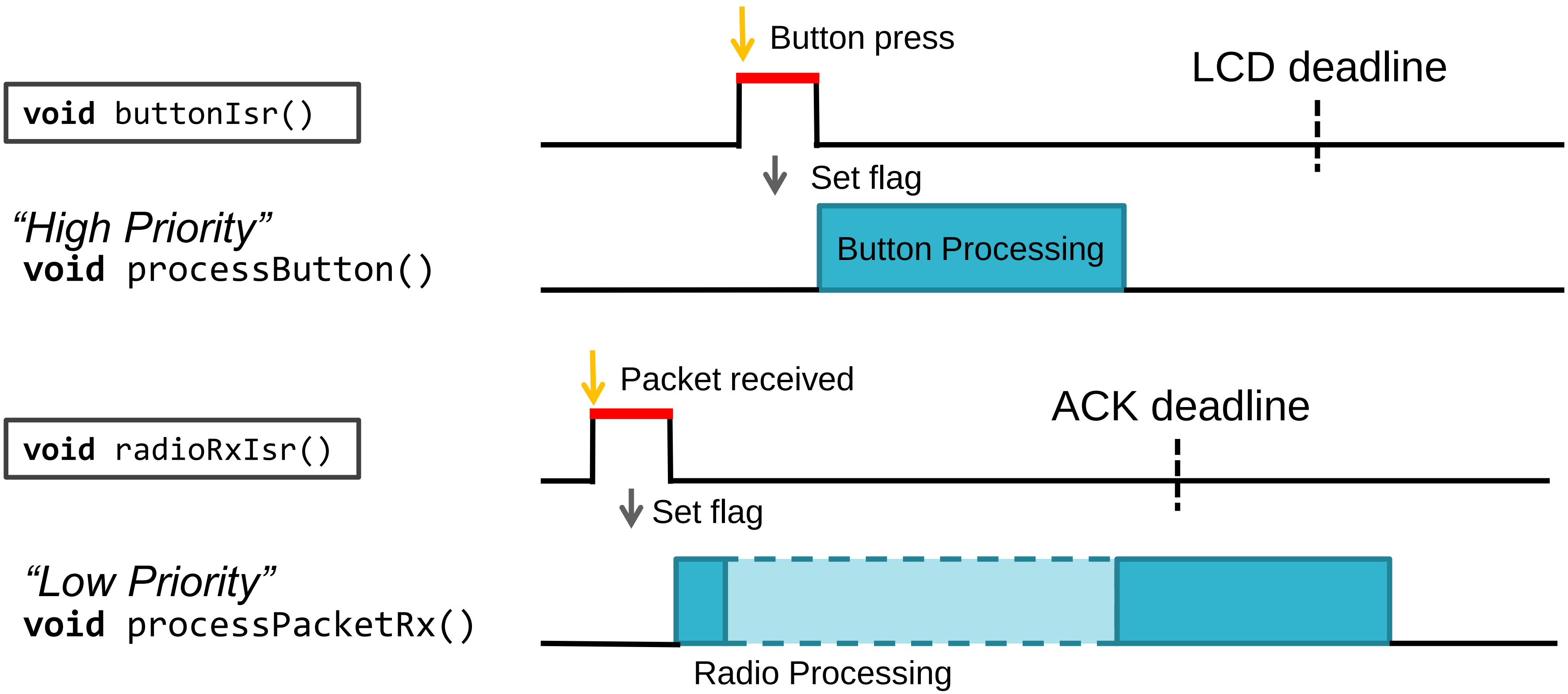
How would we have wanted this to work?

Finished in time!



Deadline missed, but that's ok

Bare Metal – Smart Thermostat

Processing running in
- different contexts
- at different priorities

“High Priority”
`void processButton()`

```
void processButton() {
  /* Which button */
  /* Do logic */
  /* Update LCD */
}
```

“Low Priority”
`void processPacketRx()`

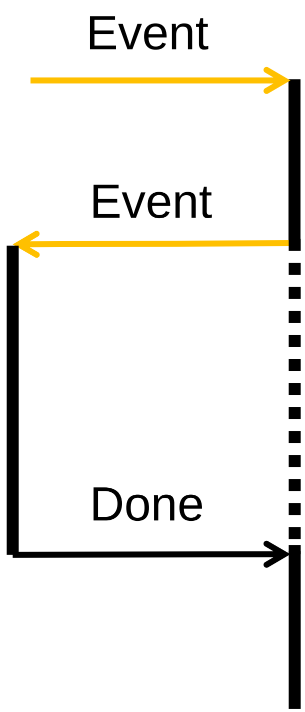
```
void processPacketRx() {
  /* Validate packet */
  /* Do logic */
  /* Send ACK */
}
```

Bare Metal – Smart Thermostat

Processing running in
- different contexts
- at different priorities

"High Priority"
`void processButton()`

```
void processButton() {
  /* Which button */
  /* Do logic */
  /* Update LCD */
}
```



"Low Priority"
`void processPacketRx()`

```
void processPacketRx() {
  /* Validate packet */
  /* Start doing logic */




  /* Continue logic */
  /* Send ACK */
}
```

Bare Metal – Smart Thermostat

This is what an RTOS is all about

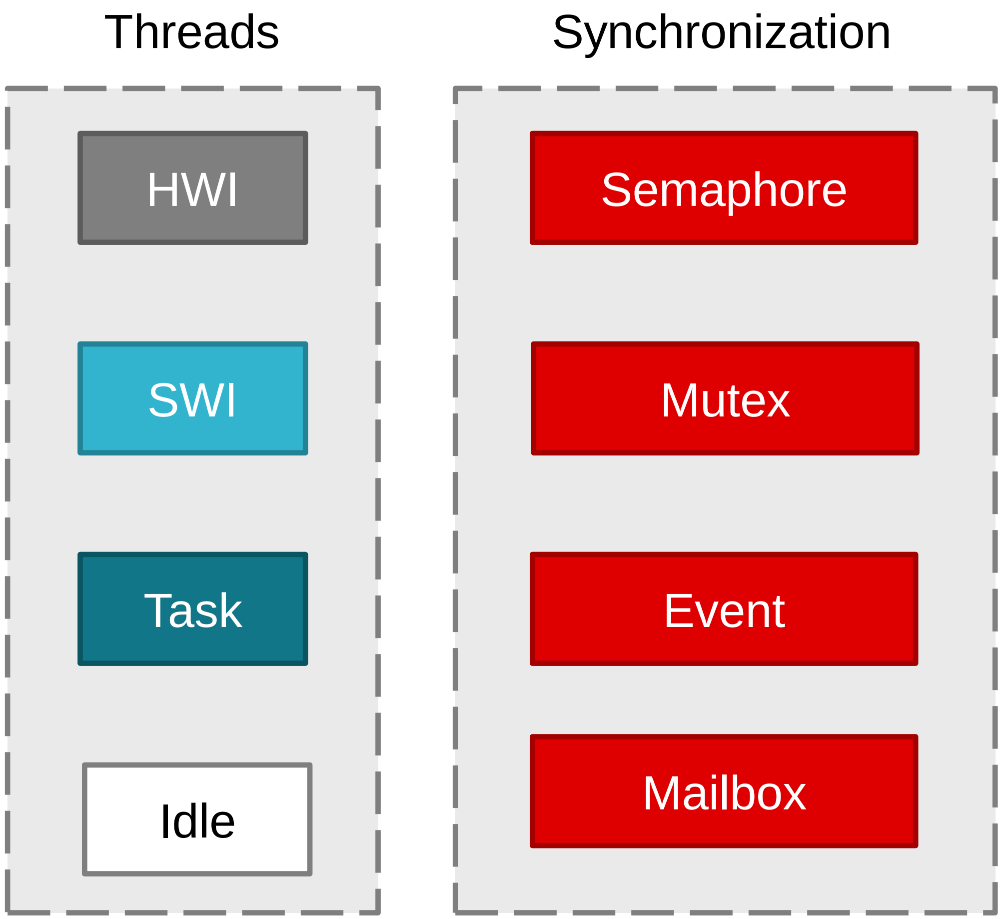
- Each process does its processing in its own context
- An event can trigger both
  - Start of a new process
    - If currently idle
  - Switching the running process
    - If the new process has higher priority than the running one

An RTOS does not do anything that cannot be without an OS, but

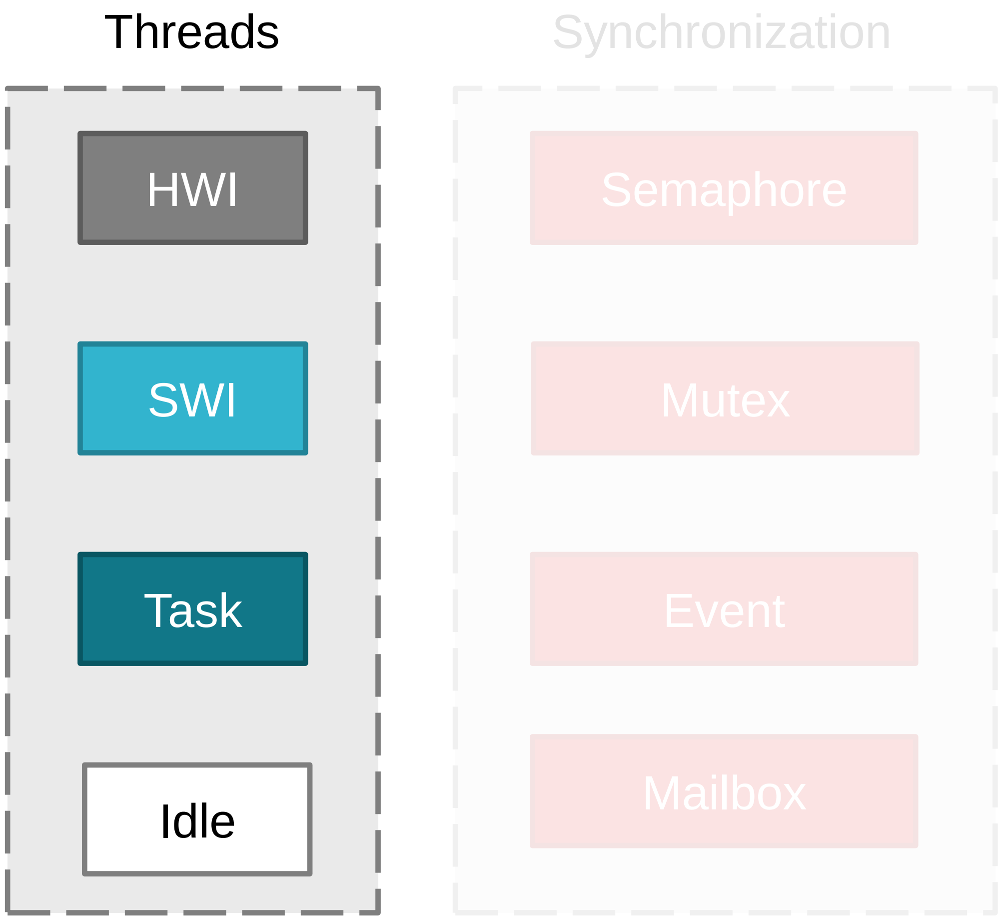
- It makes it simpler to write complex applications
  - Simpler to write event-driven code
  - Simpler to partition code
  - Simpler to guarantee deadlines

TI RTOS Concepts

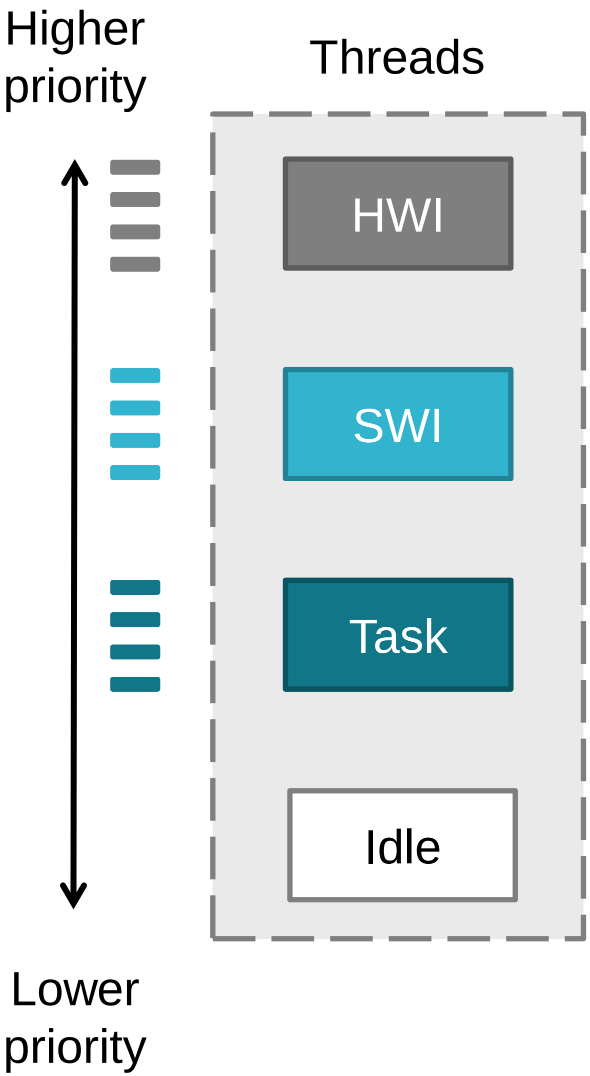
TI RTOS – Kernel Objects Overview



TI RTOS – Kernel Objects Overview



Threads overview



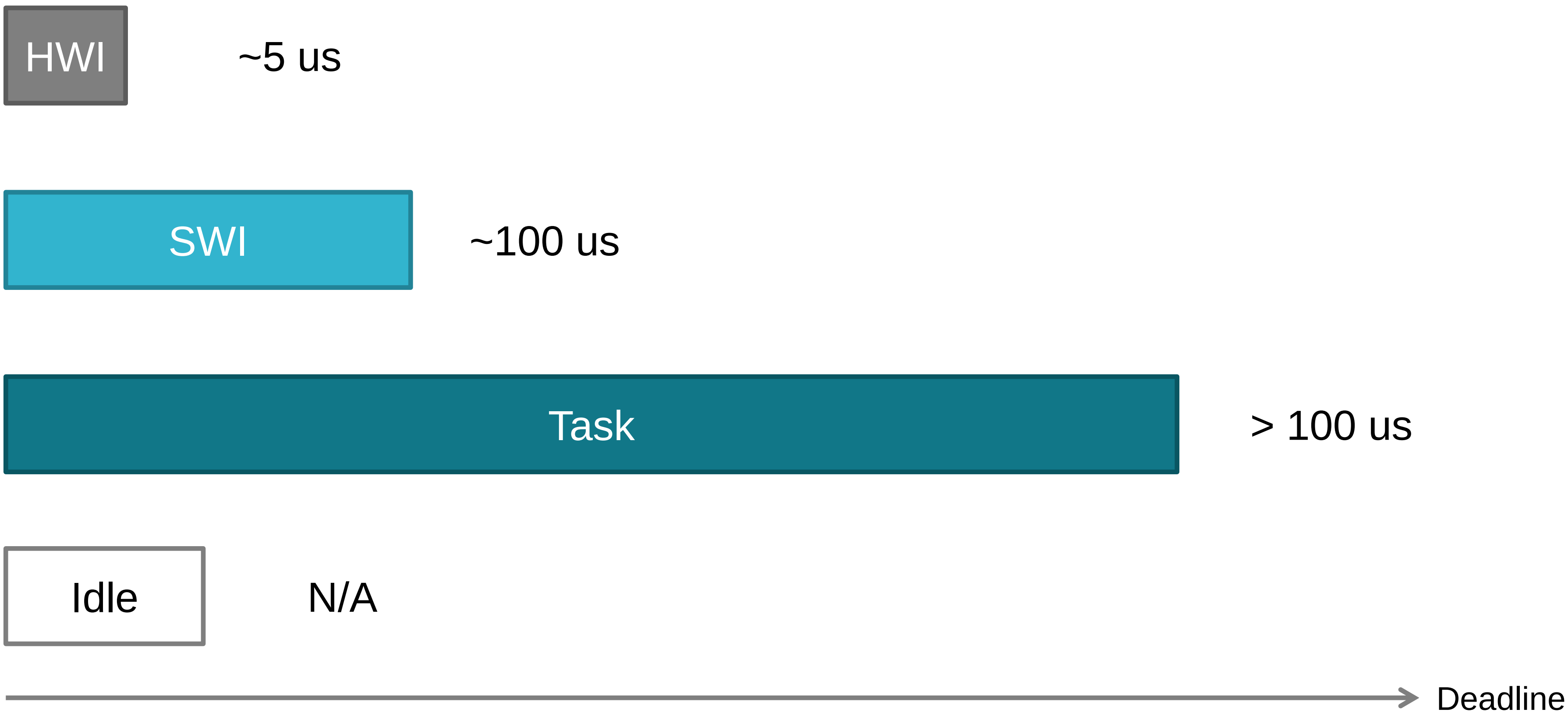
- Handles hardware interrupts
- Priorities set in hardware

- Usually used for HWI follow-up processing
- Up to 32 user configurable priorities

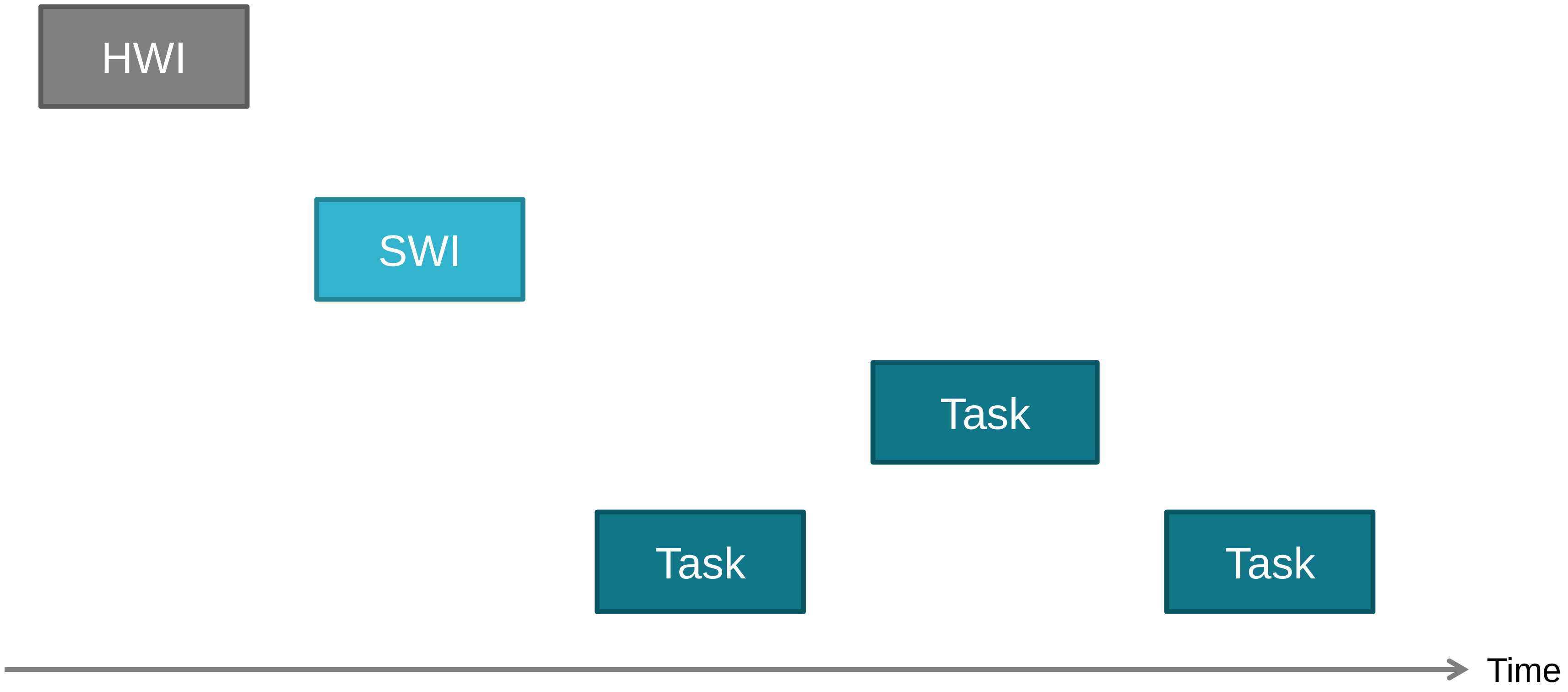
- Used for all complex and/or continuous processing
- Up to 32 user configurable priorities

- Special thread – Runs when nothing else is running

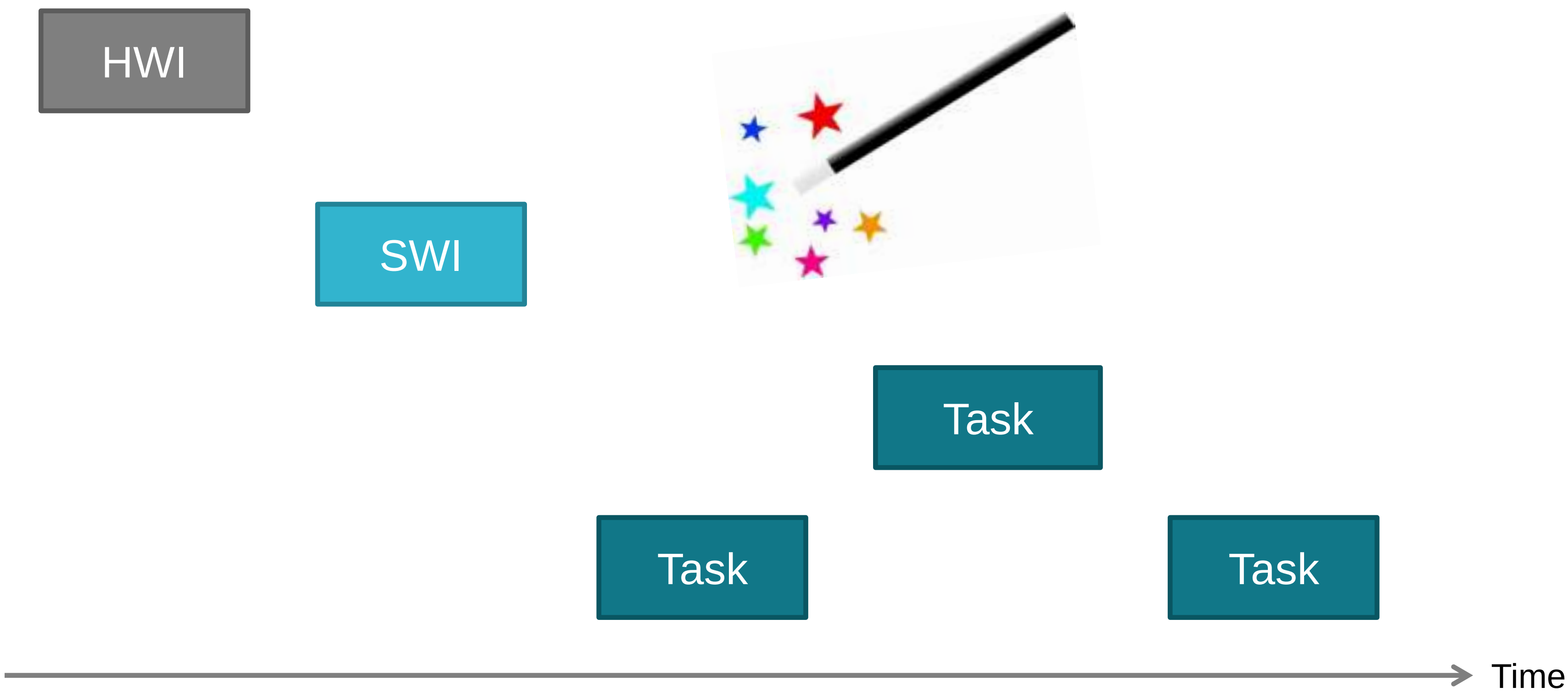
Threads and deadlines



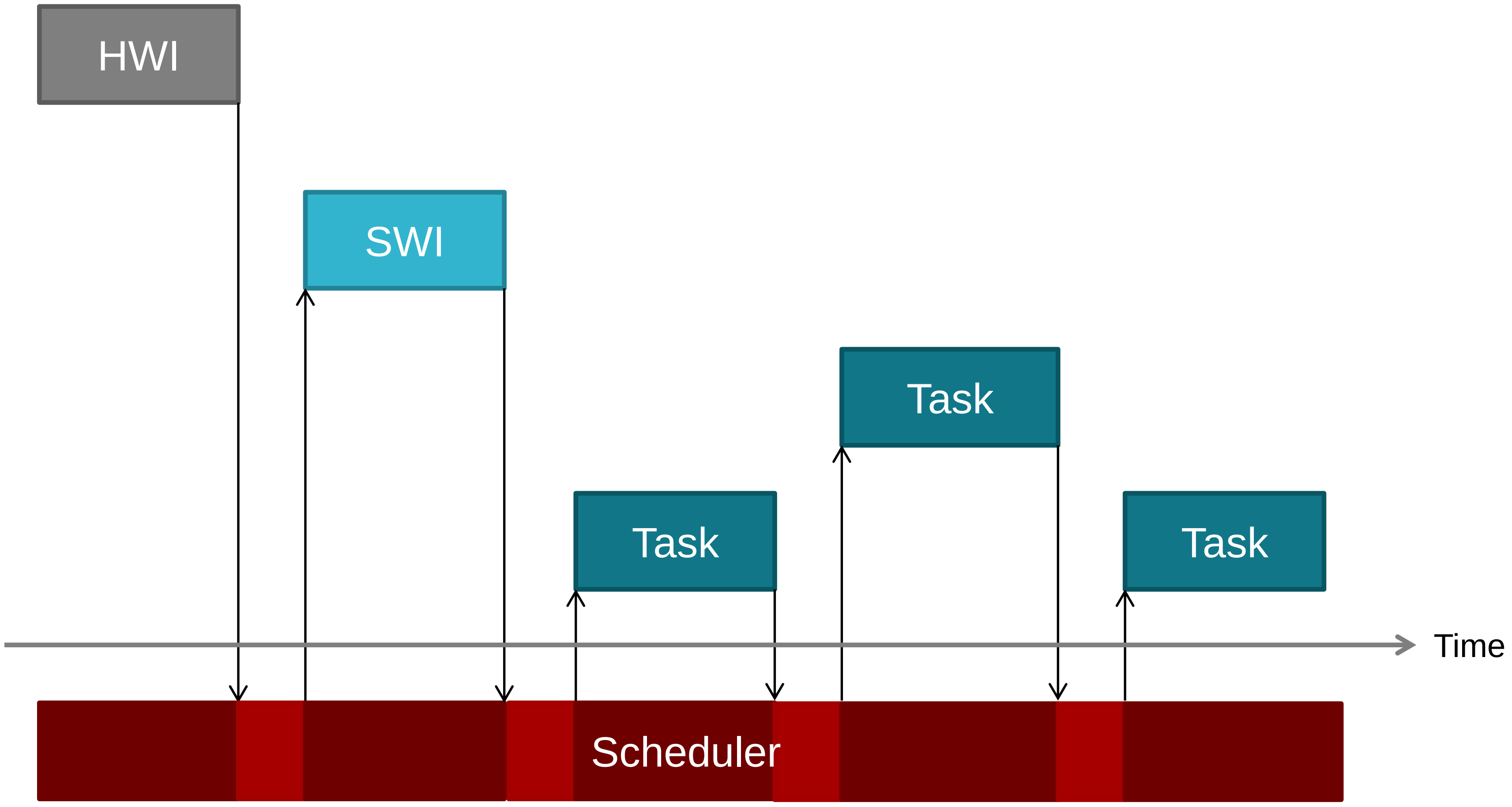
The RTOS scheduler



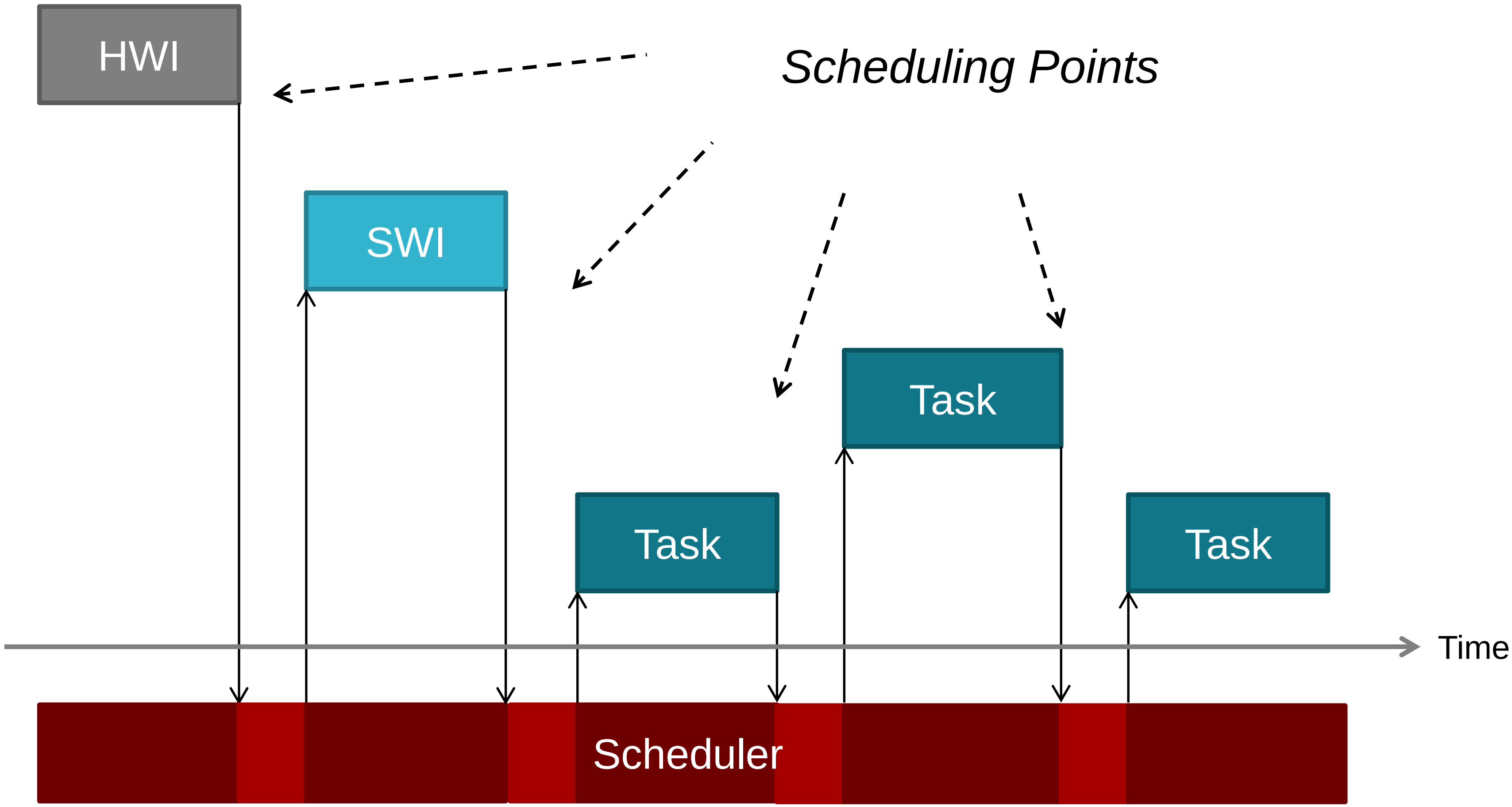
The RTOS scheduler



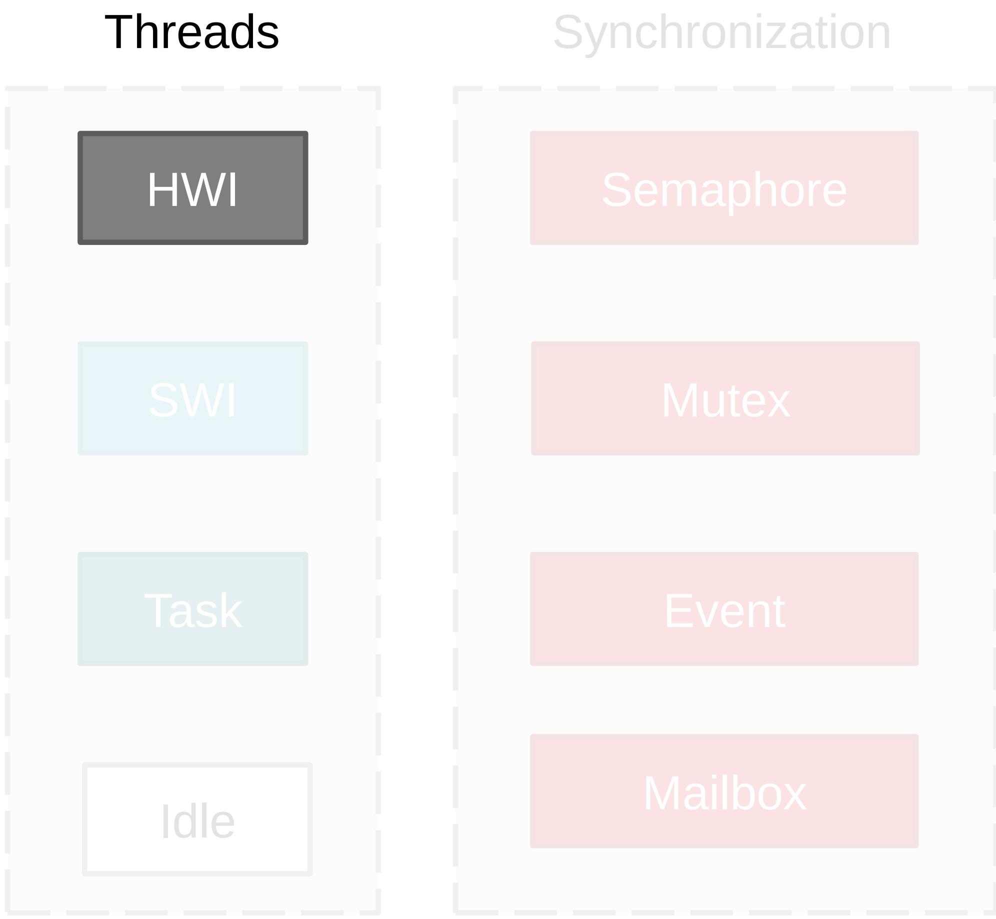
The RTOS scheduler



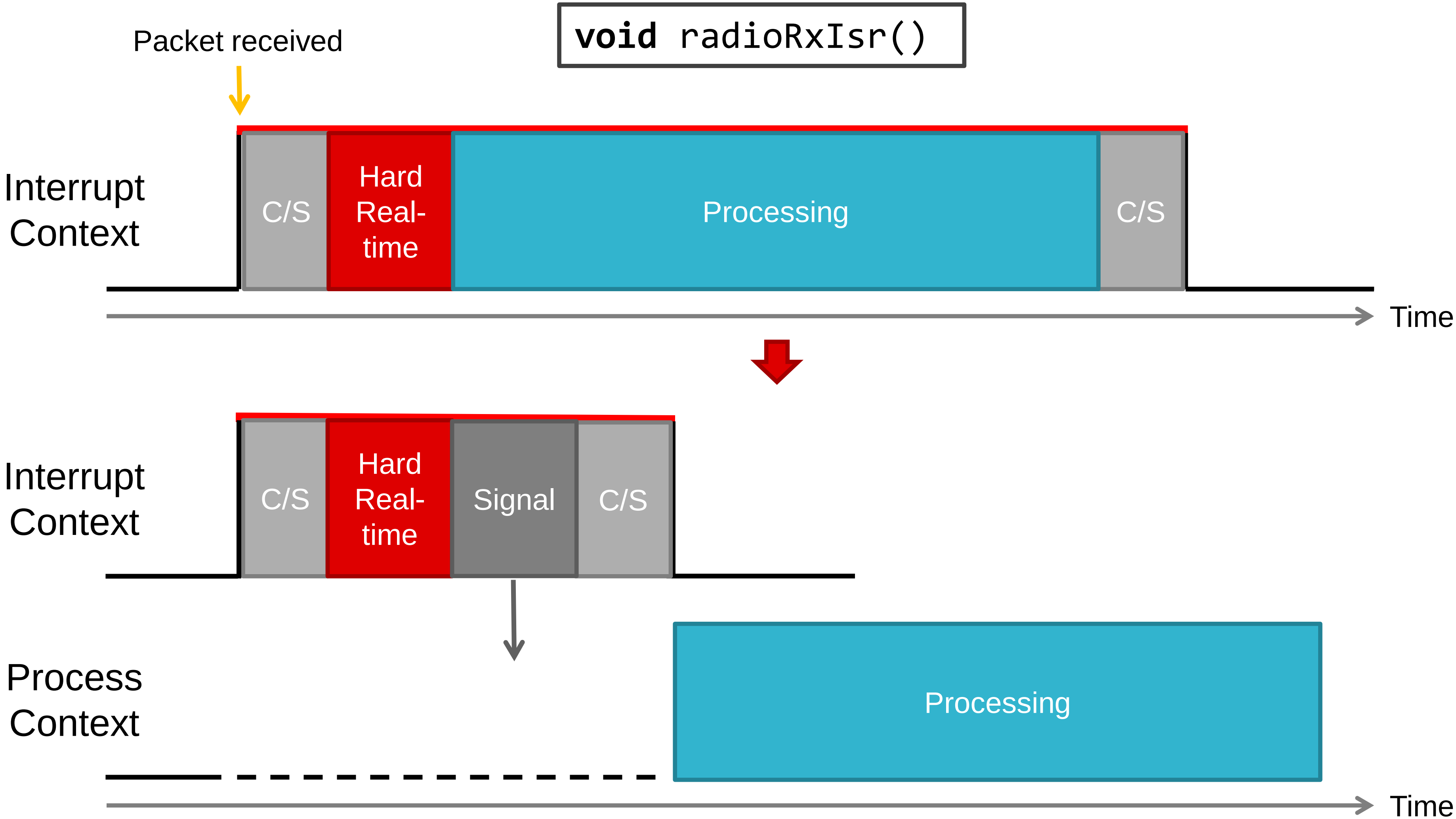
The RTOS scheduler



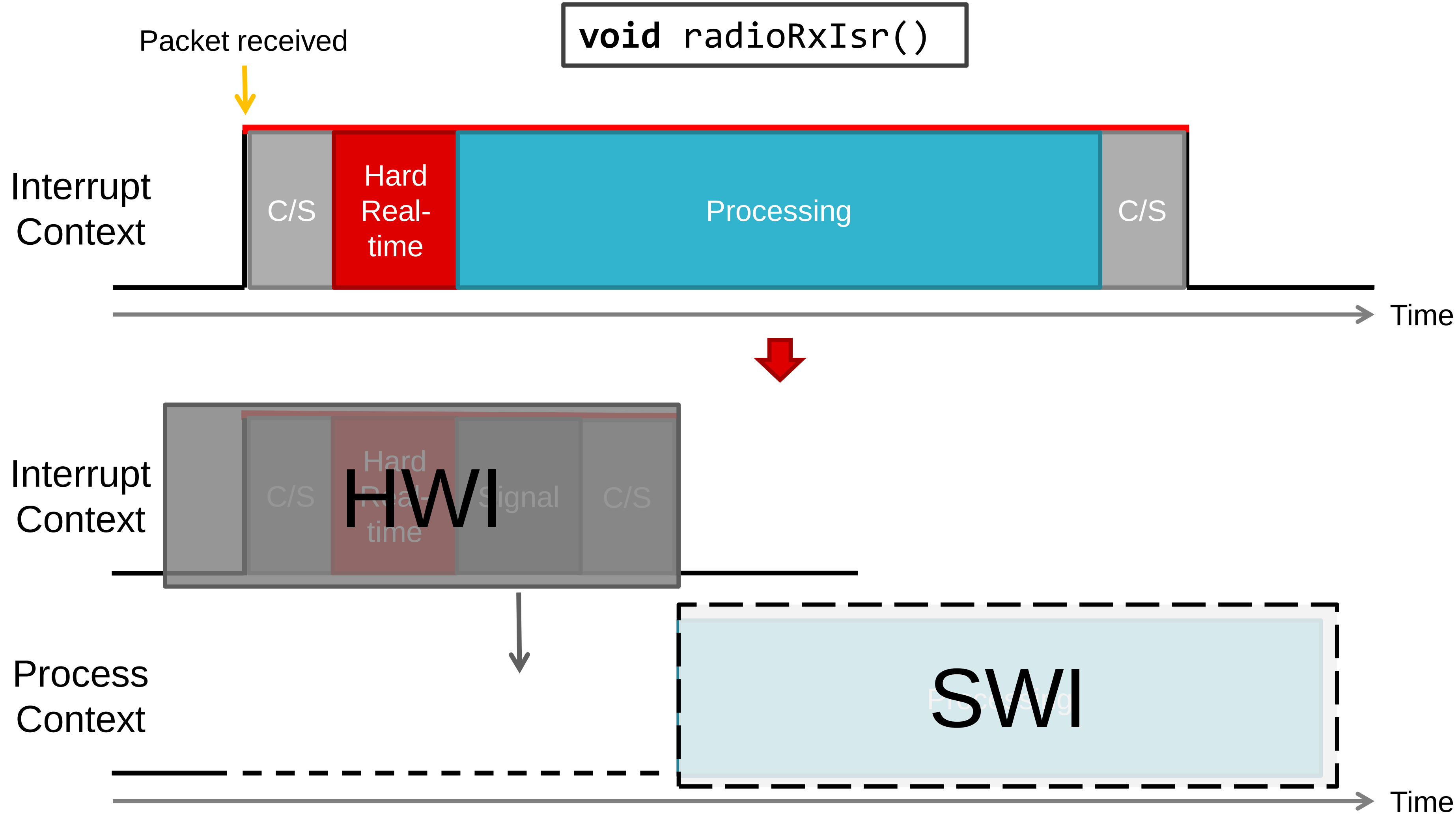
TI RTOS – HWI


Threads
Synchronization
HWI
SWI
Task
Idle
Semaphore
Mutex
Event
Mailbox

Bare Metal – Smart Thermostat



HWI – Hardware Interrupt



HWI – Hardware Interrupt

HWI's handles all hardware interrupts

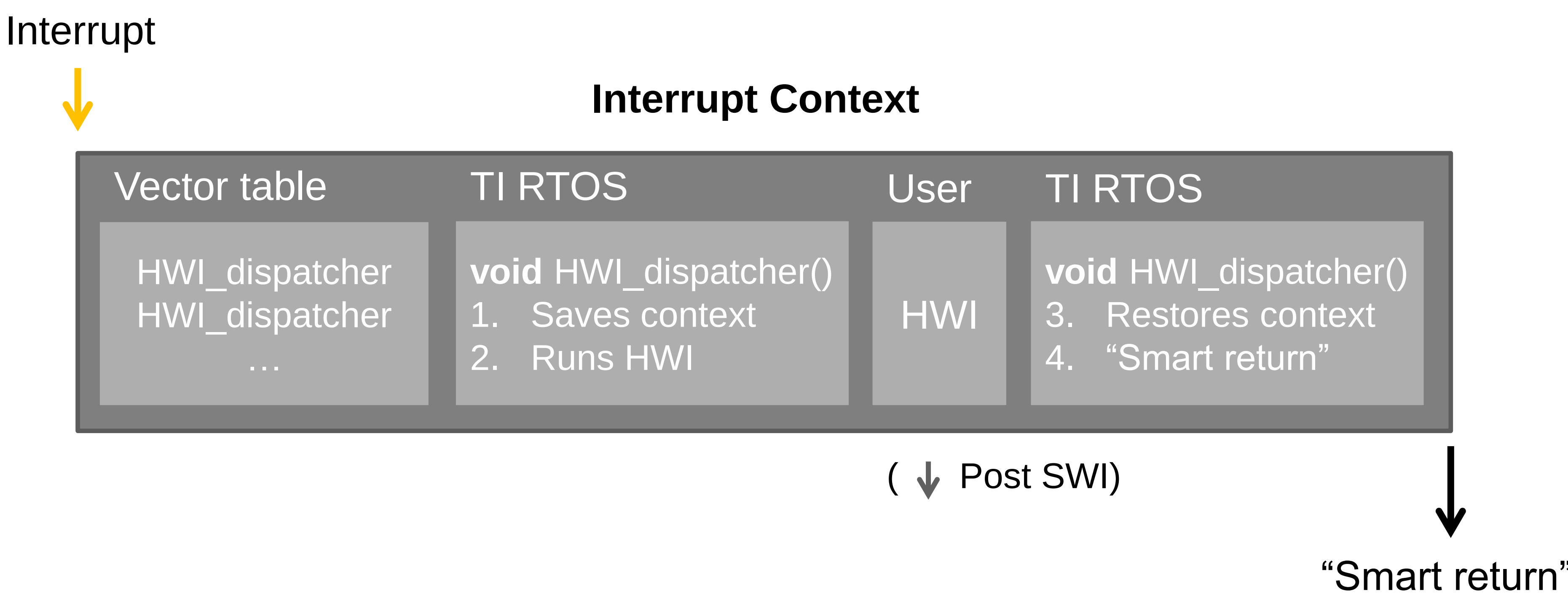
- Highest priority of all
- Always runs to completion
  - Even if interrupt happens again while currently being handled
- All HWI's shares the System Stack

Handle hardware interrupts

1. Using the RTOS HWI dispatcher (recommended)
2. Using regular, pure bare metal, interrupts

HWI – HWI dispatcher

- **Recommended** and the default
- All interrupts are mapped to the same handler
- Handles interrupt nesting
  - Default is that any interrupt preempts any other, except itself
- **Must** use this to use TI RTOS system call in ISR



TI RTOS – Smart Thermostat

Looking back

“Smart HWI return”
Returns to highest priority process

HWI

`void buttonIsr()`

SWI

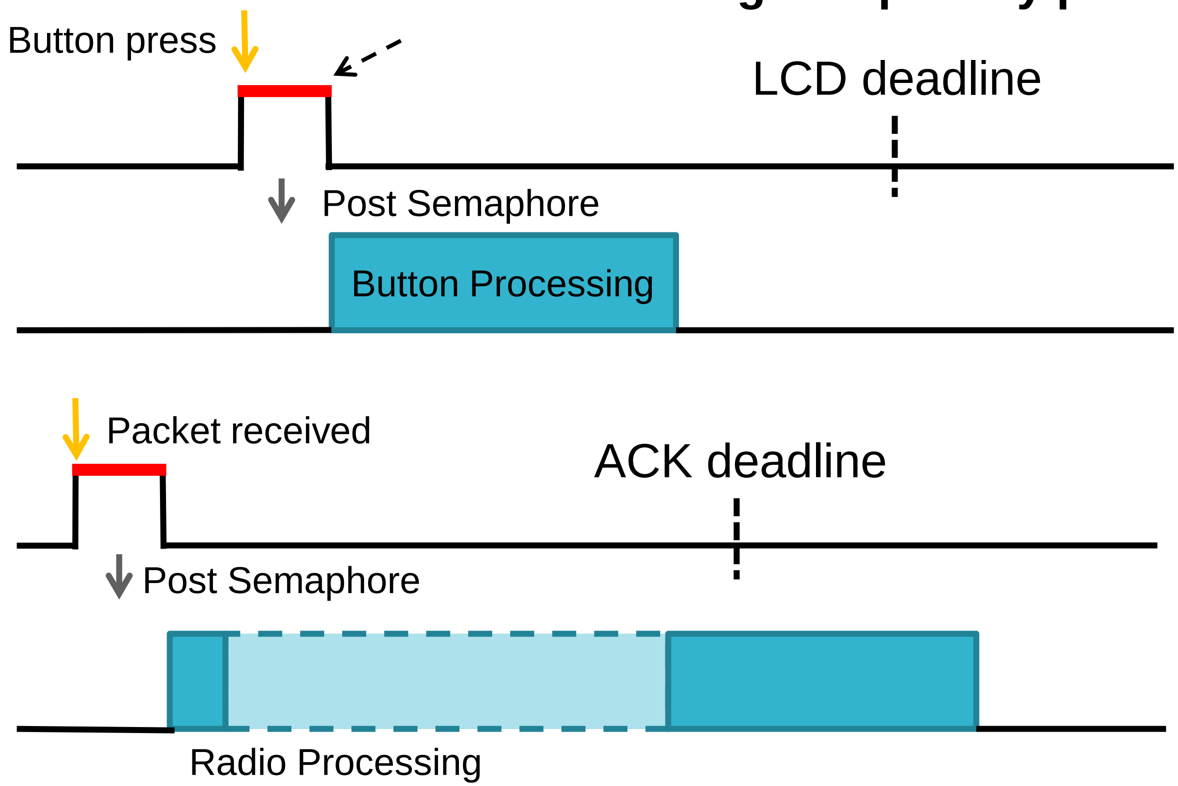
“High Priority”
`void processButton()`

HWI

`void radioRxIsr()`

SWI

“Low Priority”
`void processPacketRx()`

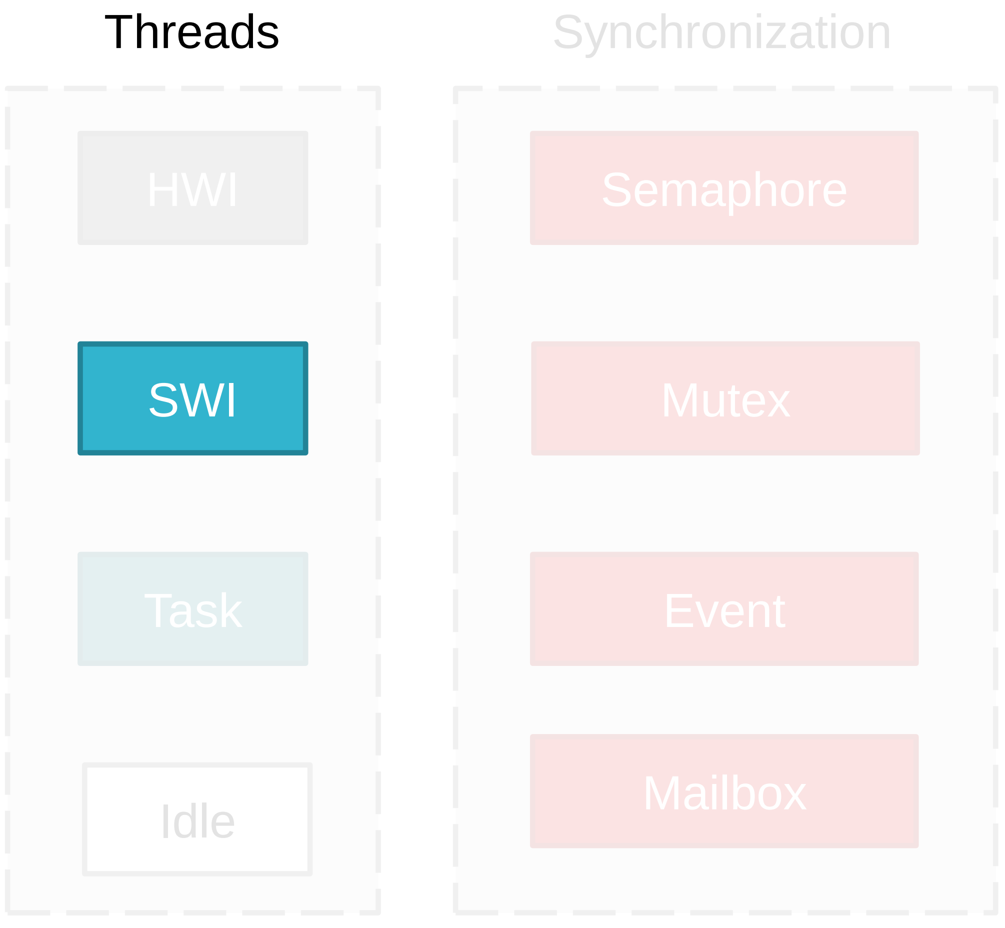


HWI – Hardware Interrupt

- Using regular interrupt handlers
- **Not recommended**
  - Cannot use any RTOS calls
- Must **explicitly** save and restore the RTOS context
- Must manually handle nesting
- Should only be used for extremely low latency ISR:s

```
void timerISR() {
  /* Save RTOS context */
  /* Do HW close stuff */
  /* Do processing */
  /* Restore RTOS context */
}
```

TI RTOS – SWI



Threads
Synchronization
HWI
SWI
Task
Idle
Semaphore
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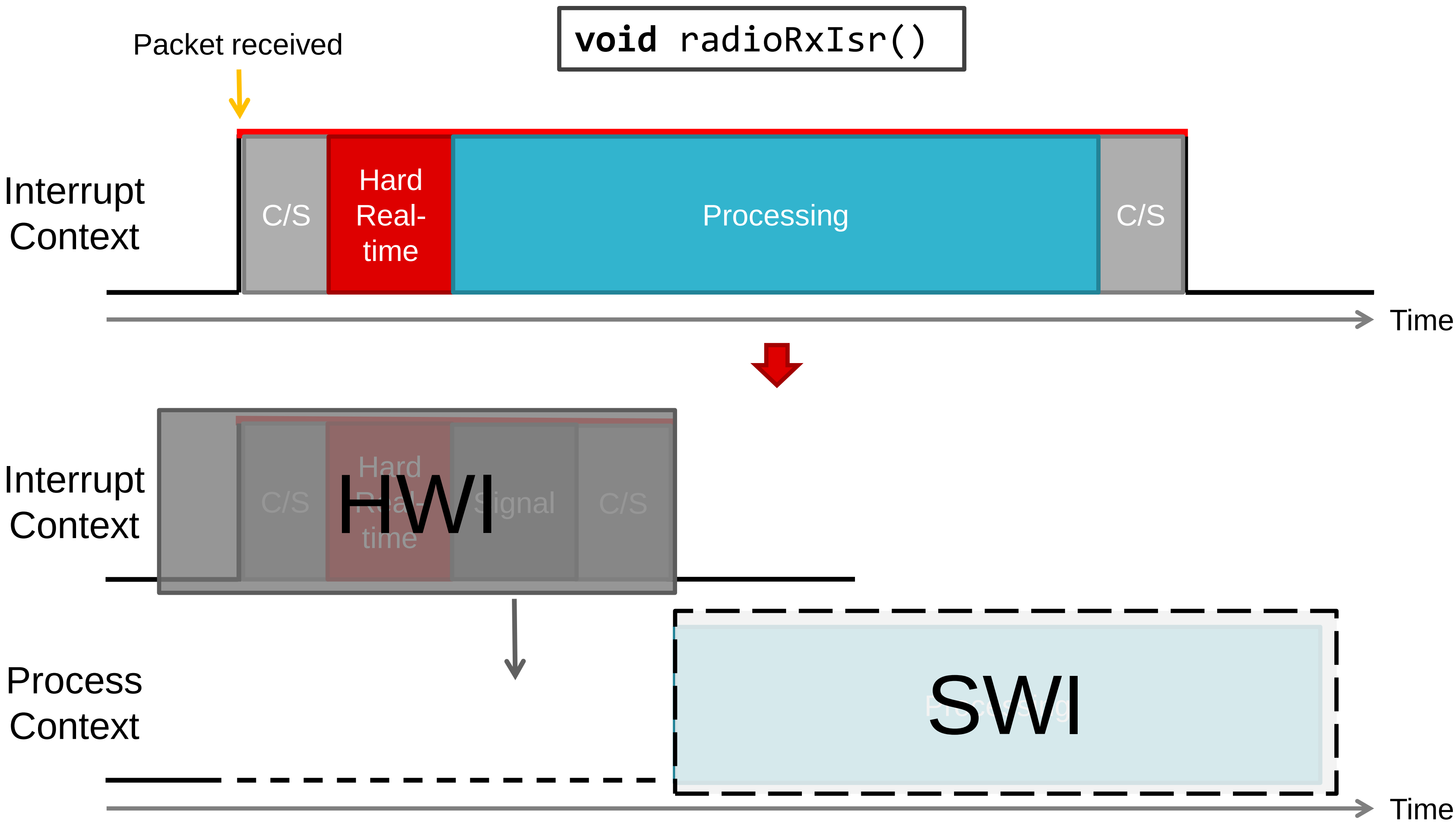
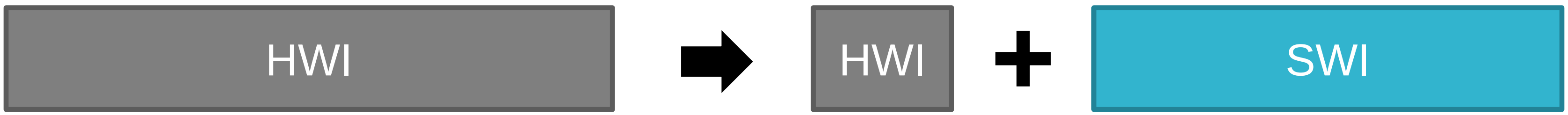
Mailbox

HWI – Hardware Interrupt



SWI vs. HWI



Move the processing from the HWI to a SWI

- Reduces the time in HW interrupt context
- Reduces the worst case HW interrupt latency
- Reduces need for HWI nesting
- Reduces the effects a HW interrupt has on high priority processing

What do we keep in the HWI?

- Hard real-time code such as reading from a HW register as fast as possible
- Storing that information at a shared location
- Posting a semaphore to the SWI that the information is available

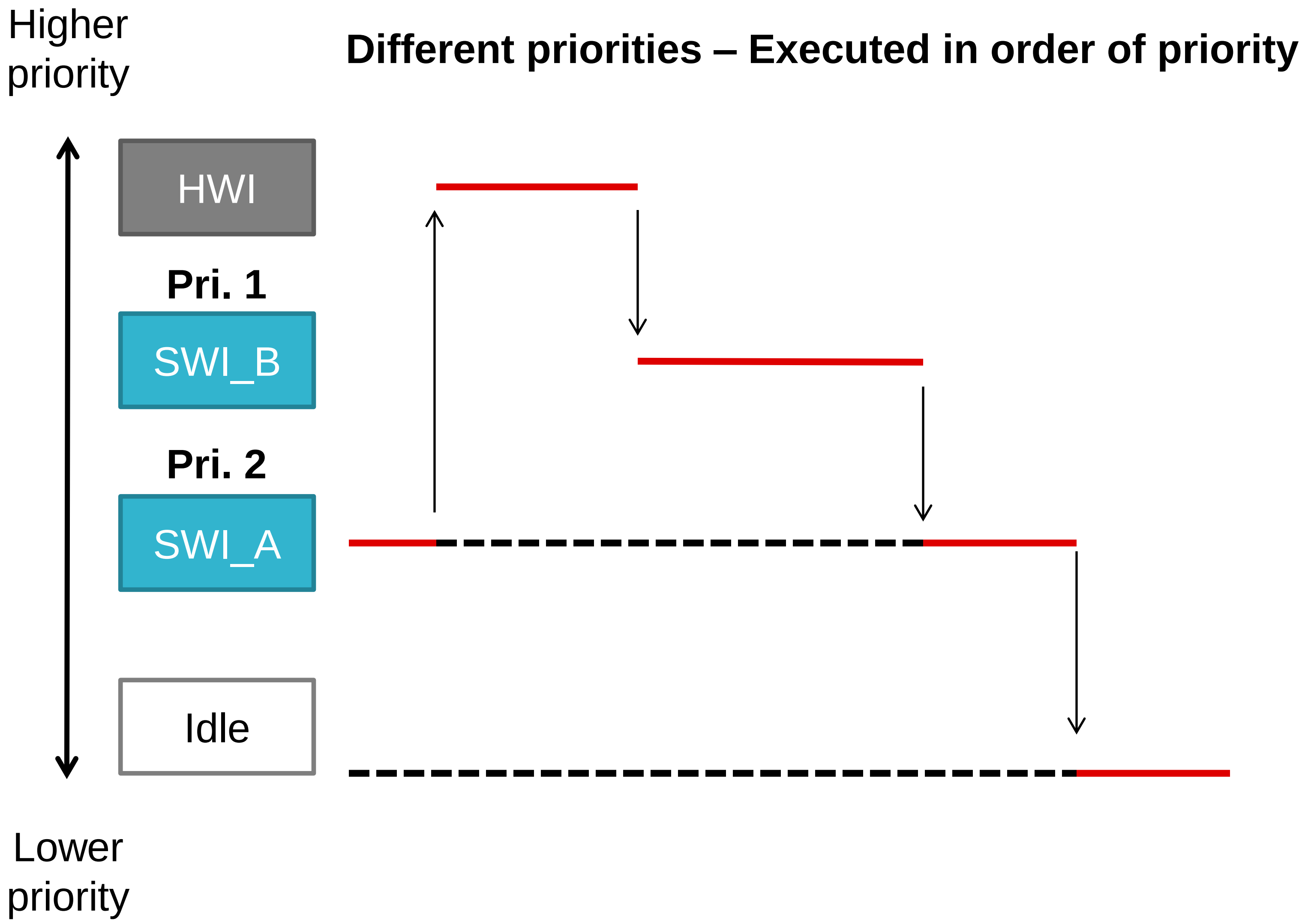
SWI properties

SWI states

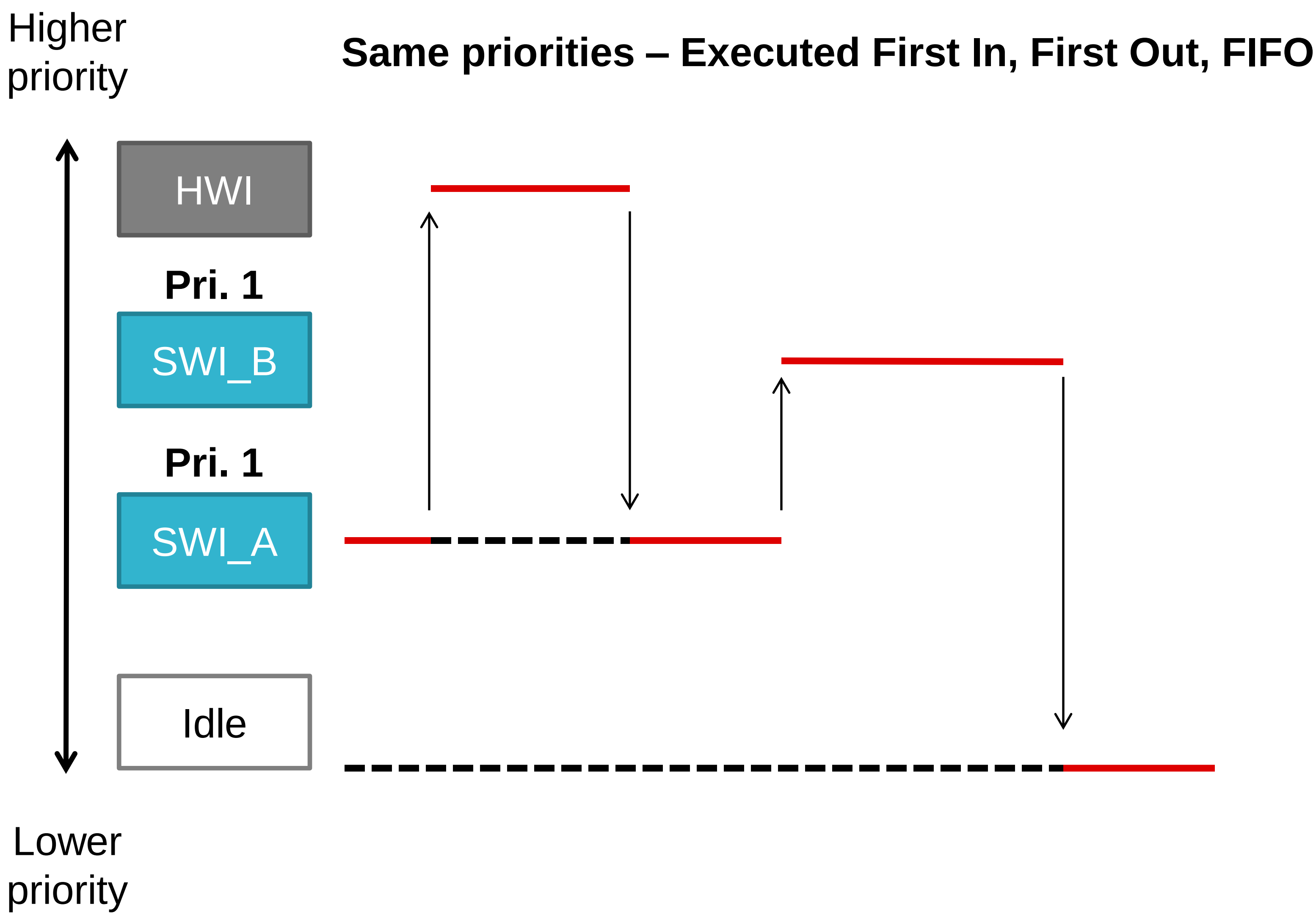
- **Running**
  - The SWI is currently executing
  - Only **one** Thread can be Running at any given time
- **Ready**
  - The SWI is ready to run, but is not since a higher priority SWI is Running
  - Any number of tasks can be Ready
- (Cannot be Blocked!)

- **Shares** the System Stack with all HWI and other SWI's
  - Important to take into account that several SWI and/or HWI may preempt each other, increasing the stack usage

SWI – Software Interrupt

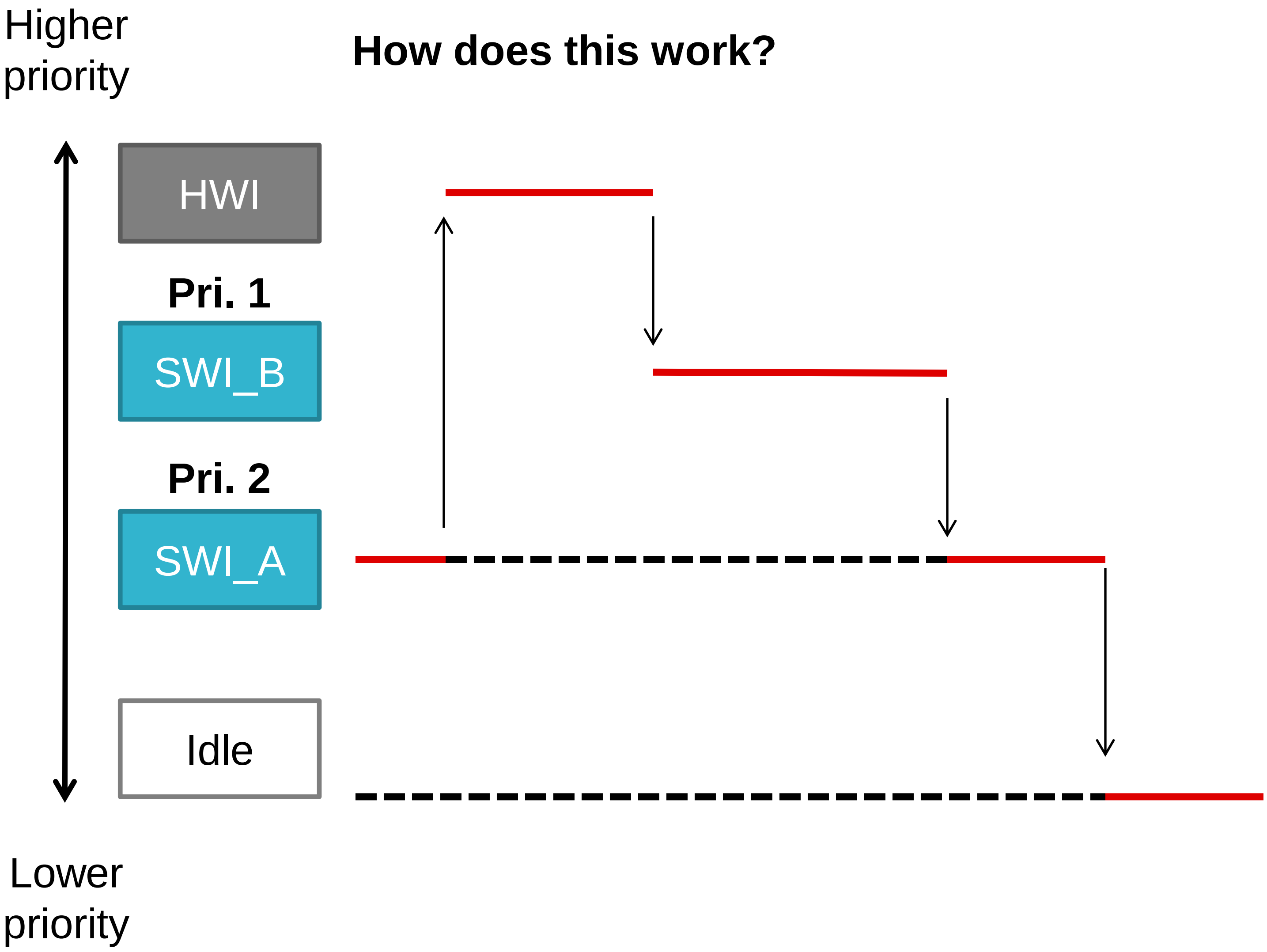


SWI – Software Interrupt



SWI – Software Interrupt

How does this work?



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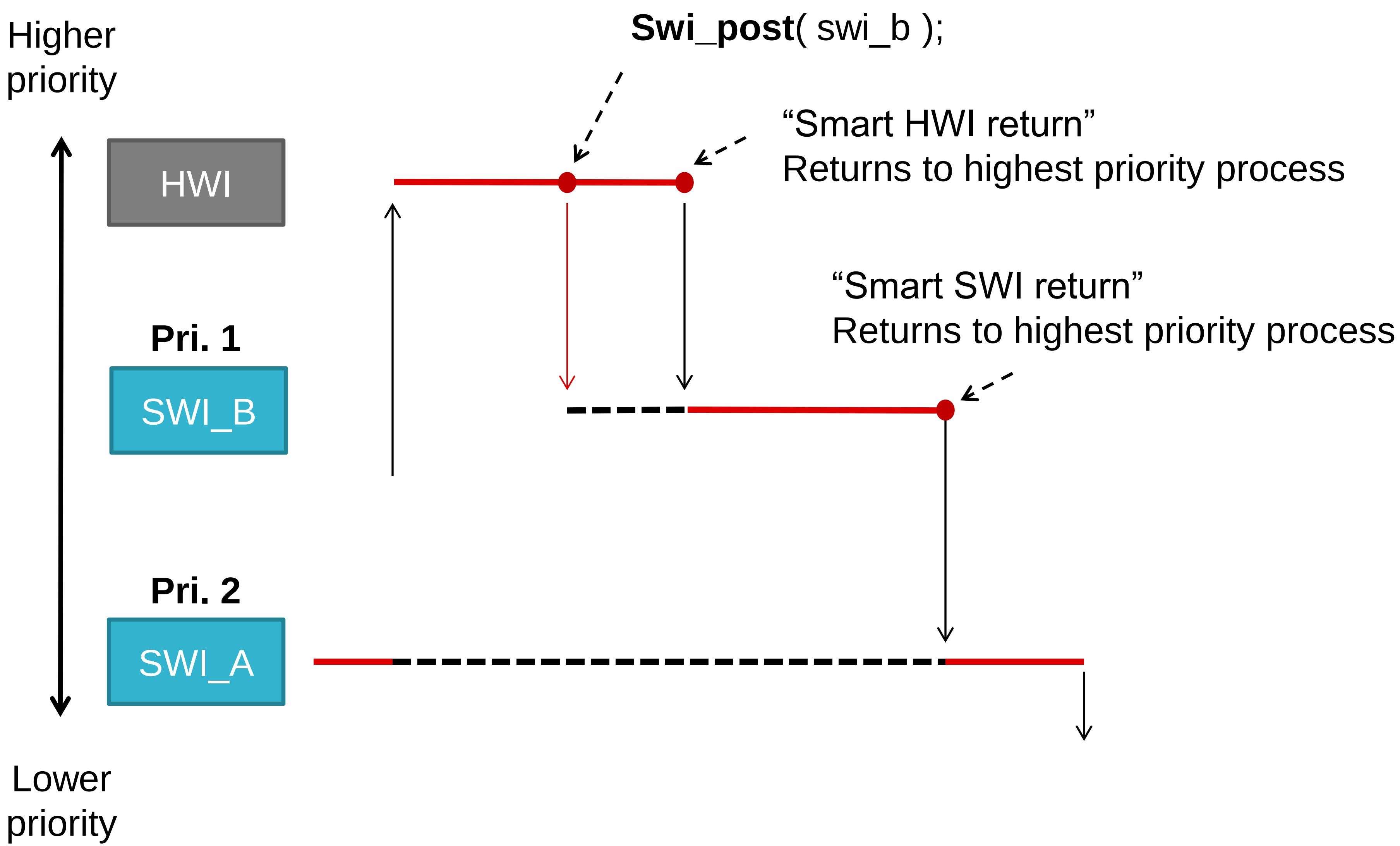
SWI – Software Interrupt



SWI API

API	Description
Swi_inc()	Post, increment count in trigger
Swi_dec()	Decrement count, post if trigger = 0
Swi_or()	Post, OR bit into trigger
Swi_andn()	Zero a bit in trigger, Post if trigger = 0
Swi_getPri()	Get any Swi Priority
Swi_raisePri()	Raise priority of any Swi
Swi_getTrigger()	Get any Swi's trigger value
Swi_enable()	Global Swi enable
Swi_disable()	Global Swi disable
Swi_restore()	Global Swi restore

What about continuous processing?

TI RTOS – Task

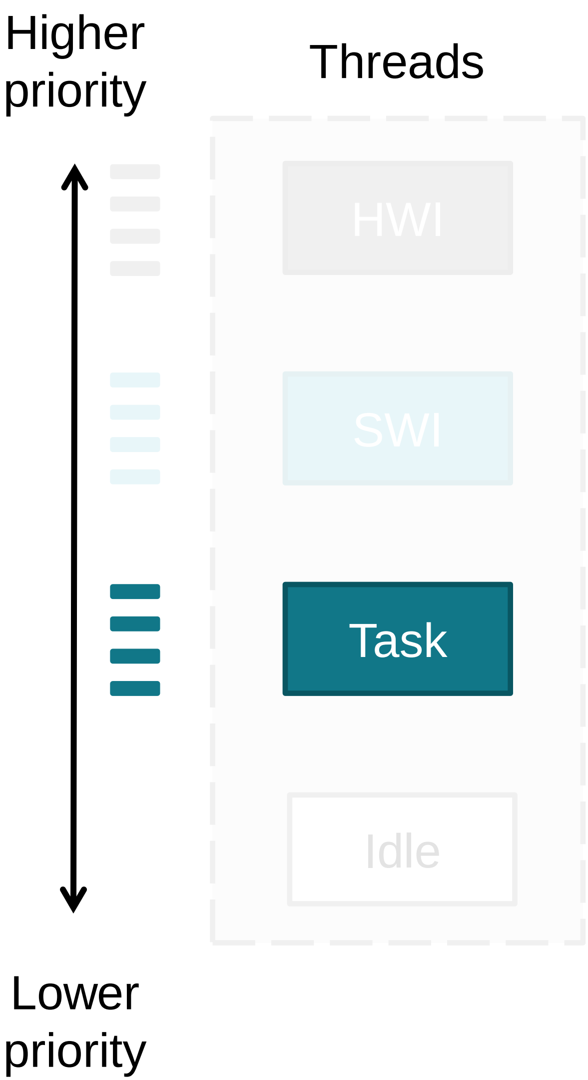
Threads

- HWI
- SWI
- Task
- Idle

Synchronization

- Semaphore
- Mutex
- Event
- Mailbox

Threads overview



- Handles hardware interrupts
- Priorities set in hardware

- Usually used for HWI follow-up processing
- Up to 32 user configurable priorities

- Used for all complex and/or continuous processing
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- Special thread – Runs when nothing else is running

SWI vs. Tasks

SWI

Intended for HWI follow-up processing

- Executed once per HWI
- Does not keep any local state between calls
- Uses the System Stack

```
void rxSwi() {
  /* Read FIFO bytes */
  /* Write to buffer */
}
```

Task

Intended to run **continuously** and concurrently

- Normally runs forever
    - Pending while waiting for data
    - Processes data
    - Then pends again
- Keeps local state
- Has its own stack

```
void packetEngineTask() {
  while(1) {
    /* Wait for bytes */
    if(bytesInBuffer == len)
      /* Decode packet */
  }
}
```

SWI vs. Tasks

Task

- Runs as soon as the system is started, or the task is created.
- Generally never exists, although it can

```
void task() {

  /* Initialization – Run once */

  while(1) {
    /* Wait for Semaphore */
    /* Processing */
  }
}
```

Task states

- Running
  - The Task is currently executing
  - Only **one** Task can be Running at any given time
- Ready
  - The Task is ready to run, but is not since a higher priority Task is Running
  - Any number of tasks can be Ready
- Blocked
  - A task is blocked because it's waiting for a shared resource that is not available
  - Any number of tasks can be Blocked
- (Inactive)
  - Priority set to -1, will not be scheduled
- (Terminated)
  - Task has exited

TI RTOS – Task

Threads

- HWI
- SWI
- Task
- Idle

Synchronization

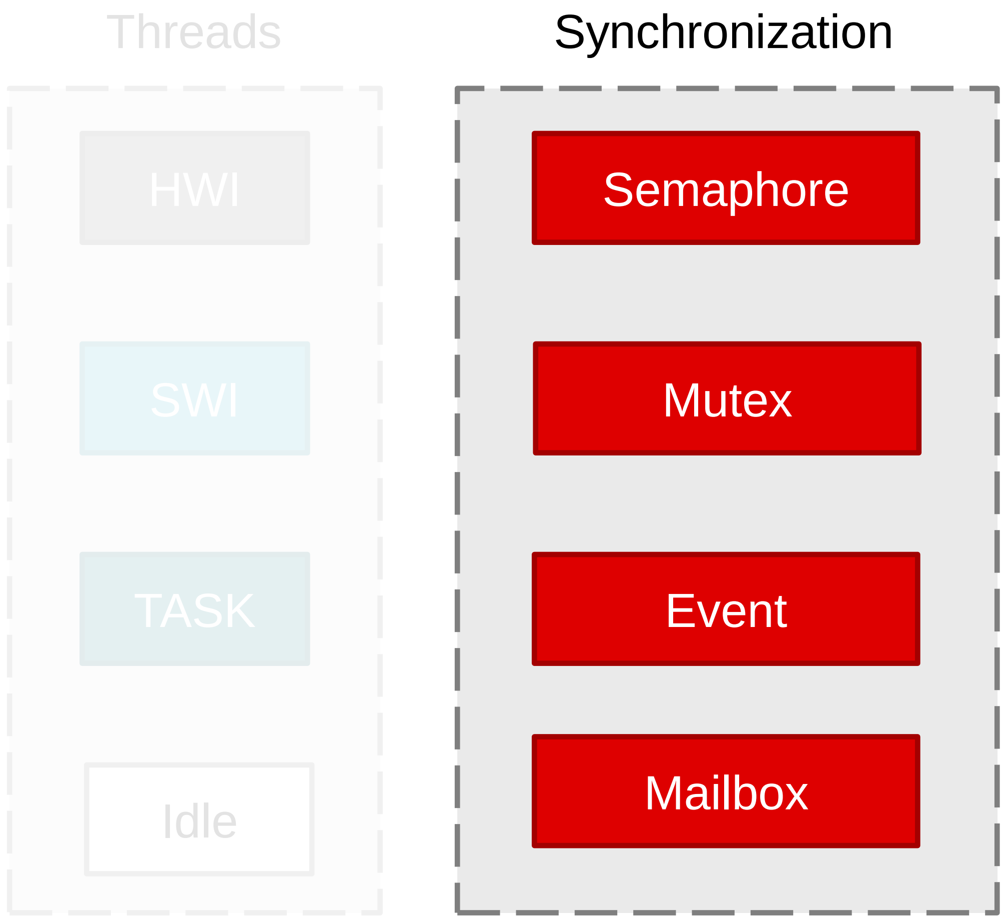
- Semaphore
- Mutex
- Event
- Mailbox

Idle thread

- The Idle thread is only run when no other thread is running
- Sets the device into the **lower possible** power mode

Signaling and resource sharing between SWI to Task and Task to Task

TI RTOS – Kernel Objects Overview



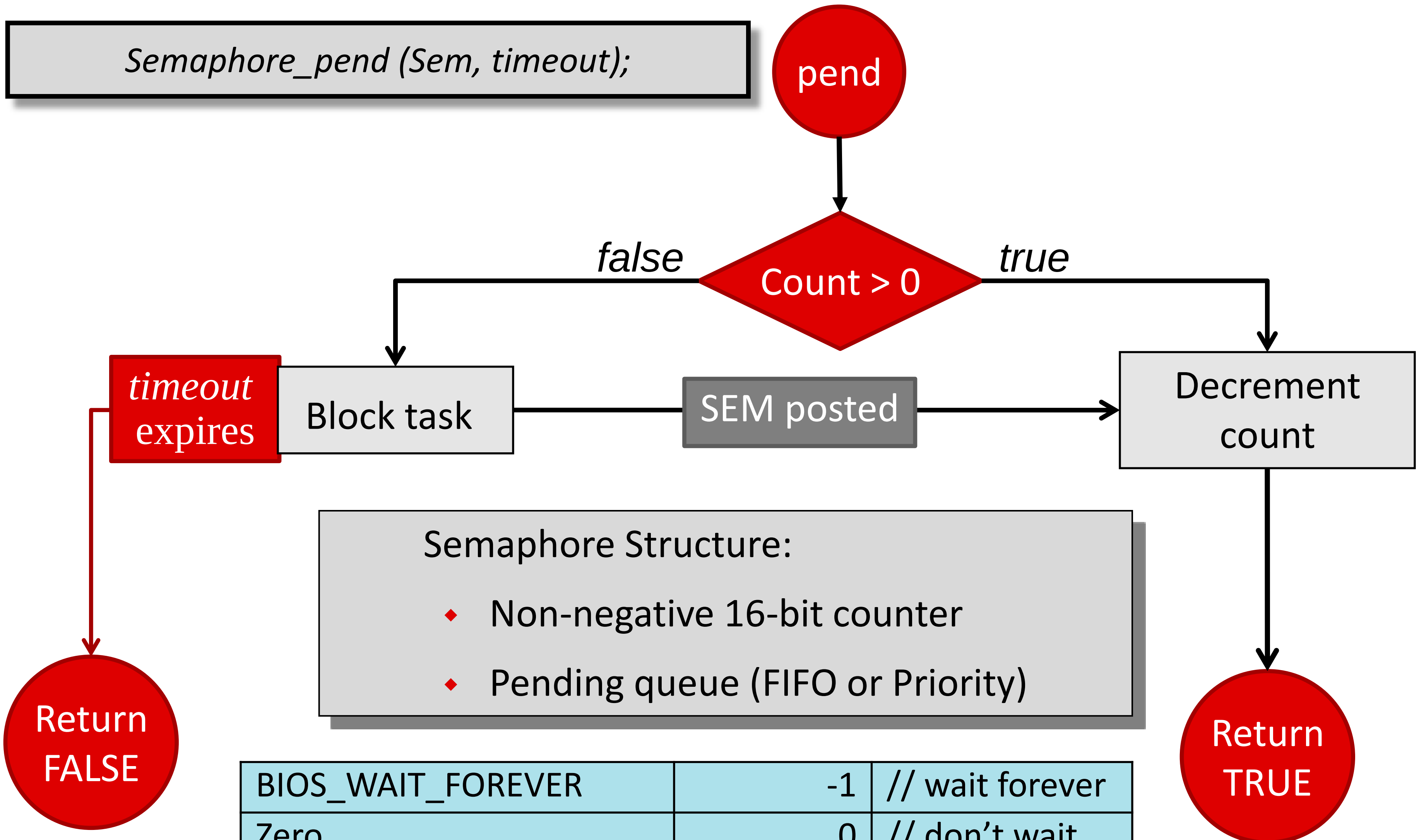
Semaphore

Semaphore is a concept used for **synchronizing** threads. Is implemented by using an internal counter which is incremented and decremented.

- Semaphore_post(Sem_1)
  - Increment semaphore counter
- Semaphore_pend(Sem_1, Timeout)
  - Decrement semaphore counter
  - Potentially blocks if count is zero

Semaphore Pend

Semaphore_pend (Sem, timeout);



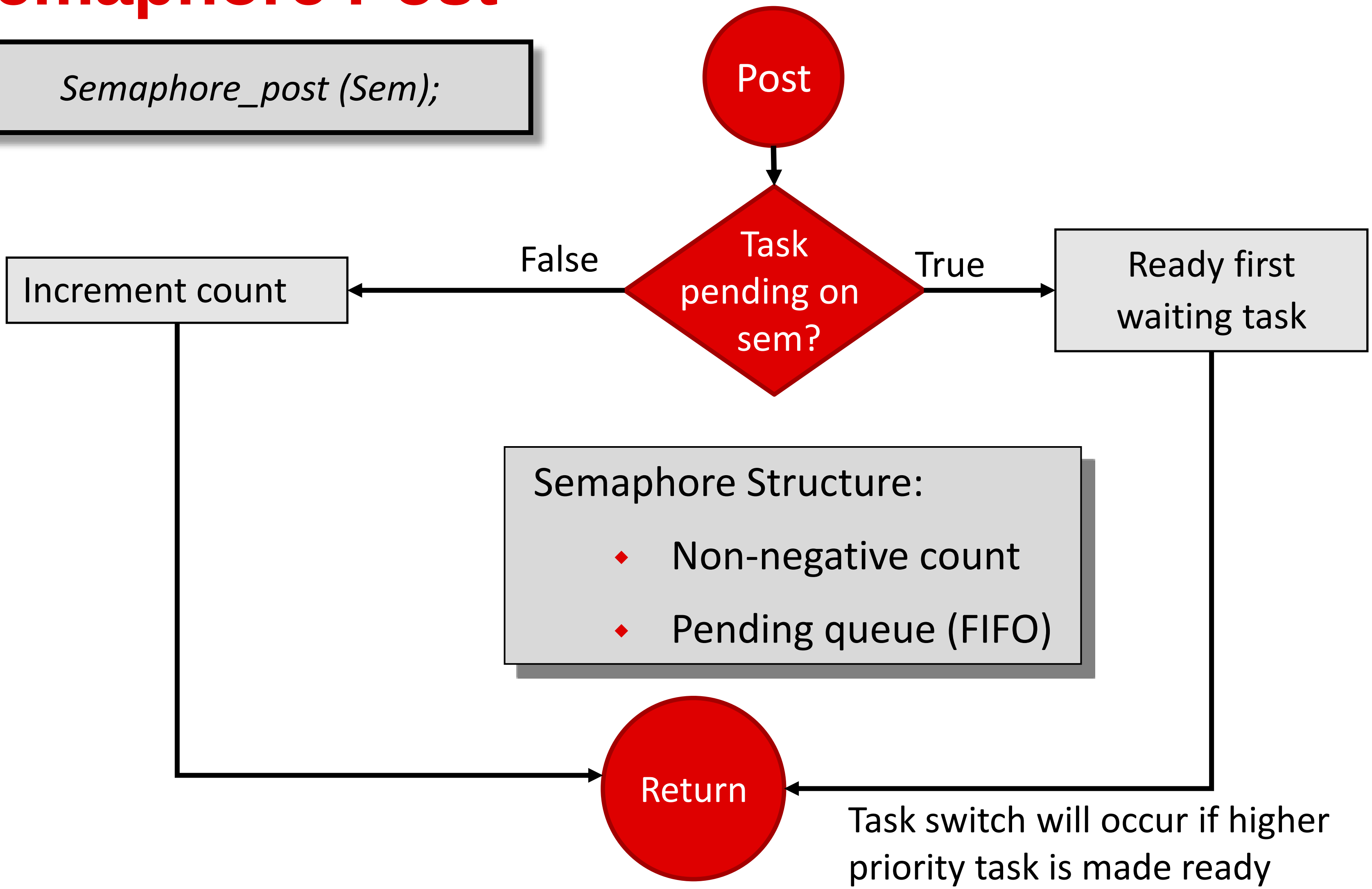
Semaphore Structure:

- Non-negative 16-bit counter
- Pending queue (FIFO or Priority)

BIOS_WAIT_FOREVER	-1	// wait forever
Zero	0	// don't wait
value	timeout	// system ticks

Semaphore Post

Semaphore_post (Sem);



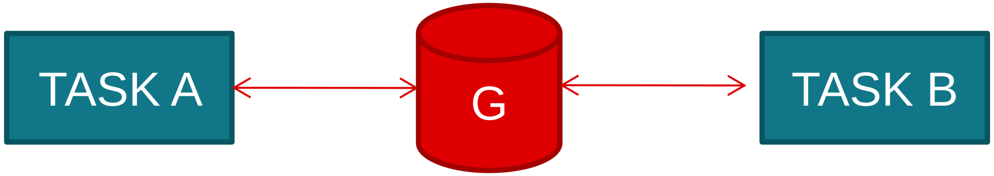
Semaphore

```
void timerSwi() {
  Semaphore_post(Sem_1);
}
```

```
void task() {
  while(1) {
    Semaphore_pend(Sem_1, Timeout);
    /* Do processing */
    /* Blink LED */
  }
}
```

Shared resource - Global variables

We have two Tasks and a shared global resource:



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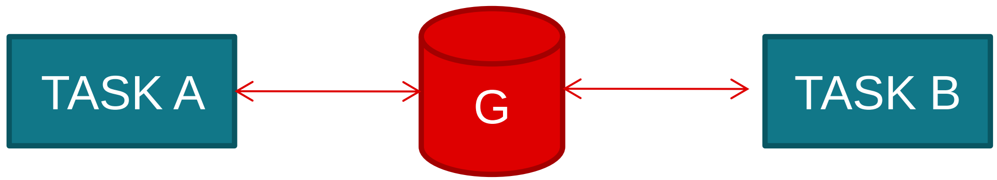

Worst case:

TASK A

```
void hiPriTask() {
  …
  cnt += 1;
  …
}
```

TASK B

```
void lowPriTask() {
  …
  cnt += 1;
  …
}
```

Shared resource - Global variables

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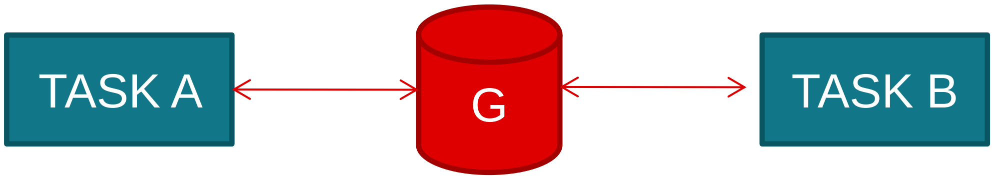


Worst case:

TASK A

```
void hiPriTask() {
  …
  cnt += 1;
  …
}
```

TASK B

```
void lowPriTask() {
  …
  cnt += 1;
     LD
     ADD
     ST
  …
}
```

Global variables with Critical Section

TASK B

TASK A

```
void Task() {
  …
  pGIE = Hwi_disable();
  cnt += 1;
  Hwi_restore(pGIE);

  …
}
```

Simple, but overkill in most cases. This will block **all** HWI's, including everyone that has nothing to do with the "cnt" resource!

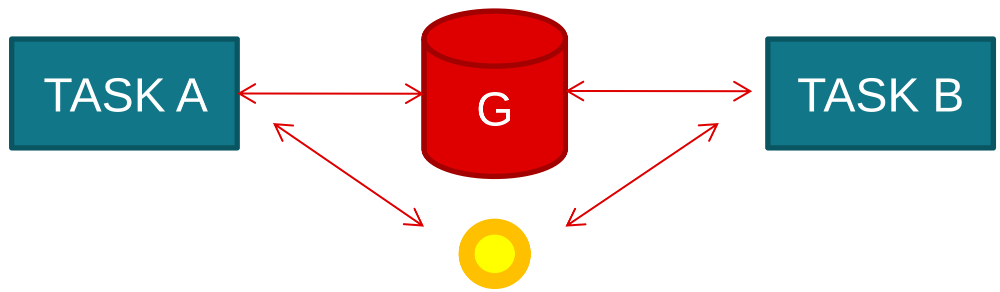
Mutex

A **Mutex** is used for **Mutual exclusion.** It provides a way to guarantee that only one thread at a time has access to a specific resource.

Similar to Semaphore with count = 1 but it has an **owner**

Global variables with Mutex

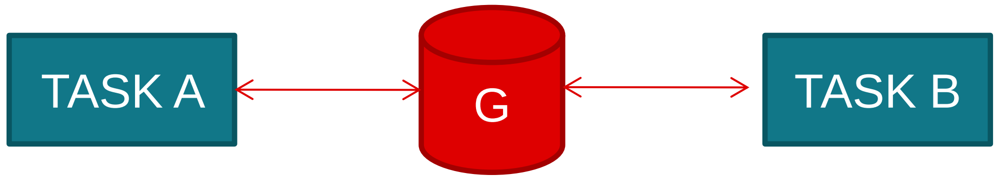
We have two Tasks and a shared global resource:

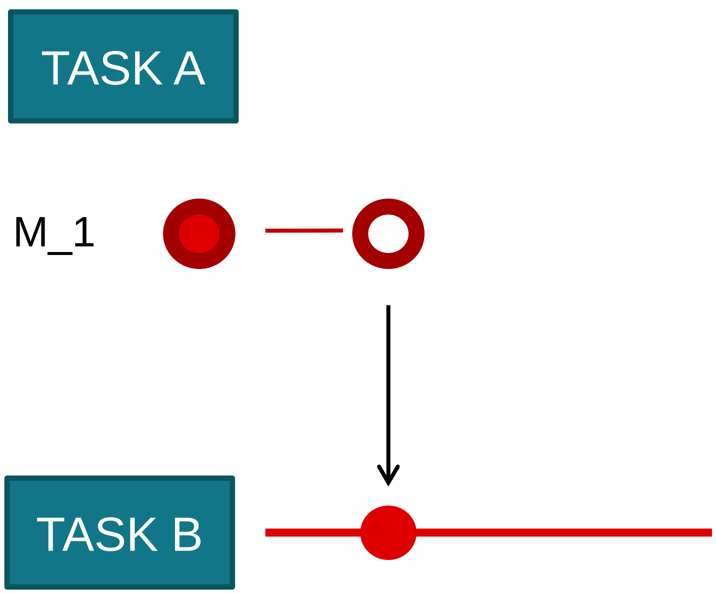


TASK B TASK A

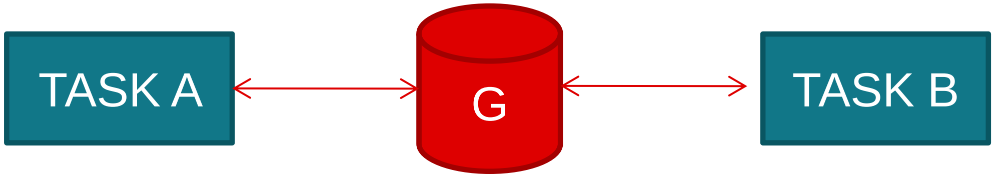
```
void Task() {
   …
   gateKey = GateMutex_enter(cntMutex);
   cnt += 1;
   GateMutex_leave(cntMutex, gateKey);
   …
}
```

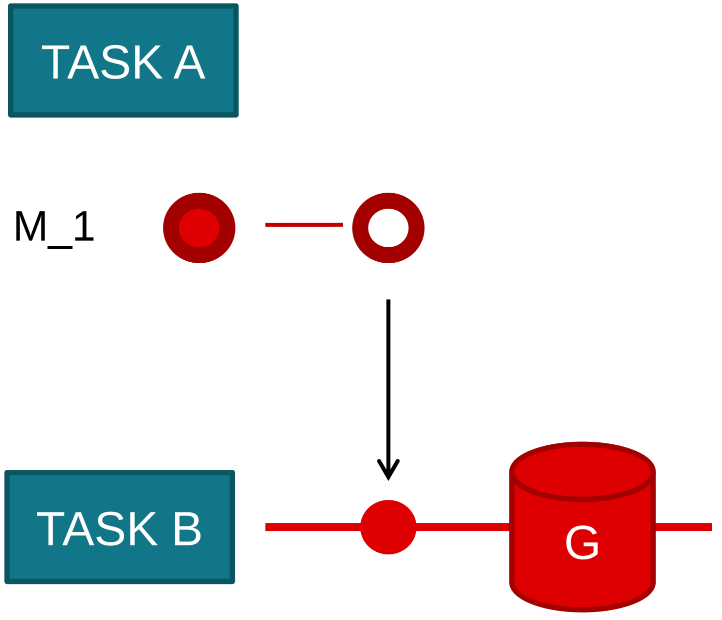
Global variables with Mutex



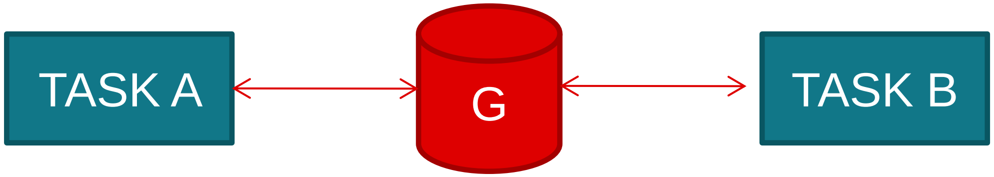


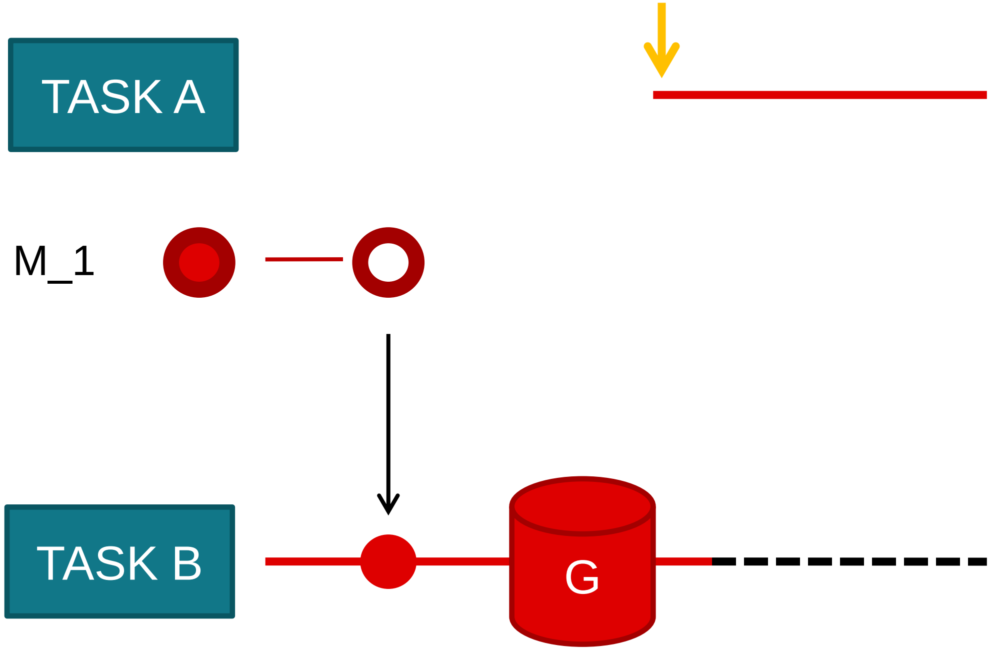
Global variables with Mutex





Global variables with Mutex





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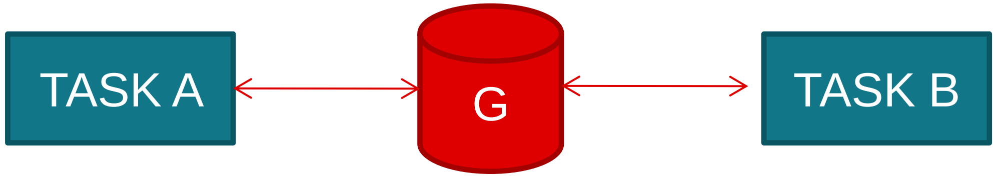

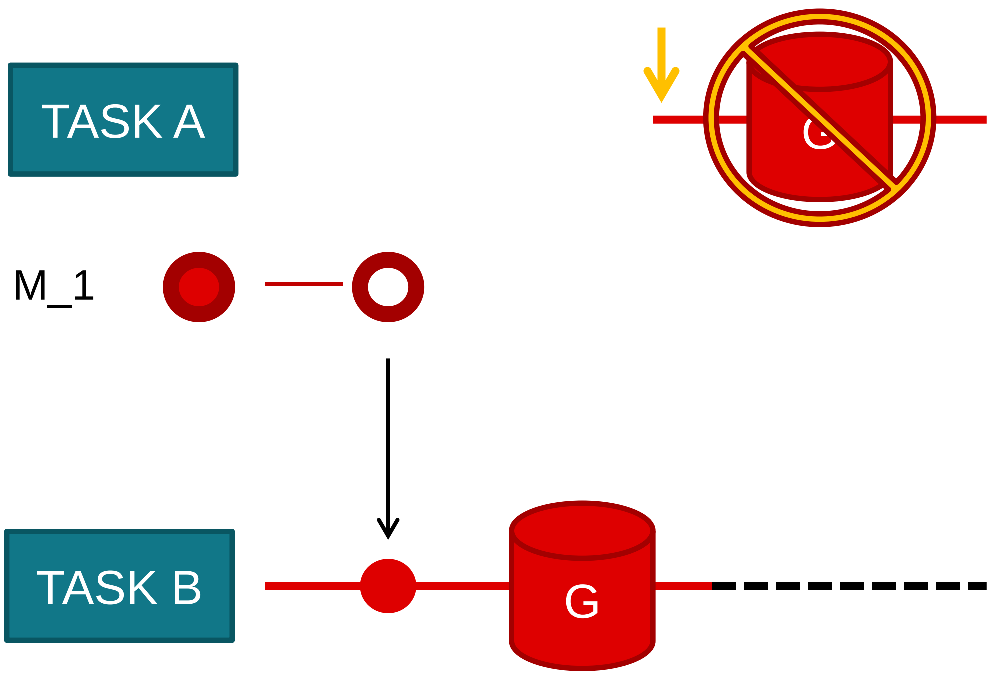

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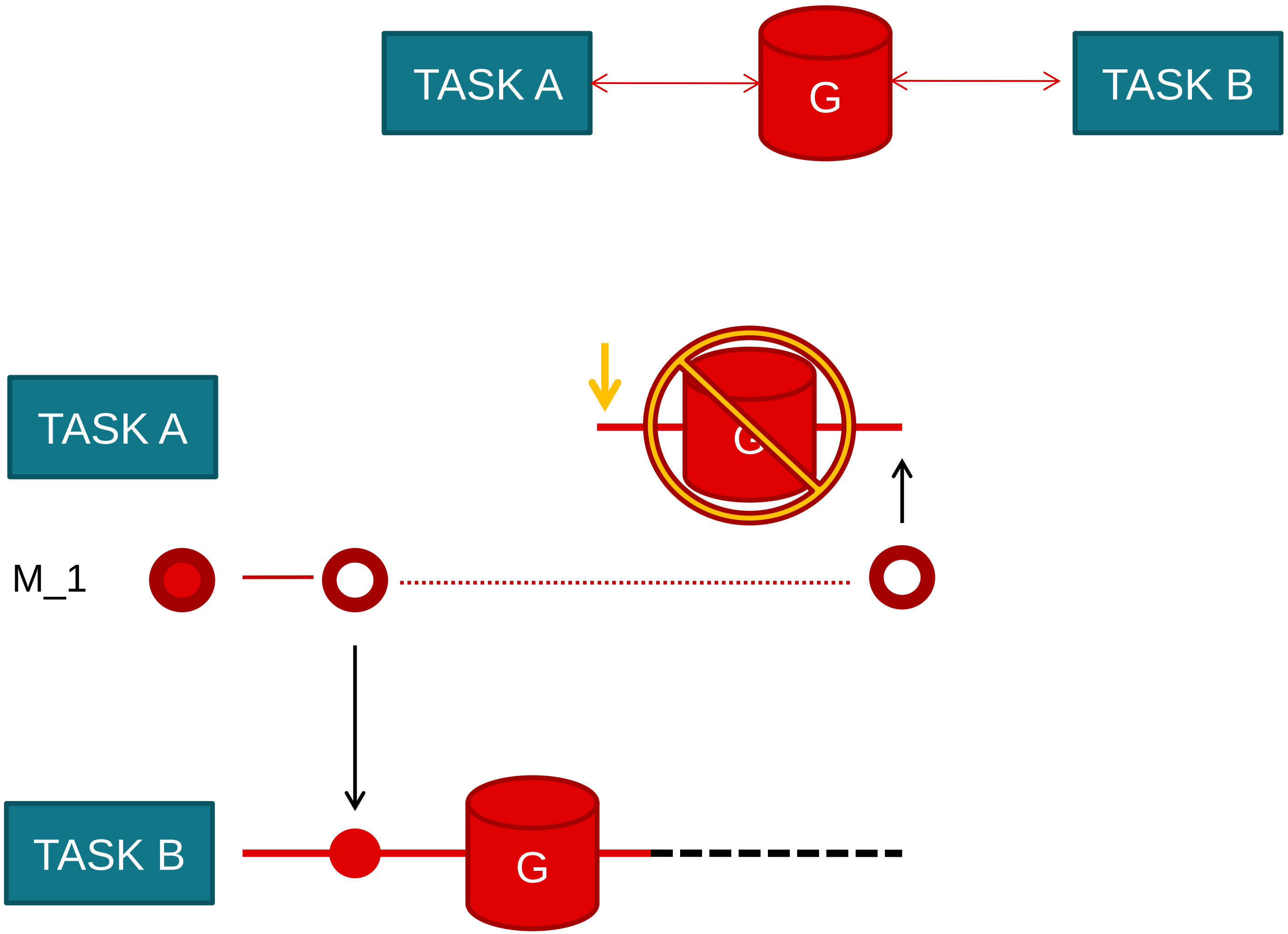

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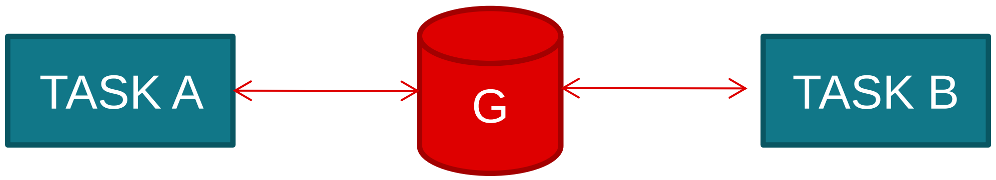
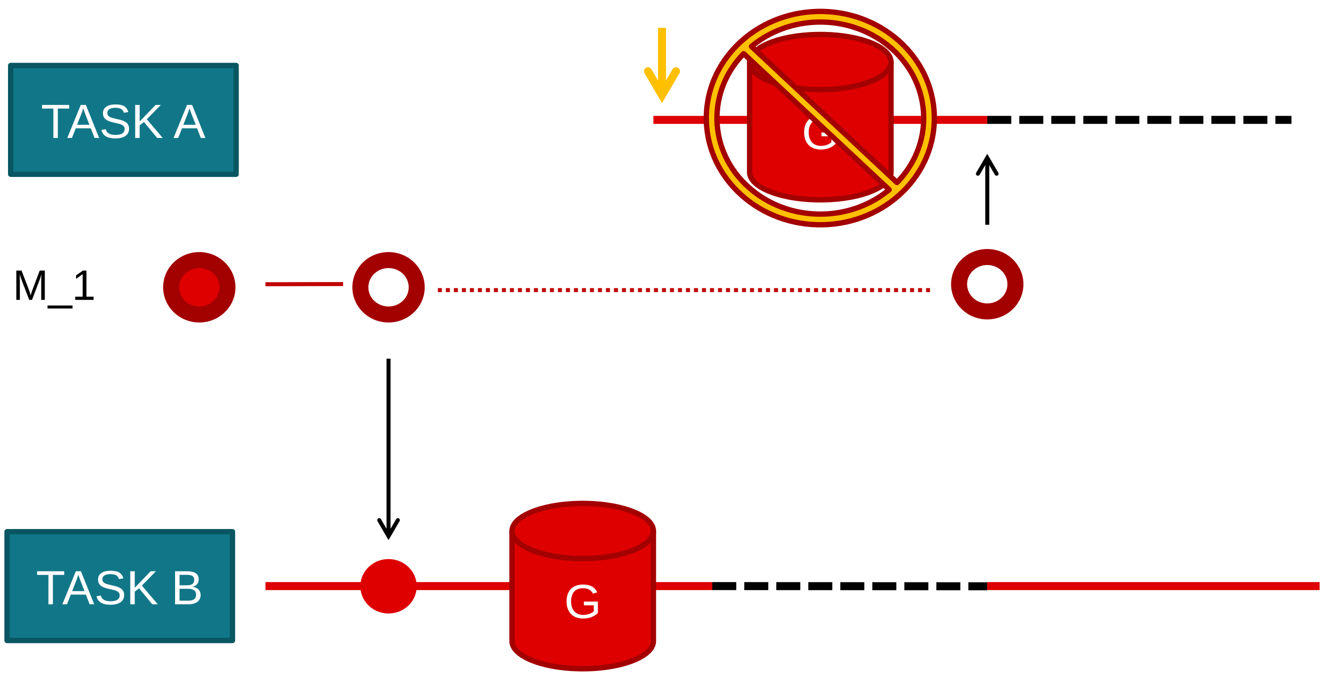
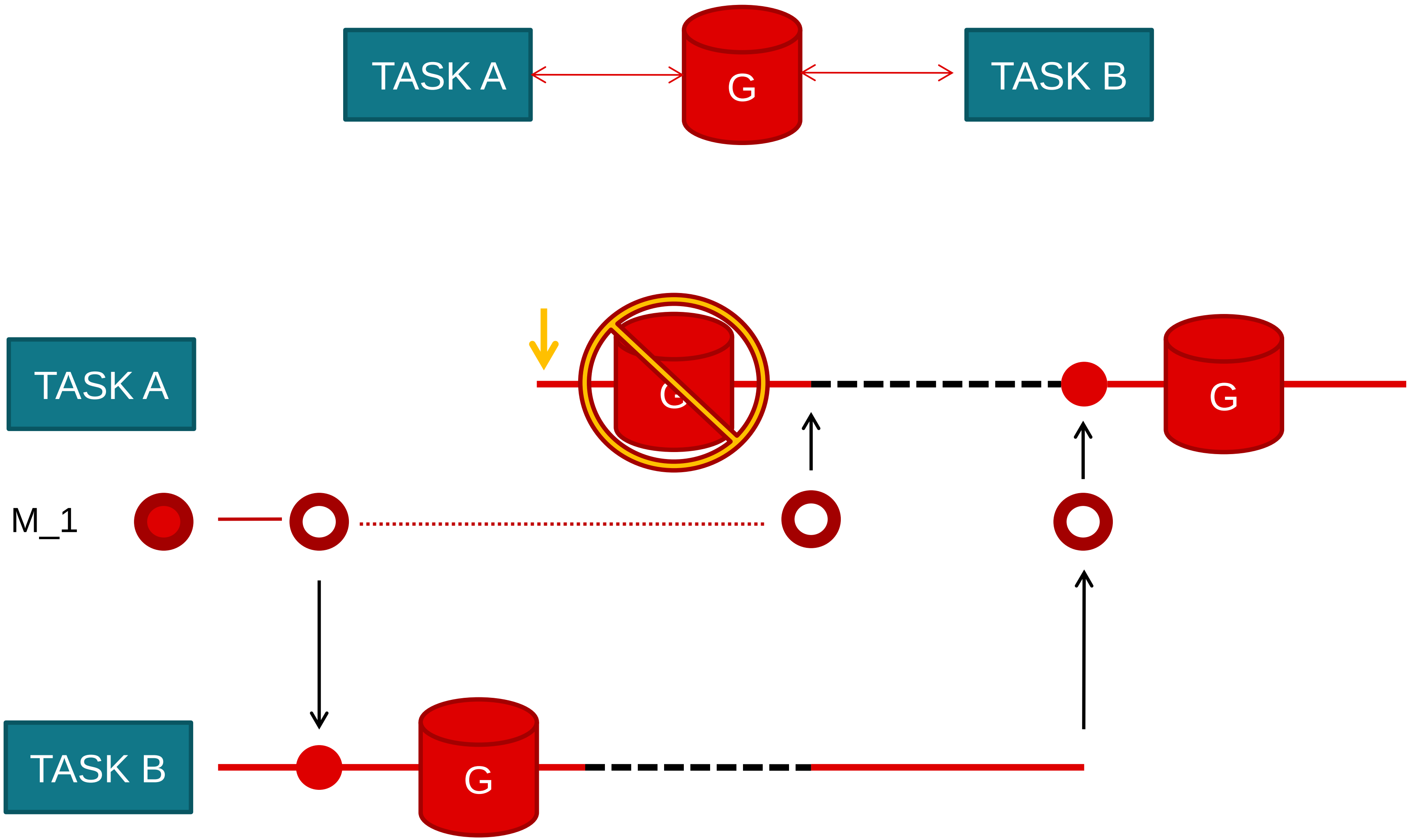
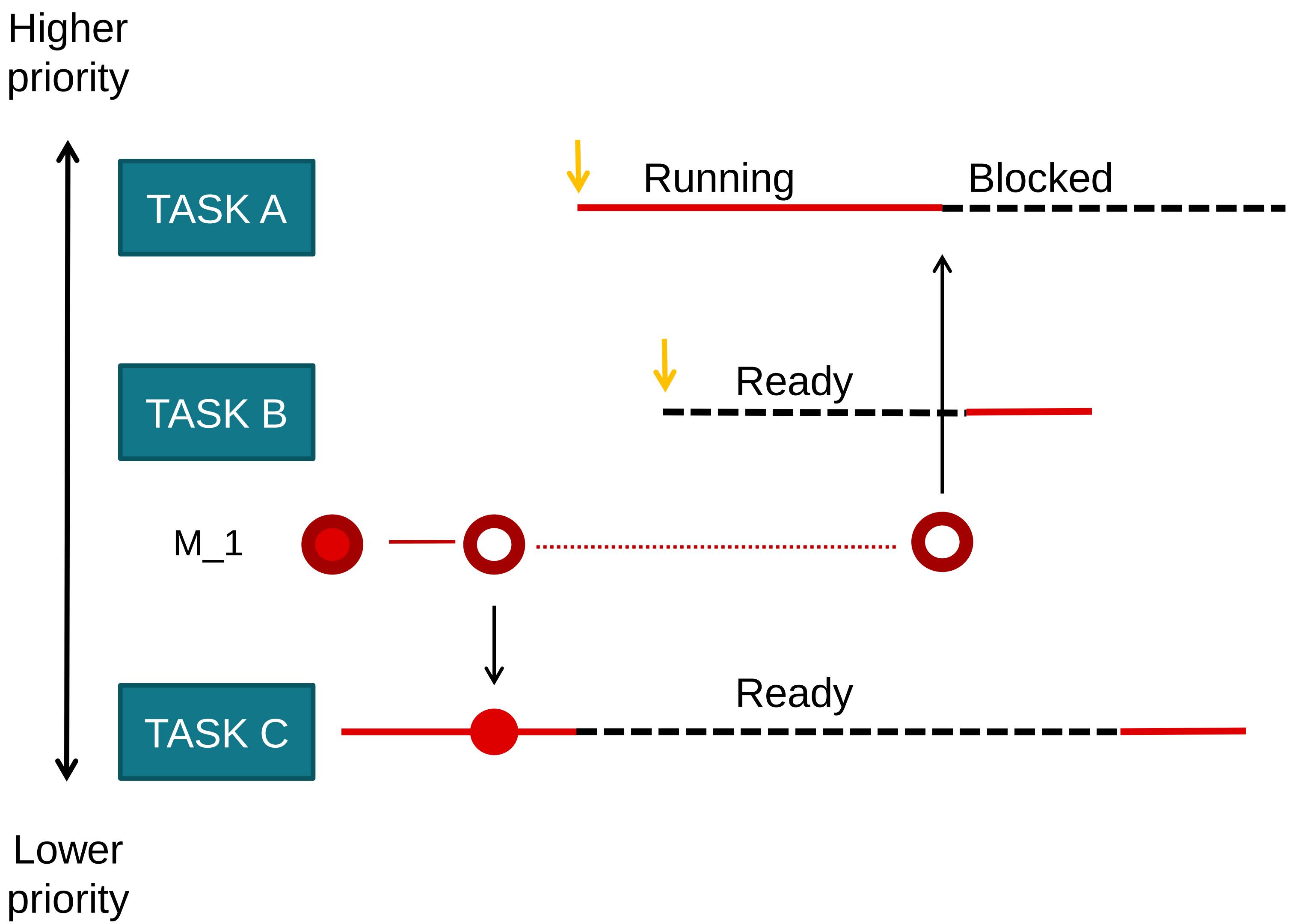




Global variables with Mutex



Task states

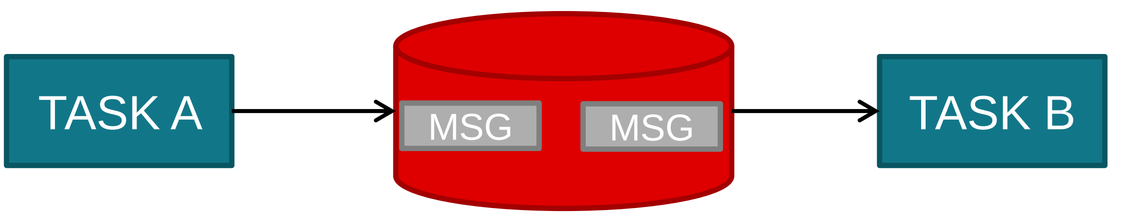

Higher
priority
TASK A
Running
Blocked
TASK B
Ready
M_1
TASK C
Ready
Lower
priority

Mailbox

- Publish – Subscribe
- Semaphore + FIFO
- Fixed size
  - Size of message
  - Number of messages

```
Mailbox_post(&msgBox, &msg, timeout)

Mailbox_pend(&msgBox, &msg, timeout)
```



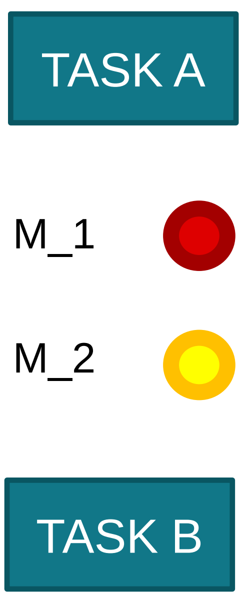
RTOS Challenges

Common challenges

Deadlock

When two threads both needs the resource the other thread has to continue their processing

- At least two Mutexes
- Two threads of different priorities



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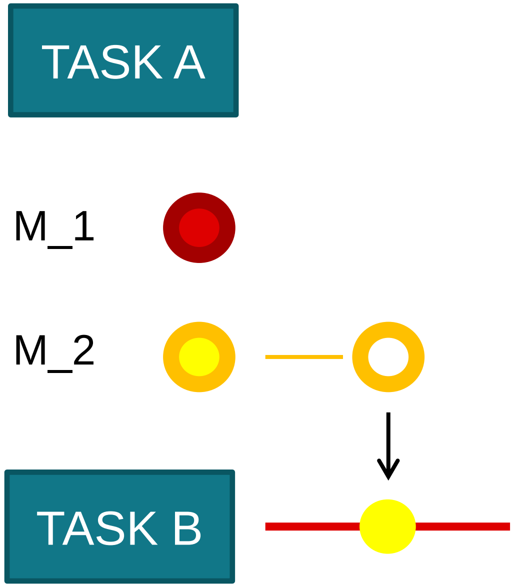

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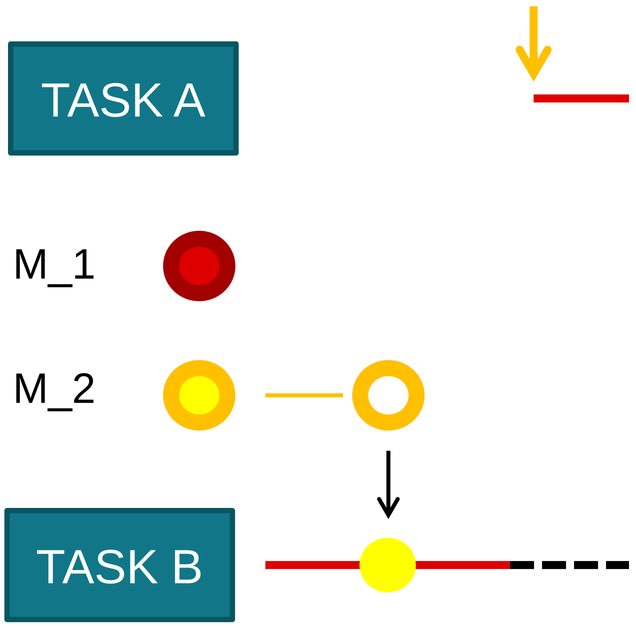

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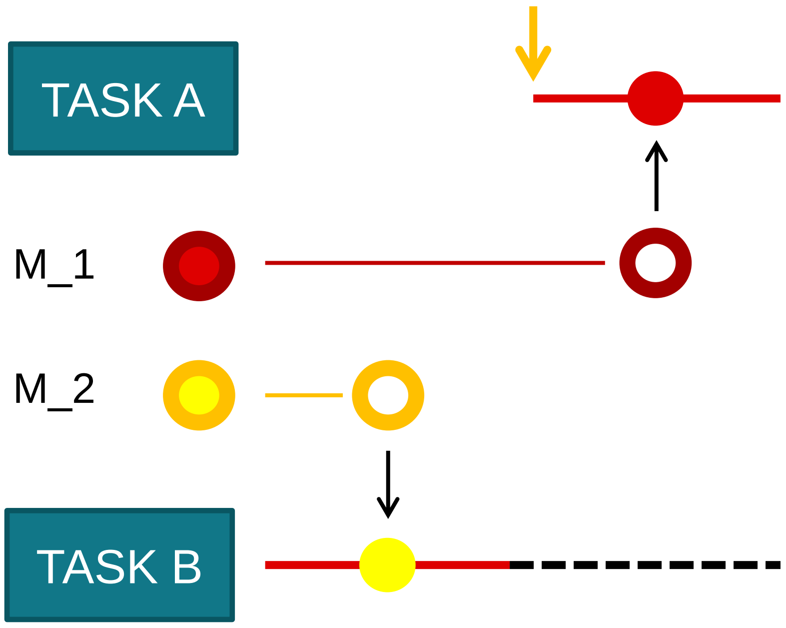

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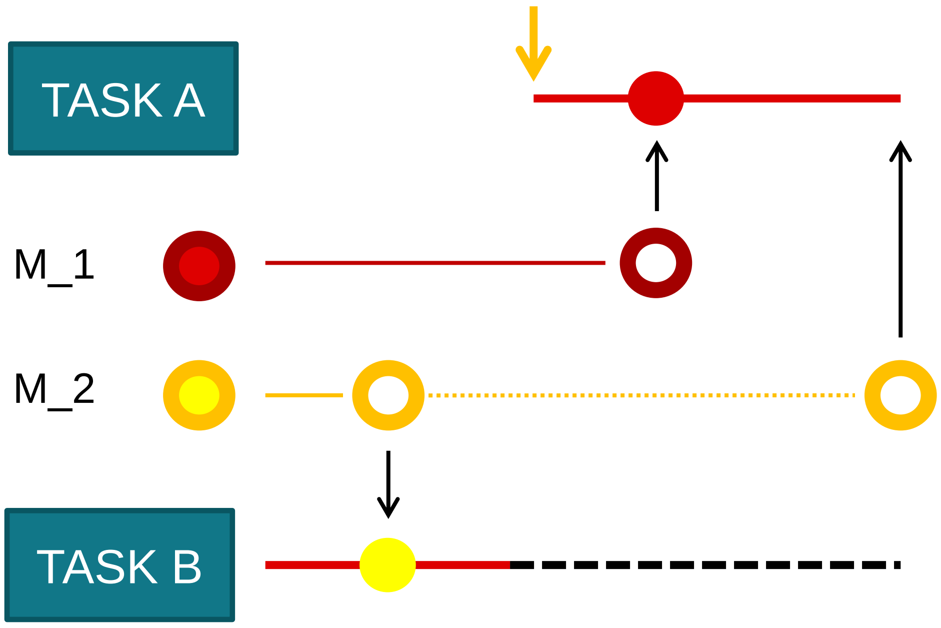

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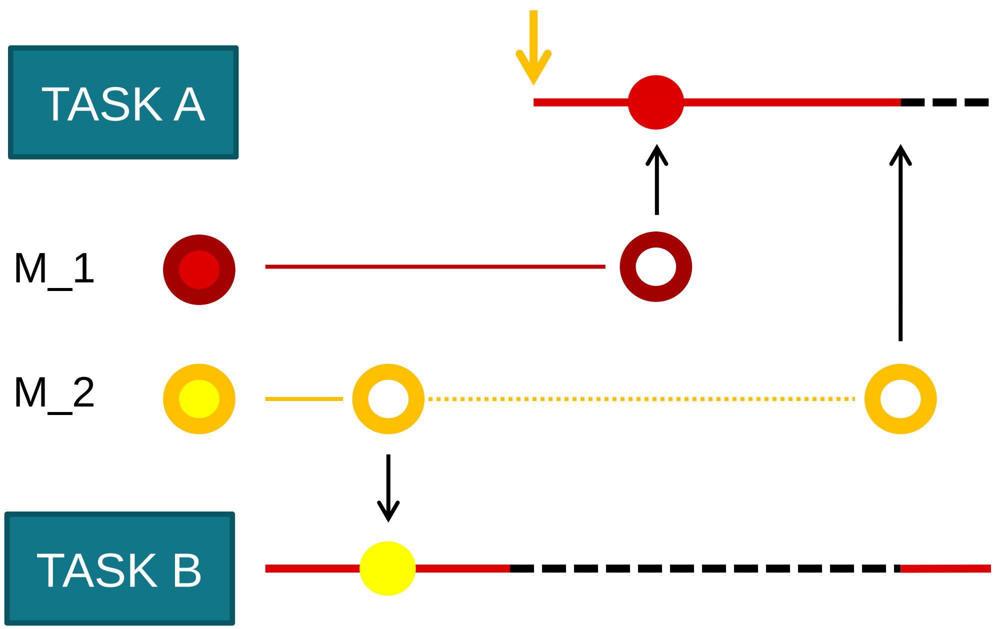

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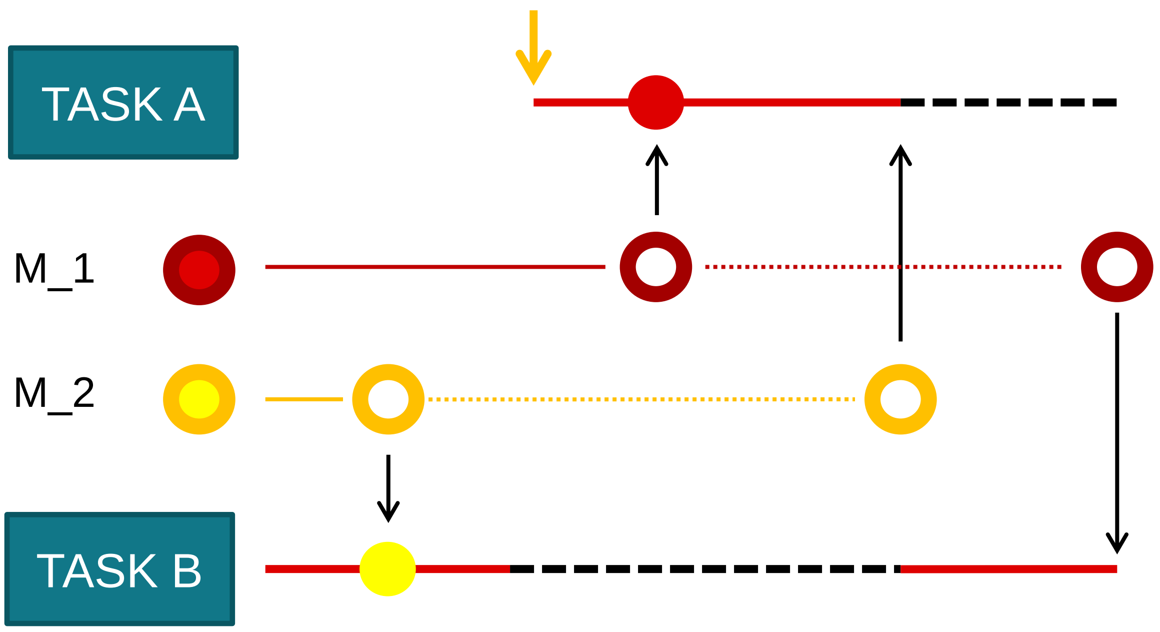

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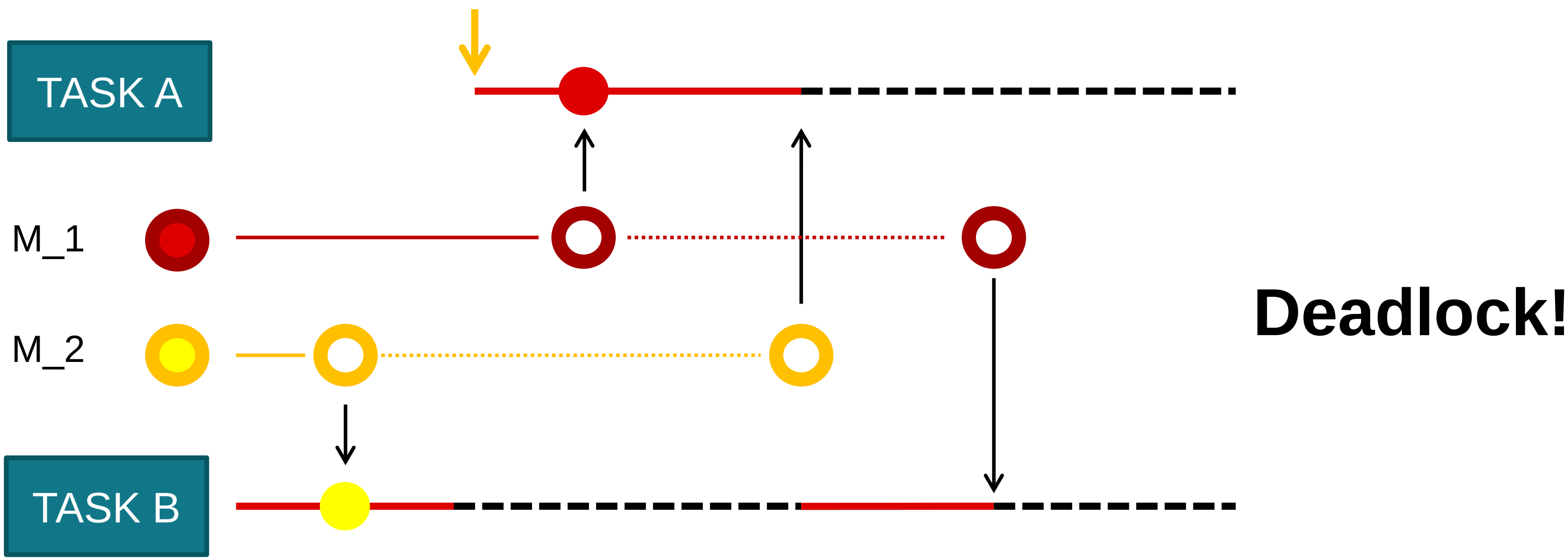

Deadlock

Ways to avoid deadlock:

- Use one big Mutex to cover both resources
- Always pend on the Mutex in the same order in all threads

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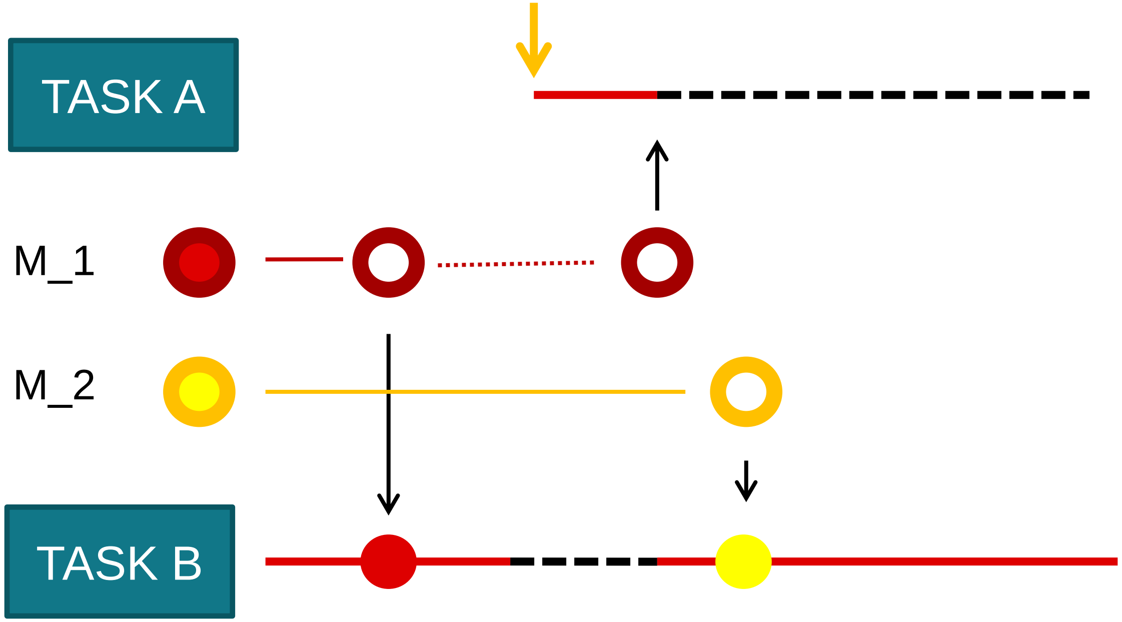

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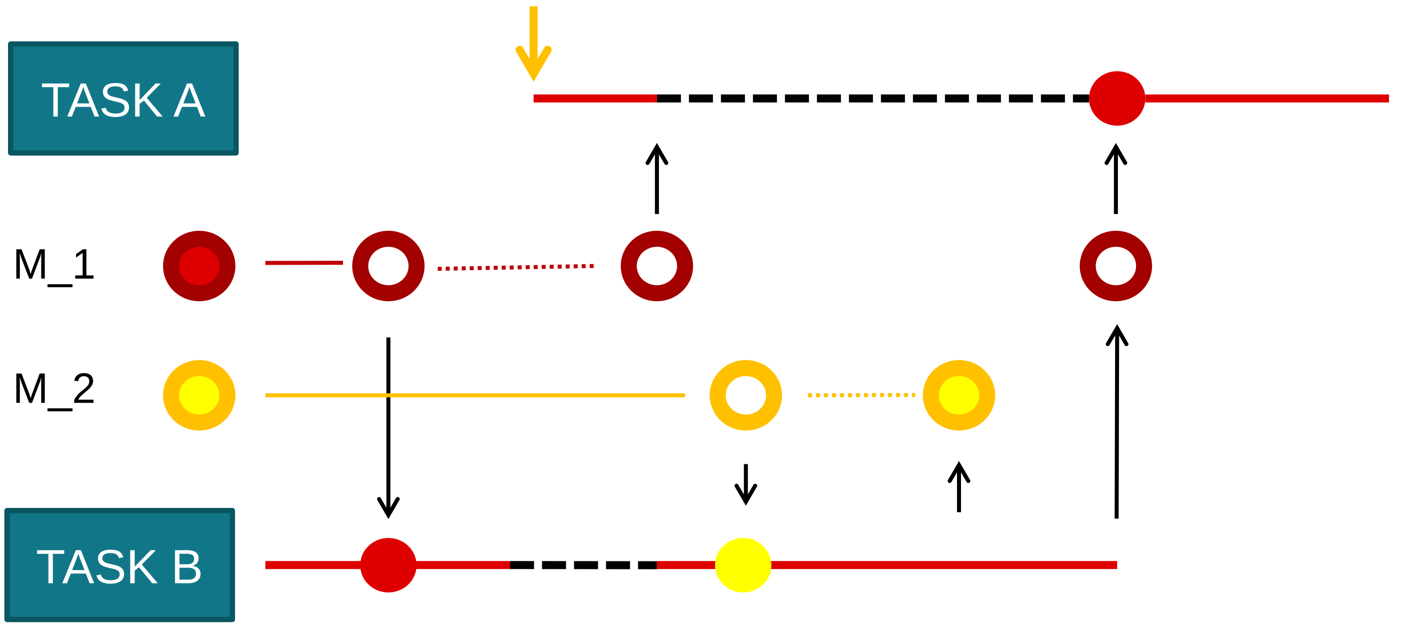

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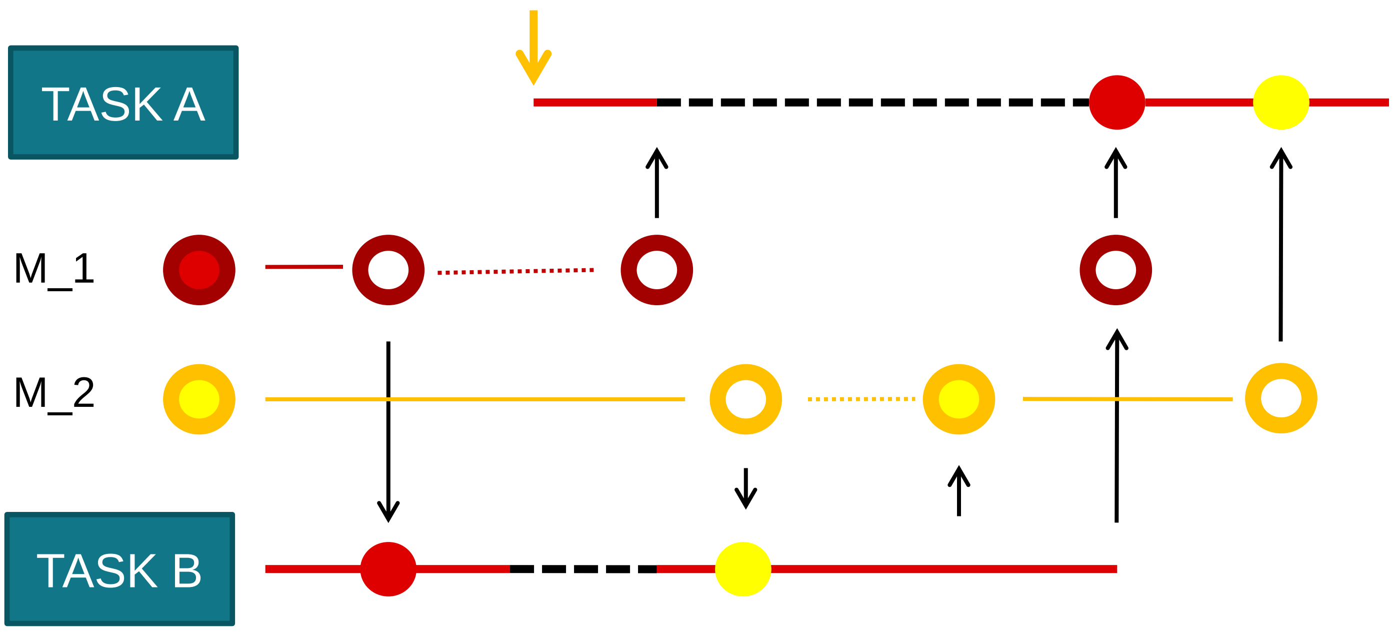
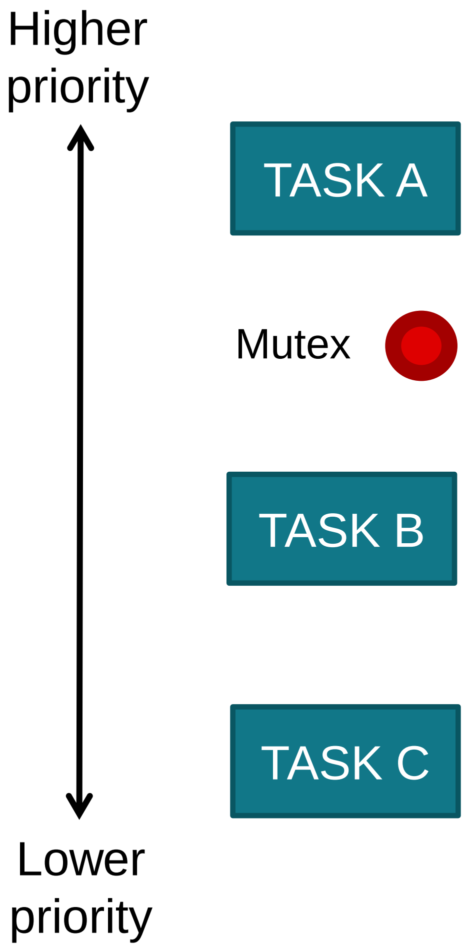


No deadlock

Priority Inversion

When a lower priority thread blocks a higher priority thread



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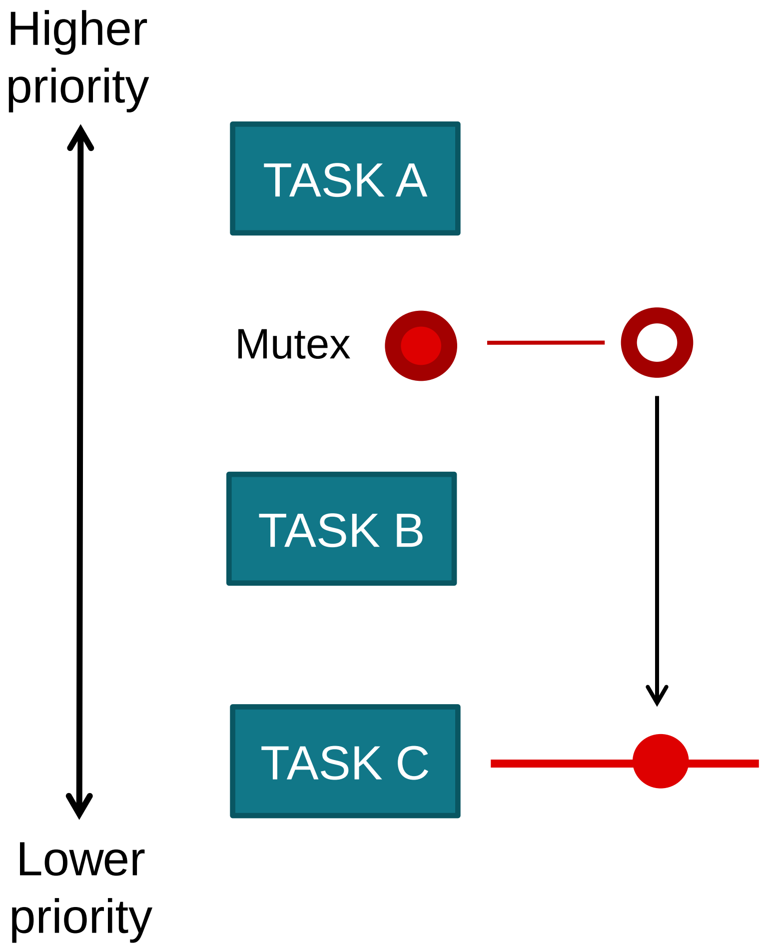

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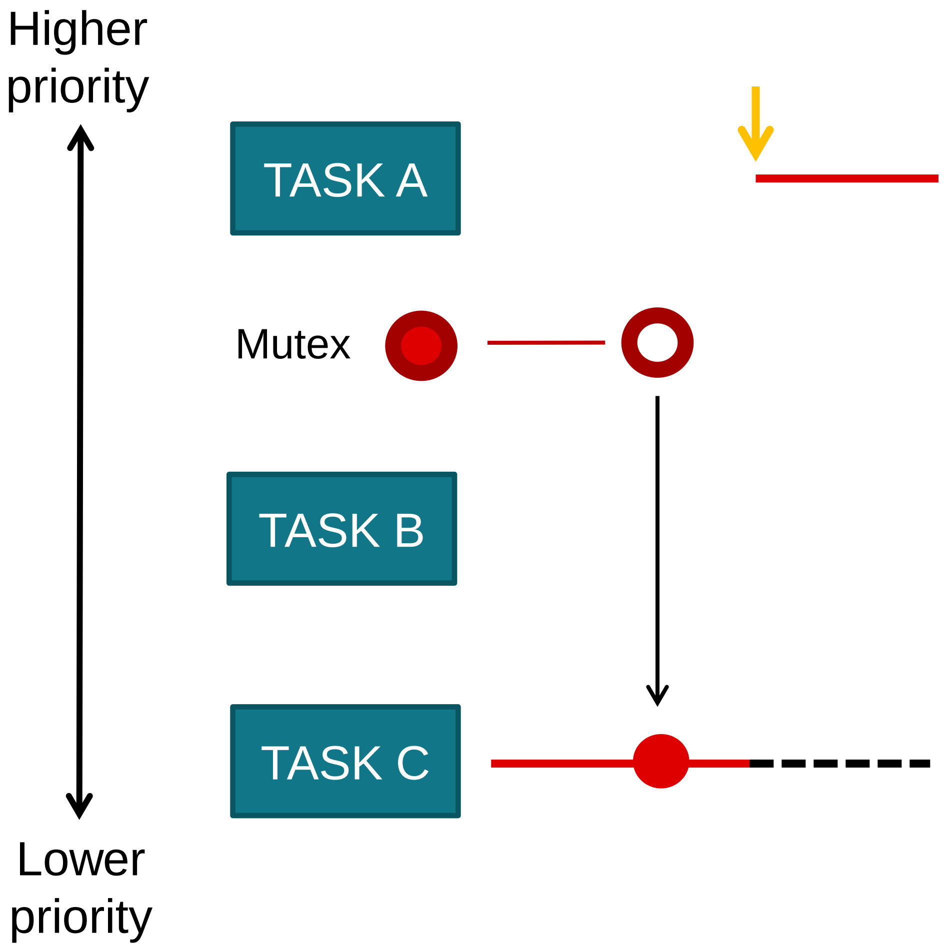

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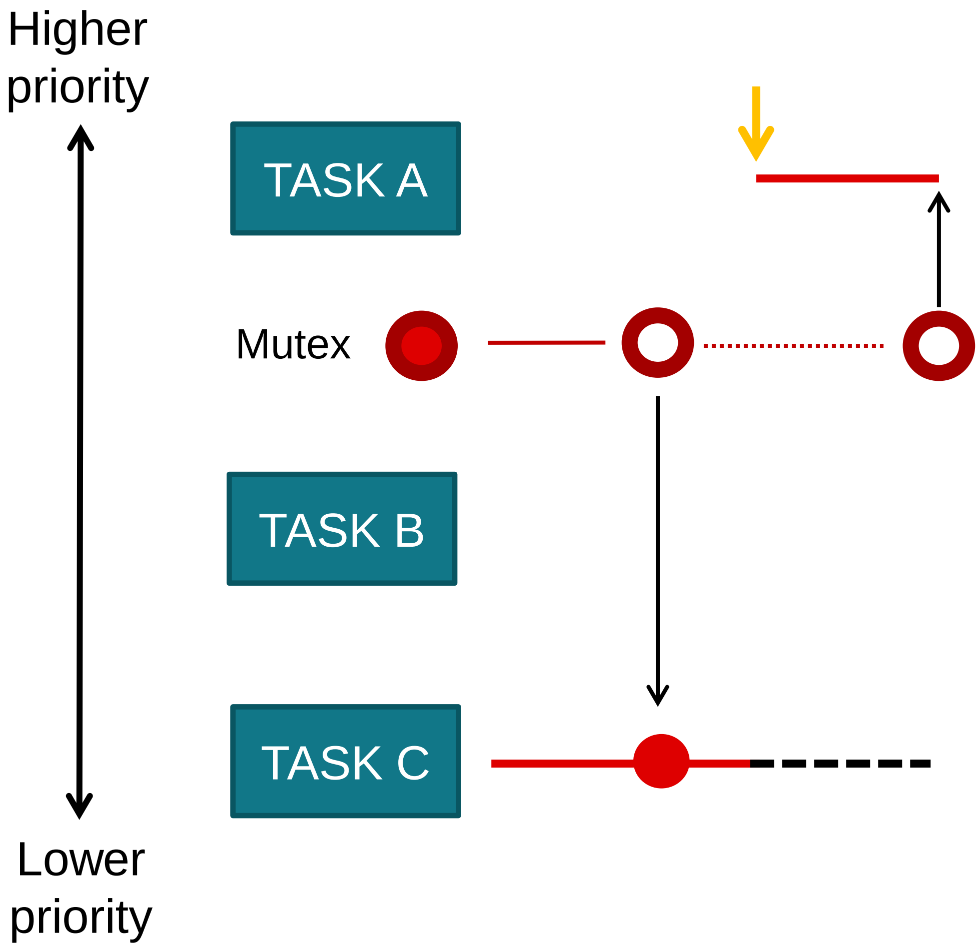

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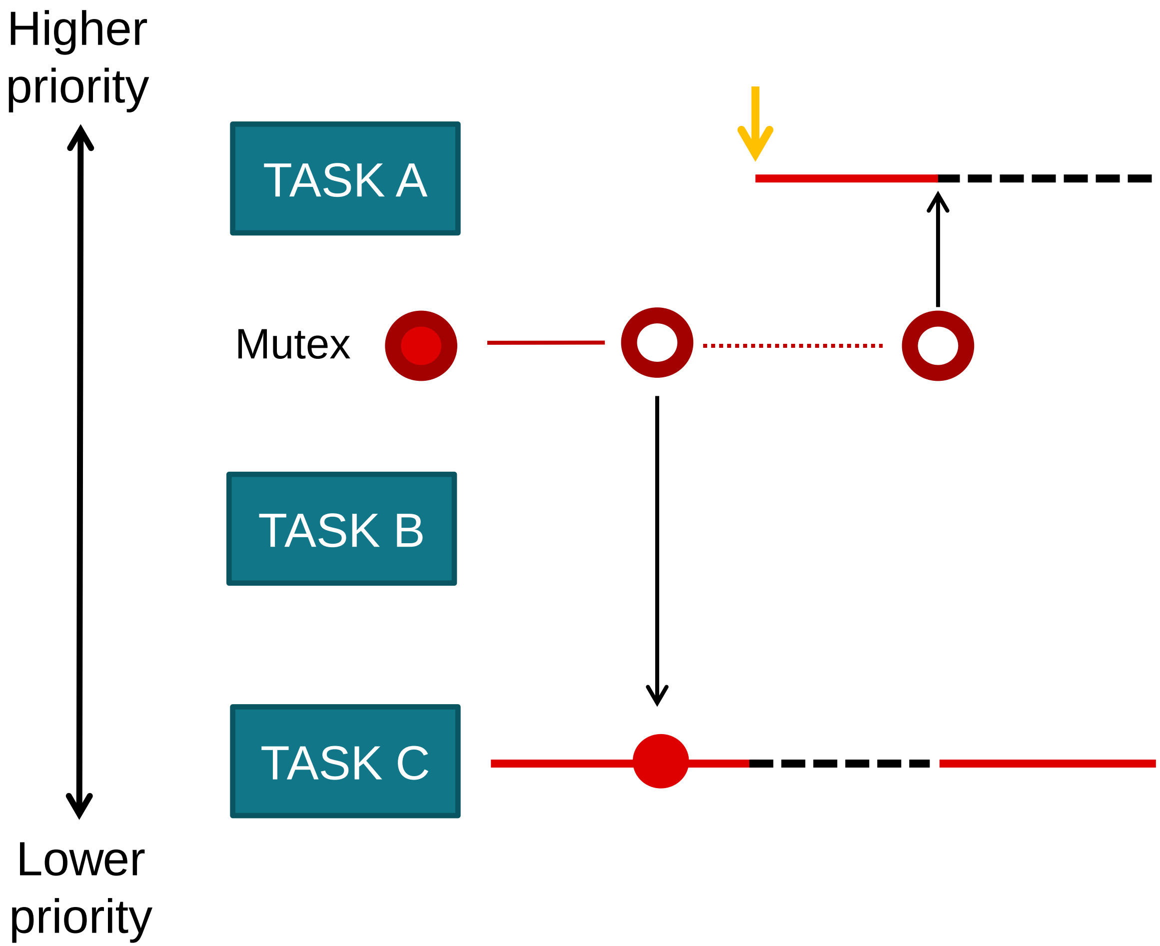

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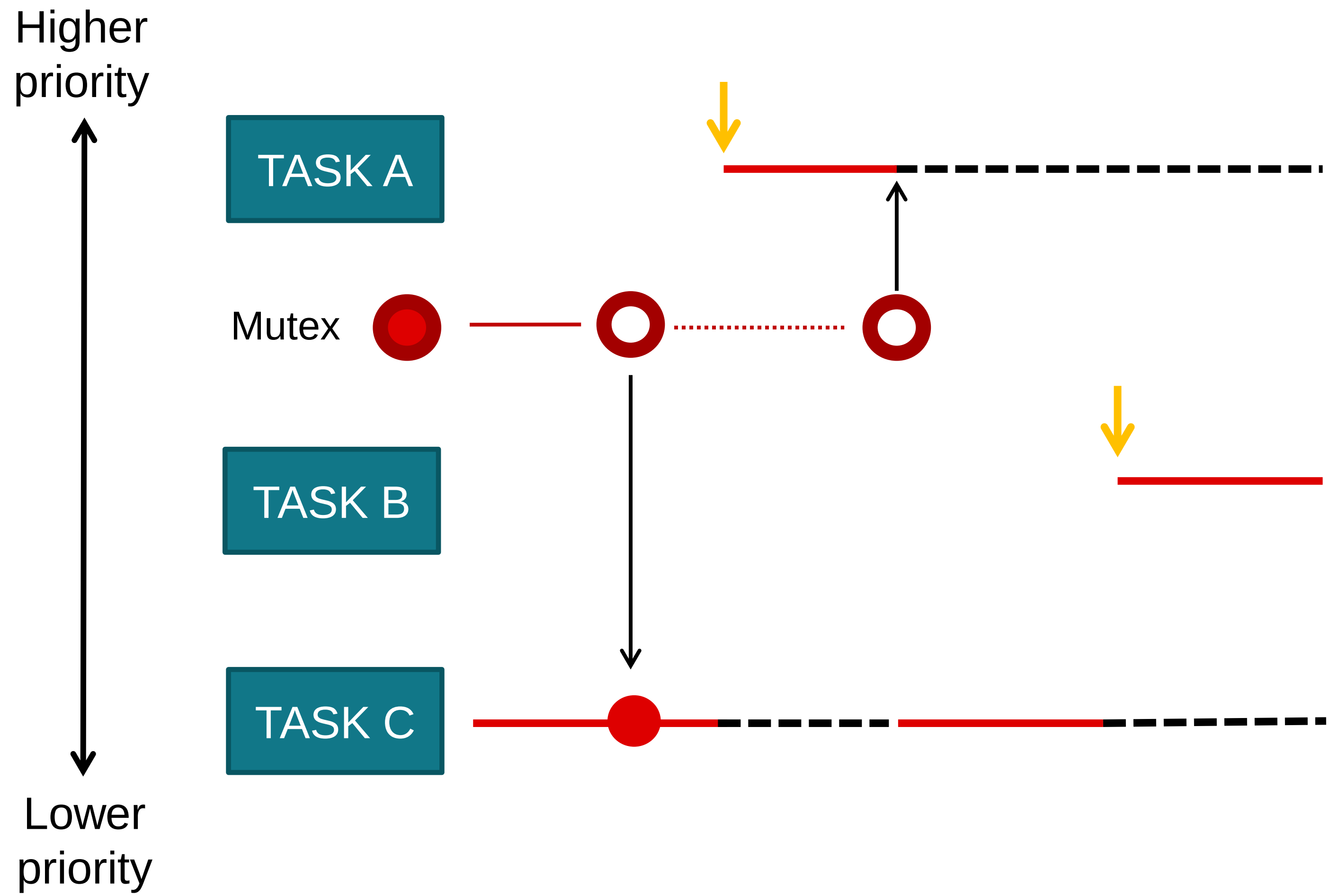
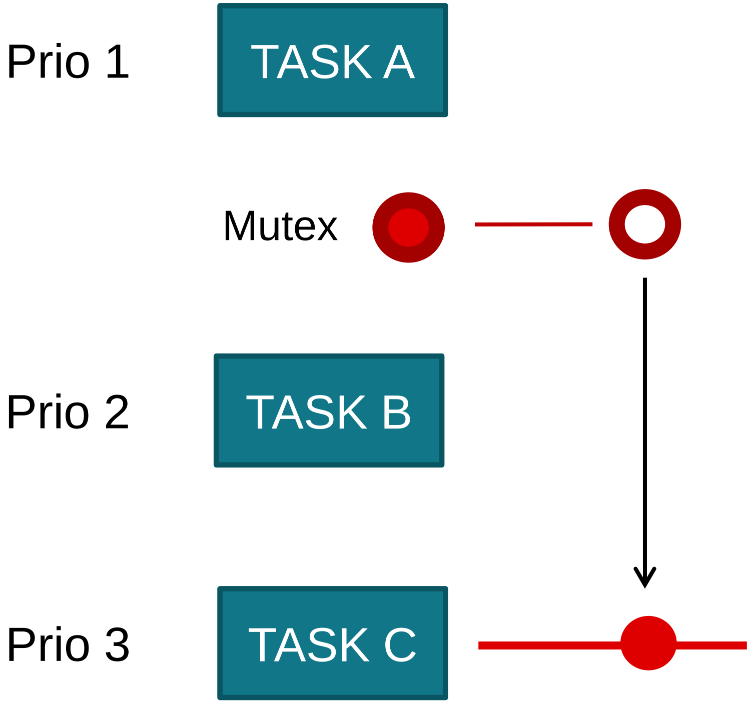


Priority inversion in effect!

Priority Inversion

How to avoid it: Temporarily promote Task C to Task A's priority



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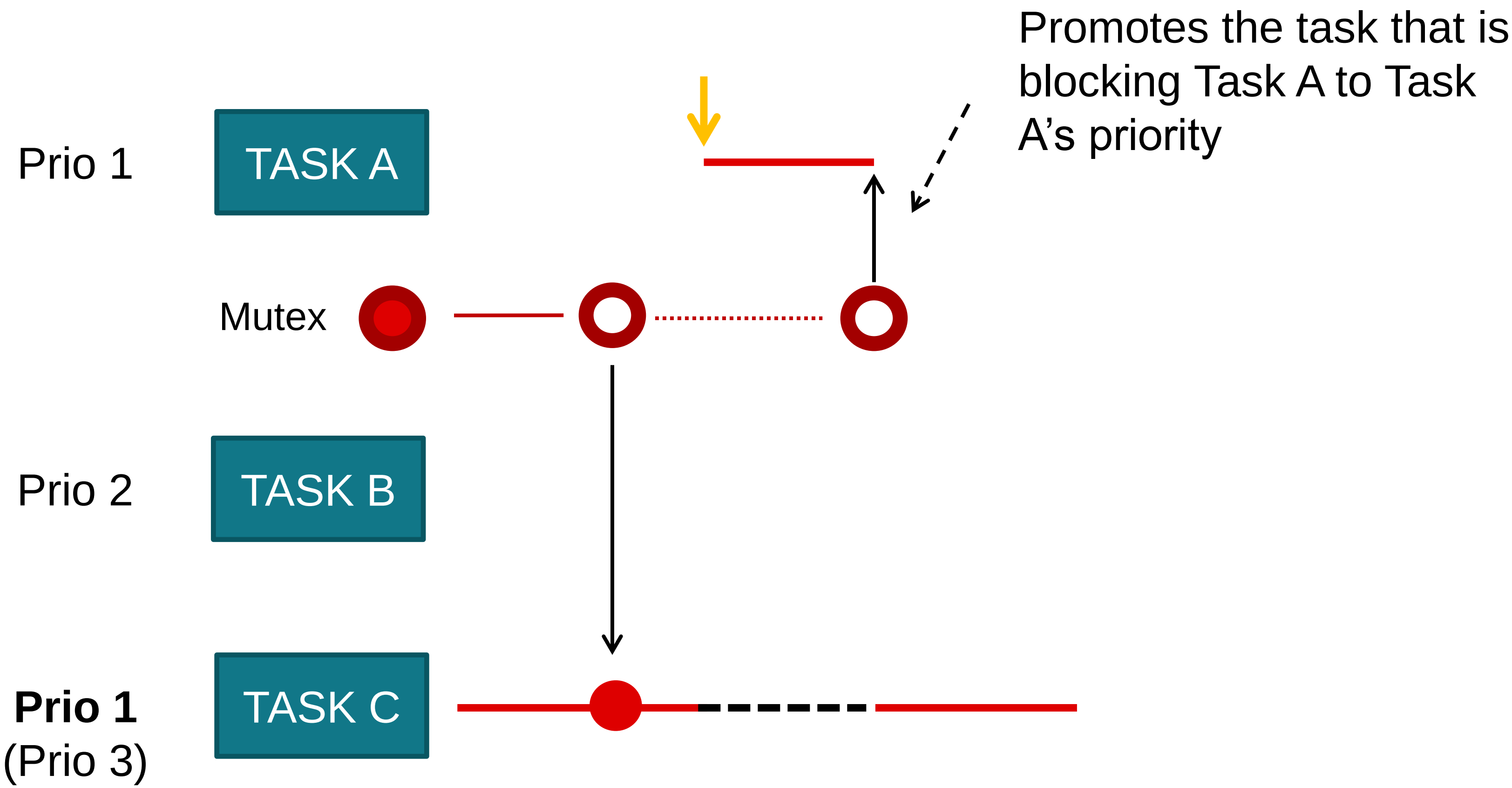

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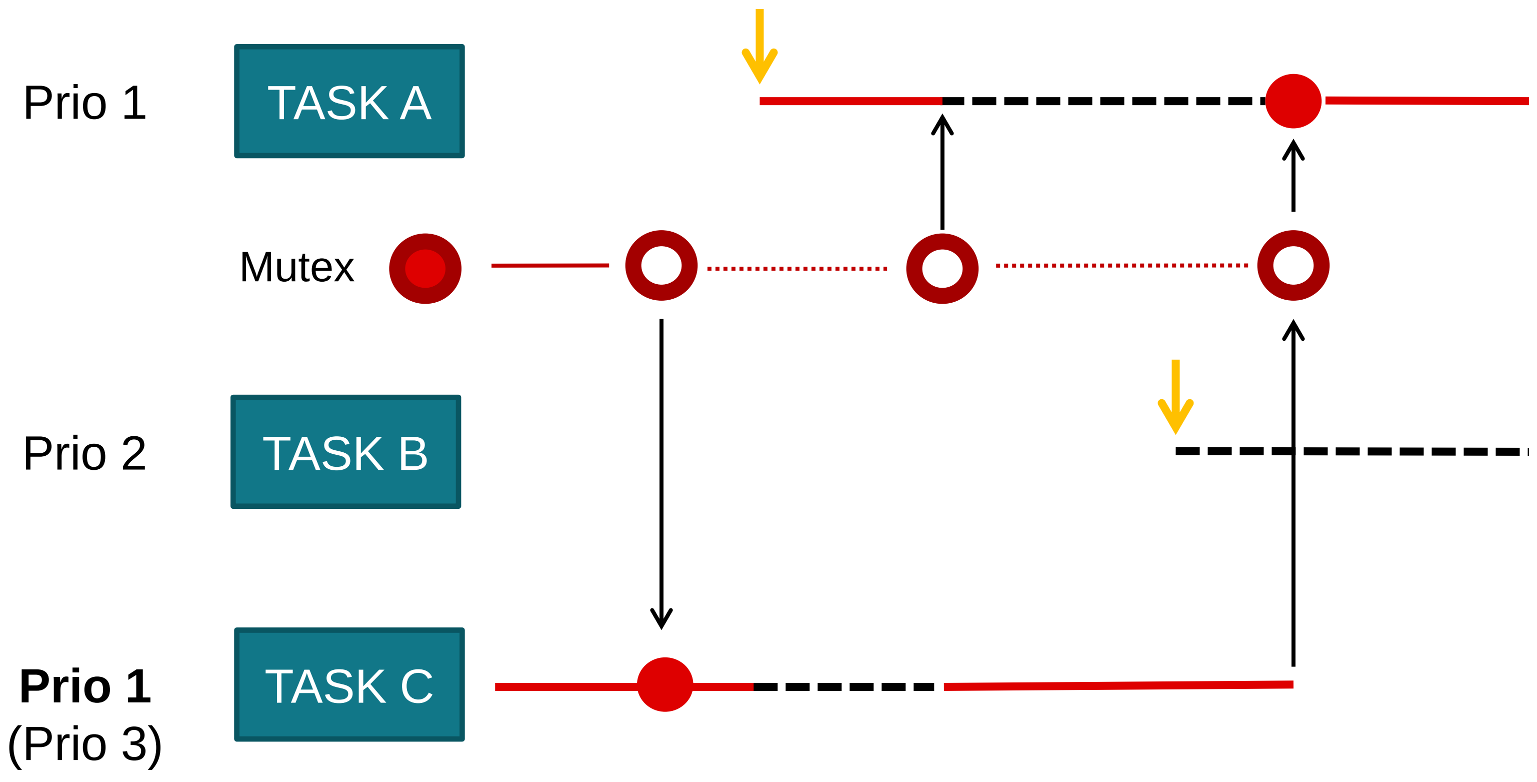

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