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ERTS - Embedded real-time systems

ERTS 9 – FreeRTOS

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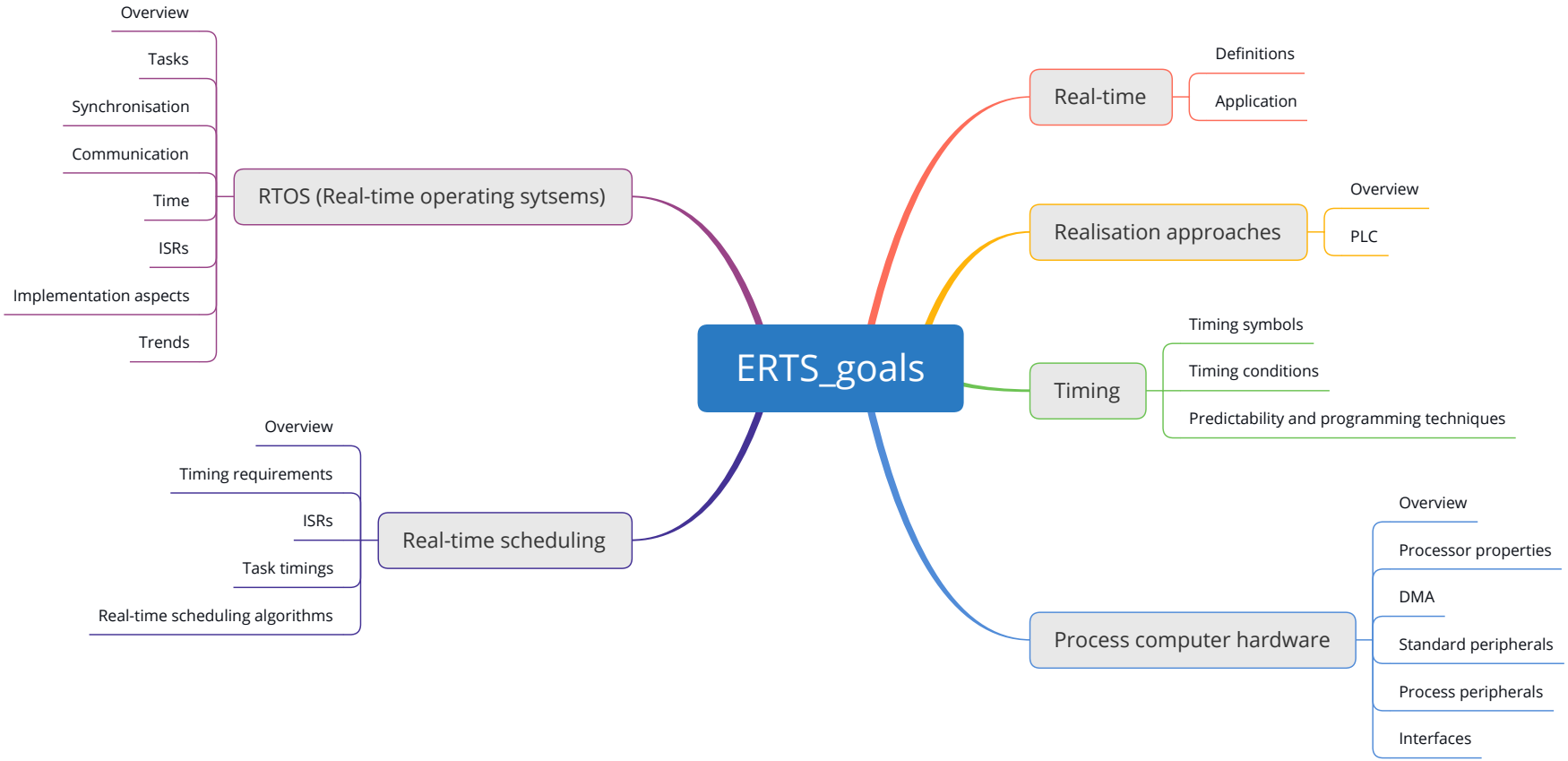
Goal



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Goal

ERTS::FreeRTOS

- FreeRTOS intro
- FreeRTOS customisation
- FreeRTOS task scheduling
- FreeRTOS task coding

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FreeRTOS

- Main Author: Richard Barry
- Started from Richard Barry around 2003
- Since 2017, acquired by Amazon Web Services (AWS)
- IoT connection stack to AWS cloud
- Supports up to 35 platforms
- License: MIT open source license
- Kernel + growing set of libraries

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FreeRTOS – features

- Tasks and scheduling
- Synchronisation and communication
  - Queues, mutexes, semaphores...
  - Task notifications
  - Events
  - Stream & message buffers
- Software Timers
- Event Groups (or *Flags*)
- Static vs dynamic memory for FreeRTOS objects
- Heap memory management
- Stack Overflow Protection
- MPU support (restricted tasks)

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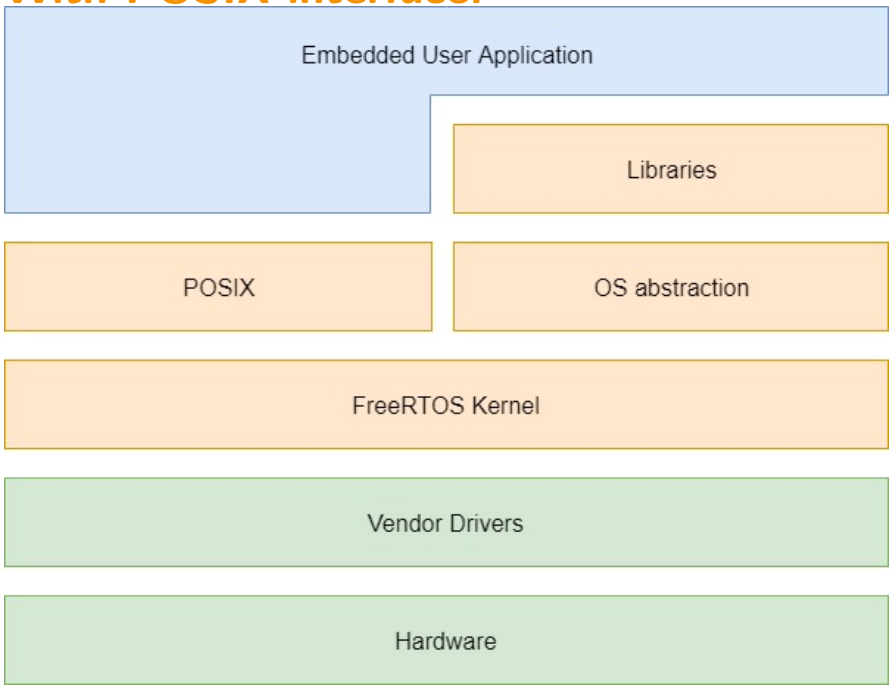
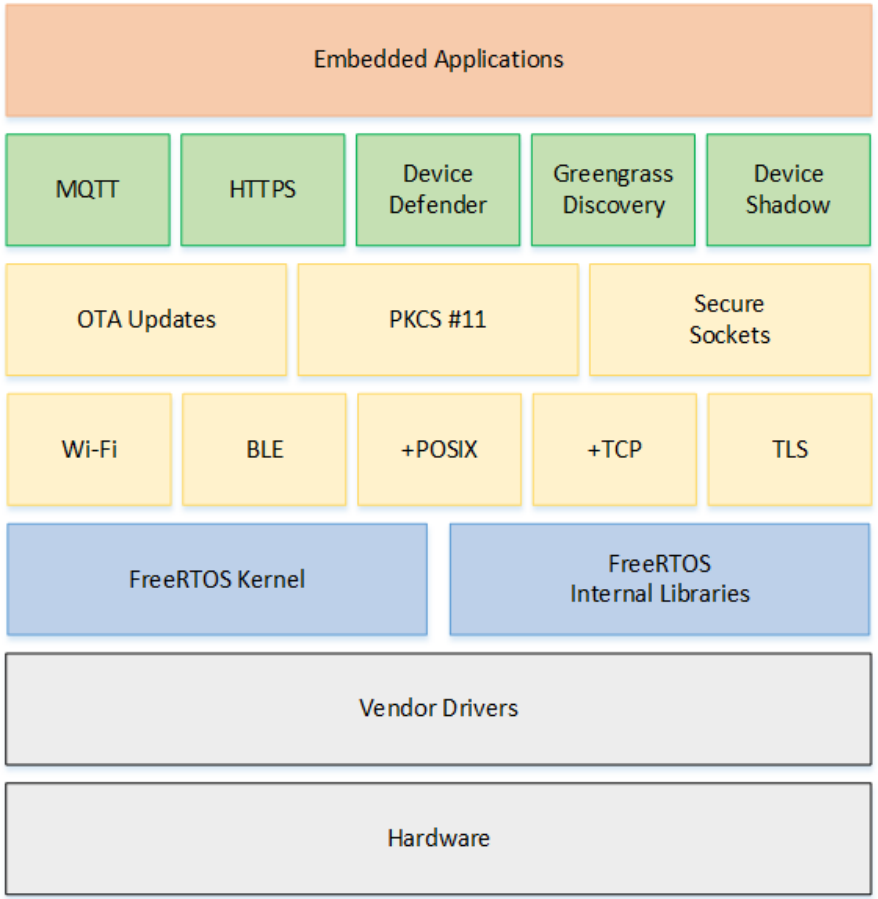
FreeRTOS – architecture

With POSIX interface:



[source: freertos.org]

With Amazon AWS libraries:



[source: aws.amazon.com]

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FreeRTOS – naming convention

Summary of FreeRTOS naming convention:

- **Variables:**
  - Prefix with type: e.g. `uint32_t` = ul, `uint16_t` = us
  - Non stdint types are prefixed x
- **Functions:**
  - Prefix with return type: e.g. `void` = v, `uint32_t` = ul
  - Function names start with the name of the file in which they are defined
- **Macros:** Prefix with file in which they are defined

More details: Naming Conventions

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FreeRTOSConfig.h

FreeRTOS can be configured with the `FreeRTOSConfig.h`

Possibilities:

- Enable/disable features
- Define details for:
  - Scheduling
  - Tasks
  - Memory management
  - Timers
  - ...

Within the Arduino framework, the `FreeRTOSConfig.h` is already pre-configured. Additionally, `FreeRTOSVariant.h` exists.

More details: `https://www.freertos.org/a00110.html`

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FreeRTOS on Arduino Mega
Priorities

`FreeRTOSConfig.h`

- Task priorities

```
1 #define configMAX_PRIORITIES 16
2 //Defines the max available priorities for application tasks.
```

- Default on Arduino: `#define configMAX_PRIORITIES 4`
- But: can be changed to higher values

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FreeRTOS on Arduino Mega

Scheduler config: SysTick

`FreeRTOSVariant.h`

- SysTick rate

```
1 #define configTICK_RATE_HZ 1000
2 //The frequency of the RTOS tick interrupt.
```

- **But:** The Atmega2560 micocontroller has no SysTick interrupt
- Uses the watchdog timeout for SysTick
- SysTick oscillator: 128 kHz (but this depends on voltage and temperature)
- SysTick duration:
  - `#define portUSE_WDTO WDTO_15MS`
  - $\texttt{t\_STK\_DR} \approx 15\ \texttt{ms}$ (or up to $\texttt{t\_STK\_DR} \approx 17\ \texttt{ms}$ (measured))
- SysTick rate (frequency): `WDG_CR`
  - $\texttt{WDG\_CR} = \frac{1}{15\ \texttt{ms}} \approx 66\ \texttt{HZ}$ (or: $\texttt{WDG\_CR} = \frac{1}{17\ \texttt{ms}} \approx 58\ \texttt{HZ}$)

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FreeRTOS on Arduino Mega
Scheduler config

FreeRTOSConfig.h

- Preemption

```
1 #define configUSE_PREEMPTION 1
2 //Set to 1 to use the preemptive RTOS scheduler, or 0 to use the
3 //cooperative RTOS scheduler.
```

- Task selection

```
1 #define configUSE_PORT_OPTIMISED_TASK_SELECTION 0
2 //Some FreeRTOS ports have two methods of selecting the next task
3 //to execute - a generic method, and a method that is specific to
4 //that port.
```

- Time slicing

```
1 #define configUSE_TIME_SLICING 1
2 //If set to 1 (or undefined) time slicing is used for tasks with the
3 //same priority. If set to 0, no time slicing is used for tasks
4 //with the same priority.
```

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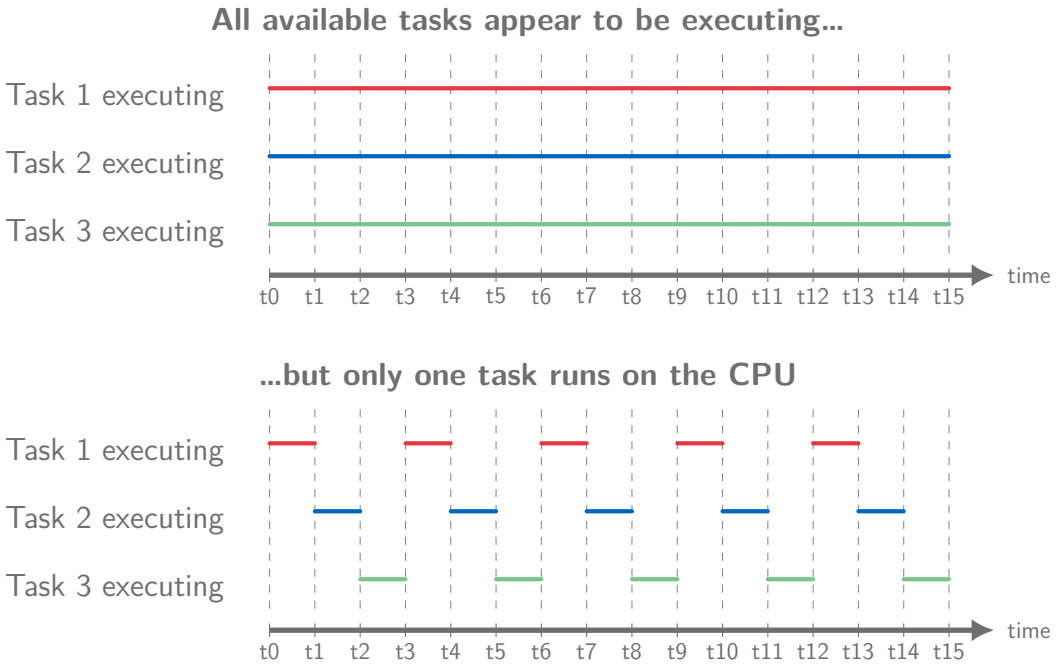
FreeRTOS – multitasking basics



source: https://www.freertos.org/implementation/a00004.html

Multitasking:

- Tasks appear to run in parallel
- On Atmega2560, only one CPU is present
- Tasks run alternating: one after another

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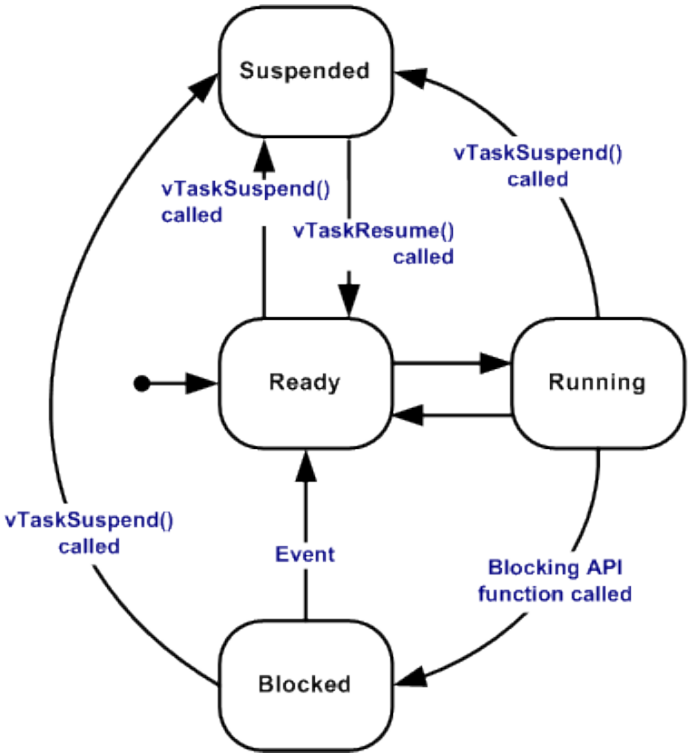
FreeRTOS – task states



source: https://www.freertos.org/RTOS-task-states.html

States:

- Ready: Task is ready to run
- Running: Task (only one) runs now
- Suspended: Task is suspended
- Blocked: Task is blocked (e.g. semaphore, delay, ...)

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Interrupt and task priorities overview

Atmega2560 interrupt priorities combined with the FreeRTOS task priorities.

	Config	Priority	Description
Task priorities			
(ISR deferred task) and	`configMAX_PRIORITIES` ⇒	4	⇐ highest prio
		3	Usable task priorities
	`configTIMER_TASK_PRIORITY` ⇒	2	
	Reserved for idle task	1	⇐ lowest prio
Interrupt/exception priorities			
		57	⇐ lowest prio
		...	
WDT (watchdog timeout) used for FreeRTOS SysTick		13	**Can** use interrupt safe FreeRTOS API
		...	
INT0 (external interrupt request 0)		2	
RESET		1	⇐ highest prio

Interrupts have higher prio than tasks

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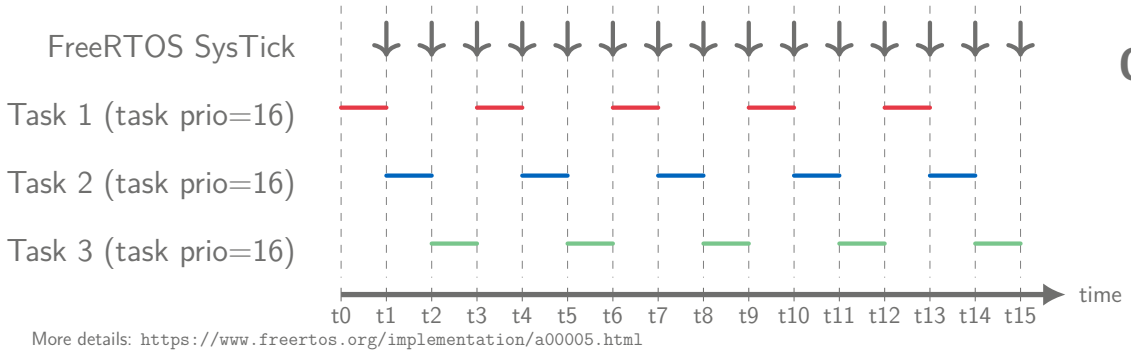
FreeRTOS – scheduling basics

Default scheduling strategy: pre-emption with time slicing



More details: https://www.freertos.org/implementation/a00005.html

On every FreeRTOS SysTick:

- The task is changed
- It uses round robin (RR)
- RR is used between similar prio

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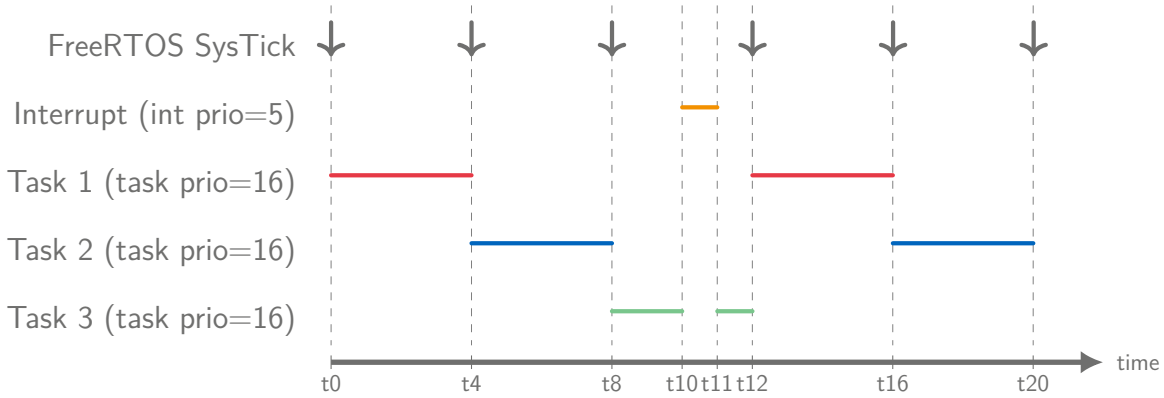
FreeRTOS – scheduling basics – interrupt

Default scheduling strategy: pre-emption with time slicing, and an interrupt



Scheduling:

- `t0`: Scheduler: Task 1 runs
- `t4`: Scheduler: Task 2 runs
- `t8`: Scheduler: Task 3 runs
- `t10`: Interrupt: ISR
- `t11`: ISR end: Task 3 runs
- `t12`: Scheduler: Task 1 runs
- `t16`: Scheduler: Task 2 runs
- `t20`: Scheduler: ...

More details: `https://www.freertos.org/implementation/a00008.html`

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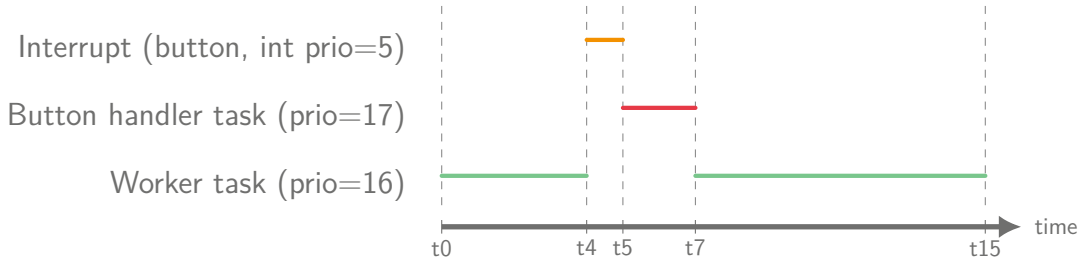
FreeRTOS – task priority

FreeRTOS scheduling with task priorities



Interrupt (Button):

- Lifts (`V()`) the semaphore for the button handler task

Button handler task:

- Works for 2 time periods
- Then finishes work and waits (`P()`) on a semaphore

Worker task:

- Works for ever (endless loop)

More details: `https://www.freertos.org/implementation/a00008.html`

Scheduling:

- `t0`: Scheduler: Worker task runs
- `t4`: Interrupt: ISR (lift (`V()`) semaphore)
- `t5`: Scheduler: Button handler task runs
- `t7`: Button handler task ends (waits on (`P()`) semaphore); Scheduler: Worker task
- ...

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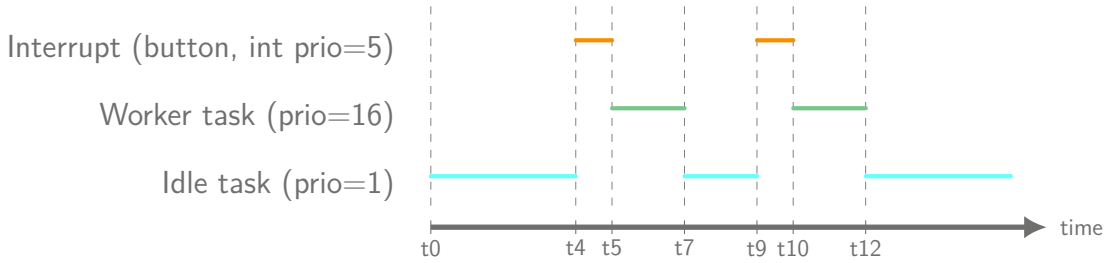
FreeRTOS – idle task

FreeRTOS scheduling with idle task



Interrupt (Button):

- Lifts (`V()`) the semaphore for the worker task

Worker task:

- Works for 2 time periods
- Then finishes work and waits (`P()`) on a semaphore

Idle task:

- Runs on the lowest priority (prio=1)
- Is executed, when no other task is ready to run

Scheduling:

- `t0`: Scheduler: Idle task runs
- `t4`: Interrupt: ISR (lift (`V()`) semaphore)
- `t5`: Scheduler: Worker task runs
- `t7`: Worker task ends (waits on (`P()`) semaphore); Scheduler: Idle task runs
- ...

More details: `https://www.freertos.org/implementation/a00008.html`

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Setup and start FreeRTOS kernel

Create project with FreeRTOS

- Create Arduino project with Arduino Mega 2560
- Add FreeRTOS library to project

Start kernel

```
1 //Start scheduler
2 vTaskStartScheduler();
3
4 //within the Arduino framework, this is done behind the scenes
5 //in variantHooks.cpp: initVariant()
```

setup() function

```
1 void setup() {
2   //here, the FreeRTOS primitives are created and initialised:
3   // - semaphores
4   // - tasks
5   // - ...
6 }
```

loop() function

```
1 void loop() {
2   //if the idle task functionality is activated, this function can act
3   //as the idle task (default)
4
5   //otherwise, this is kept empty because the FreeRTOS scheduler
6   //controls everything
7 }
```

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Create tasks

Define task handle

```
1  TaskHandle_t worker_task_handle = NULL;
```

Define task function

```
2  void worker_task(void* pvParameters) {
3      while(true){
4          //work...
5      }
6  }
7  //A task never ends. If it should be deleted,
8  //call vTaskDelete(nullptr) within the worker_task() function
```

Create task

```
9  BaseType_t result = xTaskCreate(
10   worker_task,          //address of task function
11   "worker_task",        //name of task
12   128L,                 //task stack size in words: 128*2=256 bytes (configSTACK_DEPTH_TYPE)
13   NULL,                 //task parameters
14   16,                   //task priority (2-55)
15   &worker_task_handle //pointer to task handle
16 );
17
18 configASSERT(result == pdPASS);           //assert that the task could be created
19 configASSERT(worker_task_handle != NULL); //assert that task handle is valid
```

- FreeRTOS doc (task creation): https://www.freertos.org/a00019.html

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Semaphores: interrupt to task

Define semaphore handle

```
1  SemaphoreHandle_t worker_semaphore = NULL;
```

Create semaphore

```
2  worker_semaphore = xSemaphoreCreateBinary();
3  configASSERT(worker_semaphore != NULL);
```

Worker task implementation

```
4  void worker_task(void* pvParameters) {
5    log_message("worker_task started...");
6
7    while(true) {
8      log_message("worker_task sleep...");
9      //wait infinitely for semaphore
10     xSemaphoreTake(worker_semaphore, portMAX_DELAY);
11     log_message("worker_task wake up...");
12
13     for (uint8_t i = 0; i < 10; ++i) {
14       log_message("worker_task: toggle led");
15       digitalWrite(LED_PIN, !digitalRead(LED_PIN));
16       vTaskDelay(pdMS_TO_TICKS(100));
17     }
18   }
19 }
```

ISR implementation

```
20 void button_isr() {
21   BaseType_t taskChangeRequired = pdFALSE;
22   xSemaphoreGiveFromISR(worker_semaphore,
23                         &taskChangeRequired);
24
25   //to immediately run the scheduler (change task)
26   if (taskChangeRequired == pdTRUE) {
27     taskYIELD();
28   }
29 }
```

Inside ISRs:

- Only use FreeRTOS functions that end with `FromISR()`
- Be aware to not use HW/HAL functions that are used from other tasks (needs to by synchronised)

- FreeRTOS doc (semaphores): `https://www.freertos.org/a00113.html`

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Semaphores: task to task

Example with two tasks: ping/pong example

Create semaphores

```
1  ping_semaphore = xSemaphoreCreateBinary();
2  configASSERT(ping_semaphore != NULL);
3
4  //let the ping task start first
5  xSemaphoreGive(ping_semaphore);
6
7  pong_semaphore = xSemaphoreCreateBinary();
8  configASSERT(pong_semaphore != NULL);
```

Task implementation

```
9  void ping_task(void* pvParameters) {
10   while (true) {
11     //wait infinitely for semaphore
12     xSemaphoreTake(ping_semaphore, portMAX_DELAY);
13
14     log_message("ping...");
15     vTaskDelay(pdMS_TO_TICKS(1000));
16
17     xSemaphoreGive(pong_semaphore);
18   }
19 }
```

```
20 void pong_task(void* pvParameters) {
21   while (true) {
22     //wait infinitely for semaphore
23     xSemaphoreTake(pong_semaphore, portMAX_DELAY);
24
25     log_message("       ...pong");
26     vTaskDelay(pdMS_TO_TICKS(1000));
27
28     xSemaphoreGive(ping_semaphore);
29   }
30 }
```

- FreeRTOS doc (semaphores): https://www.freertos.org/a00113.html

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Task notification: interrupt to task

Define task handle and task function as usual...

```
1  TaskHandle_t deferred_isr_task_handle = NULL;
```

Worker task implementation

```
2  void deferred_isr_task(void* pvParameters) {
3    log_message("worker_task started...");
4
5    while(true) {
6      log_message("worker_task sleep...");
7      //wait infinitely for a task notification
8      ulTaskNotifyTake(pdFALSE, portMAX_DELAY);
9      log_message("worker_task wake up...");
10
11     for (uint8_t i = 0; i < 10; ++i) {
12       log_message("worker_task: toggle led");
13       digitalWrite(LED_PIN, !digitalRead(LED_PIN));
14       vTaskDelay(pdMS_TO_TICKS(100));
15     }
16   }
17 }
```

ISR implementation

```
18 void button_isr() {
19   BaseType_t taskChangeRequired = pdFALSE;
20   vTaskNotifyGiveFromISR(deferred_isr_task_handle,
21                          &taskChangeRequired);
22
23   //to immediately run the scheduler (change task)
24   if (taskChangeRequired == pdTRUE) {
25     taskYIELD();
26   }
27 }
```

Inside ISRs:

- Only use FreeRTOS functions that end with `FromISR()`
- Be aware to not use HW/HAL functions that are used from other tasks (needs to by synchronised)

- FreeRTOS doc (task notifications): `https://www.freertos.org/RTOS-task-notification-API.html`
- FreeRTOS doc (deferred interrupt handling): `https://www.freertos.org/deferred_interrupt_processing.html`

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Software timers

Timers run in the context of the timer service task (with its own priority).

Only one callback is served at a time.

Define timer handle

```
1  TimerHandle_t timer = NULL;
2  int timerId = 1; //optional: id for timer
```

Define timer callback function

```
3  void timerCallback(TimerHandle_t xTimer) {
4    //work...
5  }
```

Create timer

```
6  timer = xTimerCreate(
7    "SW Timer",                 //name of timer
8    pdMS_TO_TICKS(1000),        //period in ticks
9    pdTRUE,                     //true=auto reload, false=one shot
10   &timerId,                   //address timer id variable
11   timerCallback               //address of timer callback function
12 );
13
14 configASSERT(timer != NULL); //assert that timer handle is valid
```

Start timer

```
15 xTimerStart(timer, 100);      //starts the timer in 100 ticks
```

Timer callbacks are not allowed to block: Therefore don't call `vTaskDelay()`, `vTaskDelayUntil`, or specify a non zero block time to access queues or semaphores.

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Summary and outlook

Summary

- FreeRTOS intro
- FreeRTOS customisation
- FreeRTOS task scheduling
- FreeRTOS task coding

Outlook

- ROS2 on Turtlebot3