Part 3
FreeRTOS

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Part 3 - ESP-IDF FreeRTOS

Lab 1 : Task & Scheduling

- One & two cores scheduling
- Idle Task

Lab 2 : Message Queue & Interrupt

- Single Message Queue, Timeout & Blocking queue
- Interrupt
- APP: De-bouncing interrupt

Lab 3 : Semaphore & Mutex

- Semaphore : binary, counter
- Mutex

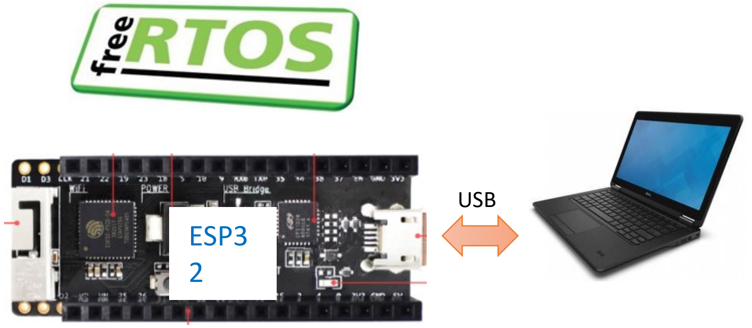
Lab 4 : Timer, Task notification & Event group

- Software Timer
- Task notification, Event group

Optional

Lab 5 : Full application

- APP: application using FreeRTOS functionalities and using keyboard terminal



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Introduction

Course mainly based on document : *Mastering the FreeRTOS™ Real Time Kernel, A Hands-On Tutorial Guide, Richard Barry*

https://www.freertos.org/

FreeRTOS

- Portable
- Open source
- Royalty free
- (Mini) Real Time Operating System
- No Input/output libraries (driver)
  - USART, I2C, SPI, CAN …
- Dedicated for microcontroller systems
  - No graphical interface
  - No I/O hard disk (SATA, SCSI …)
  - No formatting management (FAT …)

- https://www.freertos.org/

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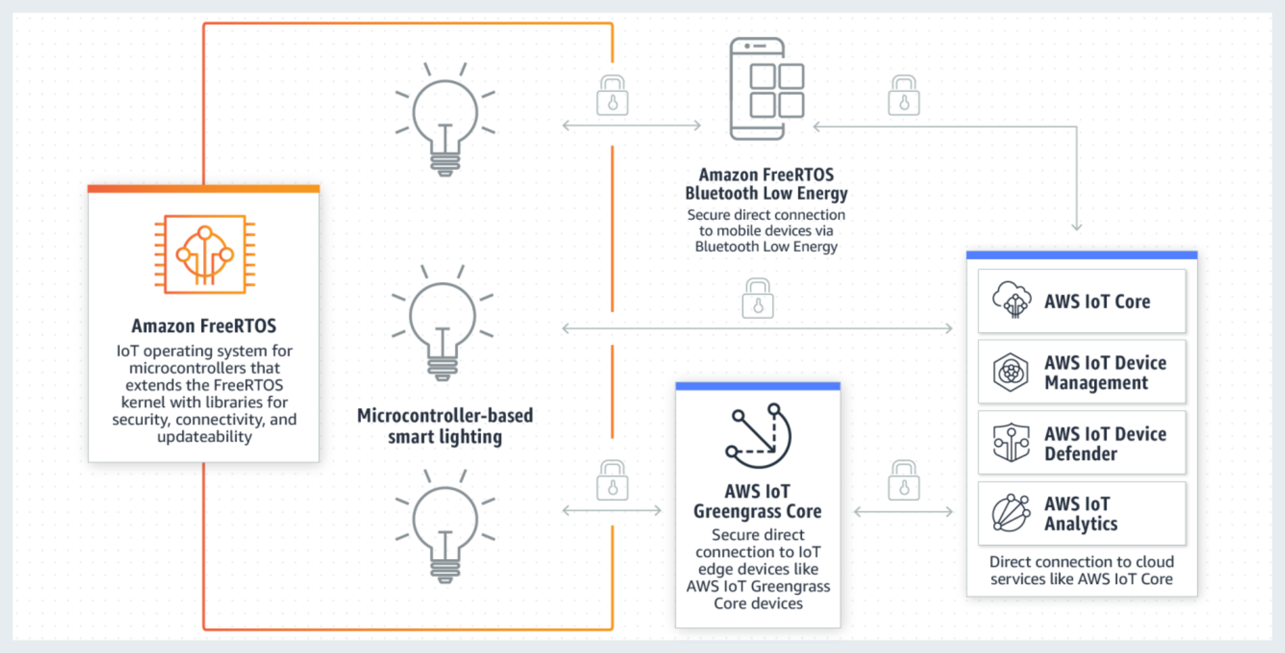
Amazon FreeRTOS - How it works

- Connected microcontroller-based devices and collect data from them for IoT applications
- AWS cloud platform offers over 165 fully featured services (end of 2019)
- https://aws.amazon.com/freertos/


Amazon FreeRTOS
IoT operating system for microcontrollers that extends the FreeRTOS kernel with libraries for security, connectivity, and updateability
Microcontroller-based smart lighting
Amazon FreeRTOS Bluetooth Low Energy
Secure direct connection to mobile devices via Bluetooth Low Energy
AWS IoT Greengrass Core
Secure direct connection to IoT edge devices like AWS IoT Greengrass Core devices
AWS IoT Core
AWS IoT Device Management
AWS IoT Device Defender
AWS IoT Analytics
Direct connection to cloud services like AWS IoT Core

Main functionnalities

- Real-Time (RT) : preemptive / cooperative scheduler
- Small kernel (4Kb to 9Kb)
- Easy to use with C language
- Illimited task number and level of priority
- Flexible management of priorities
- Communications (inter-tasks / tasks-interrupts)
  - Queues
  - Semaphore (Binary, Counting, recursive)
  - Mutex (Mutual Exclusion, priority inversion)
- Software timer
- Stack overflow checking
- Idle hook function
- Trace

Official Platforms supported

Combination of compiler and processor is considered to be a separate **FreeRTOS port**

- ARMv8-M
- Atmel
- Cadence
- Cortus
- Cypress
- Espressif ESP32 ← Labs
- Freescale
- Infineon
- Fujitsu
- Microchip
- Microsemi
- Nuvoton
- NXP
- Renevas
- SiFive
- Silicon Labs
- Spansion
- ST Microelectonics
- Texas Instrument
- Xilinx
- Intel/x86, Intel/FPGA (ex Altera)

https://www.freertos.org/RTOS_ports.html

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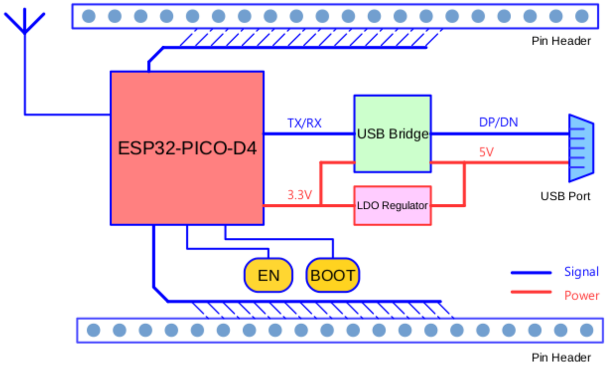
Intel/x86 - Windows simulator

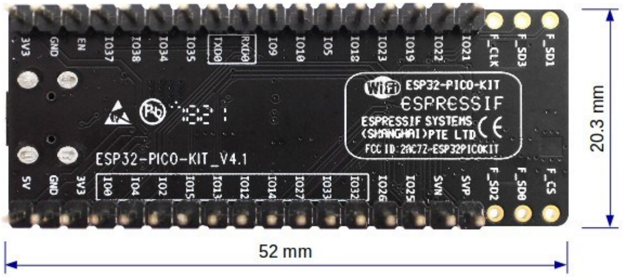
- To be run in a Windows environment
- True real time behavior cannot be achieved
- Visual Studio projects / Eclipse with MingW (GCC)
- How to use it
  - https://www.freertos.org/FreeRTOS-Windows-Simulator-Emulator-for-Visual-Studio-and-Eclipse-MingW.html

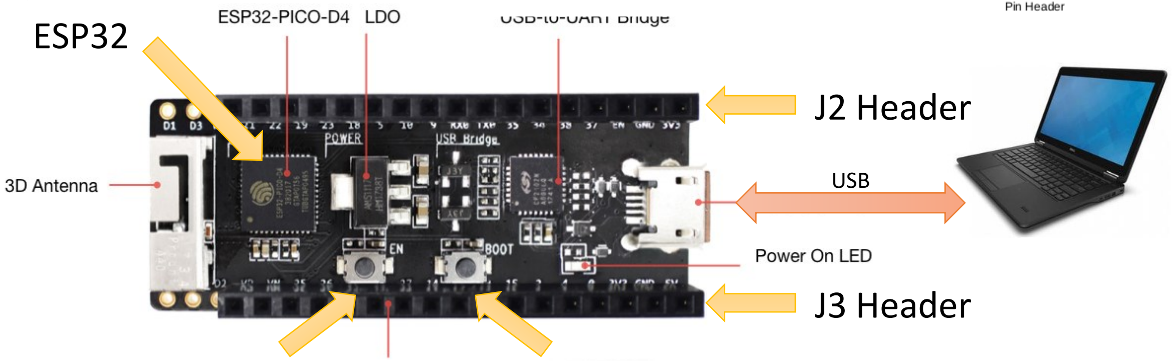
Espressif – ESP32-PICO-KIT Board

Useful for Labs

- System-in-Package (SiP) : ESP32-PICO-D4
- Including
  - 40 MHz crystal oscillator
  - 4 MiB flash
  - Filter capacitors and RF matching links in
- USB-UART bridge (up to 3 Mbps transfers rates)
- Buttons
  - BOOT : press for downloading firmware through the serial port.
  - EN: Reset







ESP32

J2 Header

J3 Header

Reset button

downloading firmware button

https://docs.espressif.com/projects/esp-idf/en/latest/esp32/api-reference/system/freertos.html

https://docs.espressif.com/projects/esp-idf/en/latest/esp32/hw-reference/esp32/get-started-pico-kit.html

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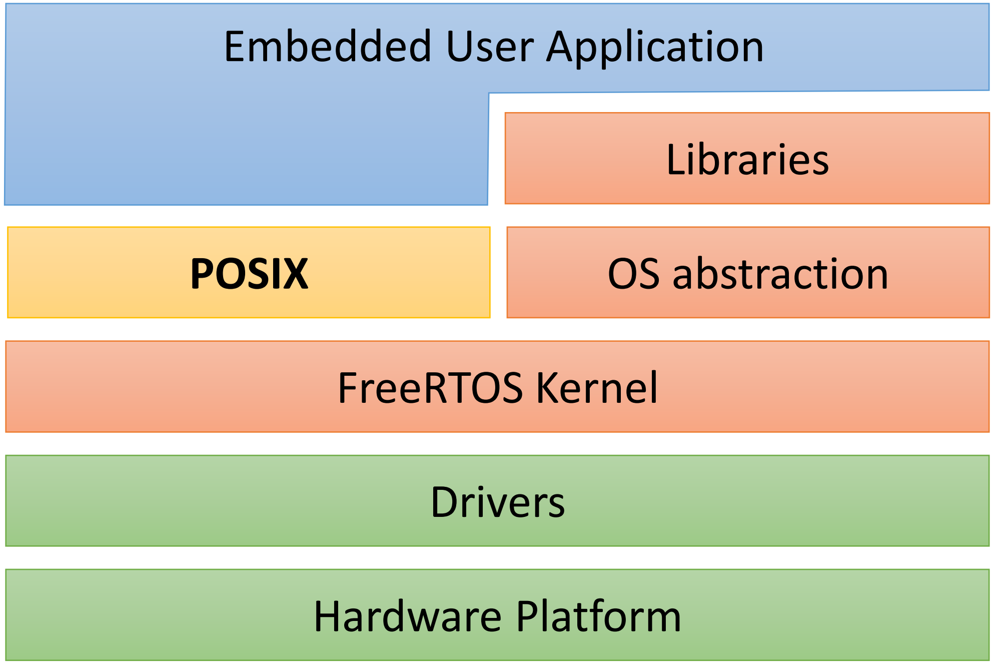
FreeRTOS & POSIX

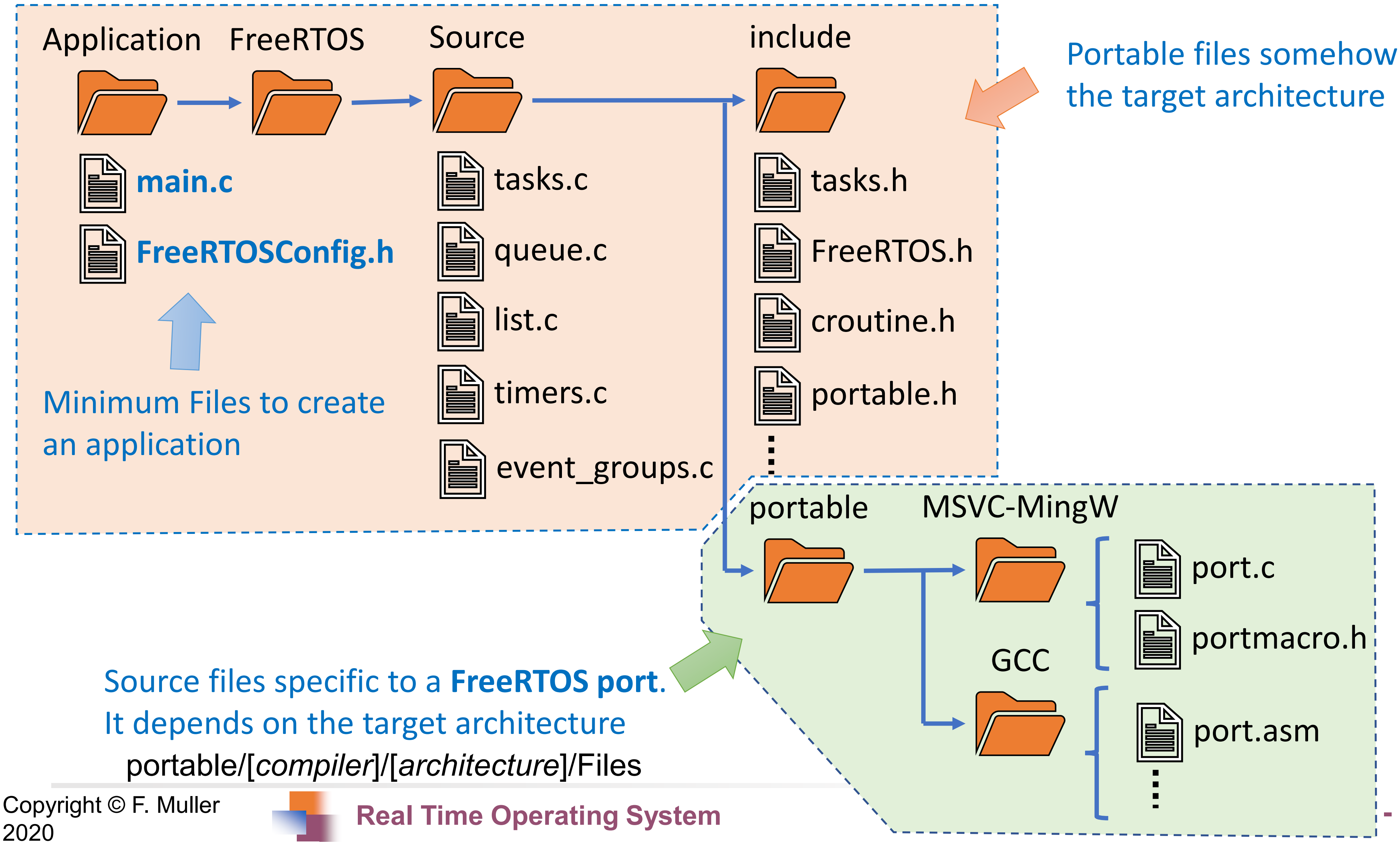
- POSIX = Portable Operating System Interface
- Standard specified by the IEEE Computer Society for maintaining compatibility between operating systems
- Implementation of a subset of the POSIX threading API
- Subset of IEEE Std 1003.1-2017



https://www.freertos.org/FreeRTOS-Plus/FreeRTOS_Plus_POSIX/index.html

Organization of FreeRTOS

Top Directories



Portable files somehow the target architecture

Minimum Files to create an application

Source files specific to a **FreeRTOS port**.
It depends on the target architecture
portable/[*compiler*]/[*architecture*]/Files

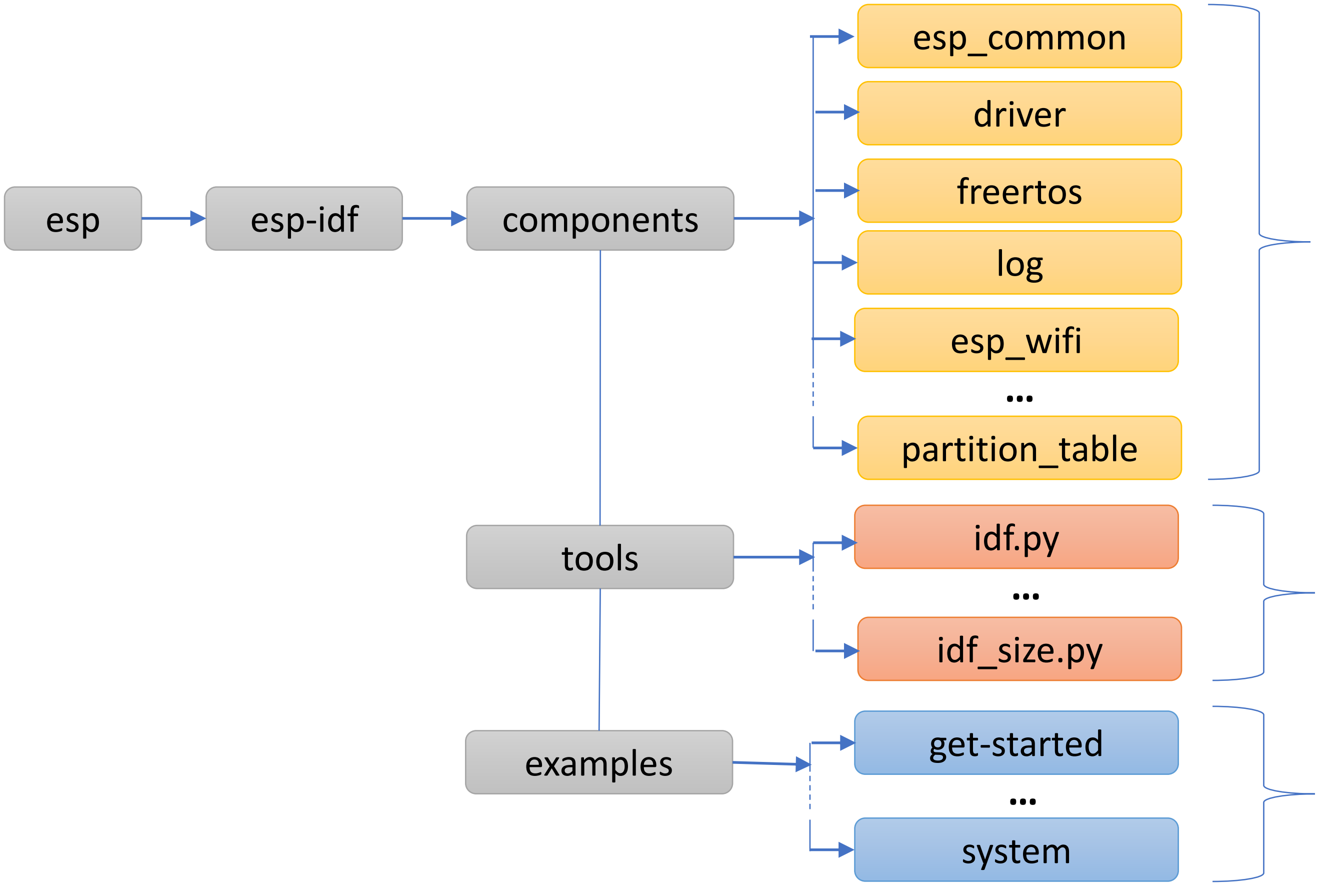
Development tool ESP32

Espressif IoT Development Framework

Espressif IoT Development Framework

- **Esp**ressif **I**oT **D**evelopment **F**ramework = **ESP-IDF**
- Included
  - Libraries
  - Tools
  - Examples
- ESP-IDF Programming Guide
  - https://docs.espressif.com/projects/esp-idf/en/latest/esp32/

ESP-IDF folder structure



Libraries

#include "driver/gpio.h"

Python scripts : compile, build, flash, monitor …
Bash script : export env, convert elf file …

Examples

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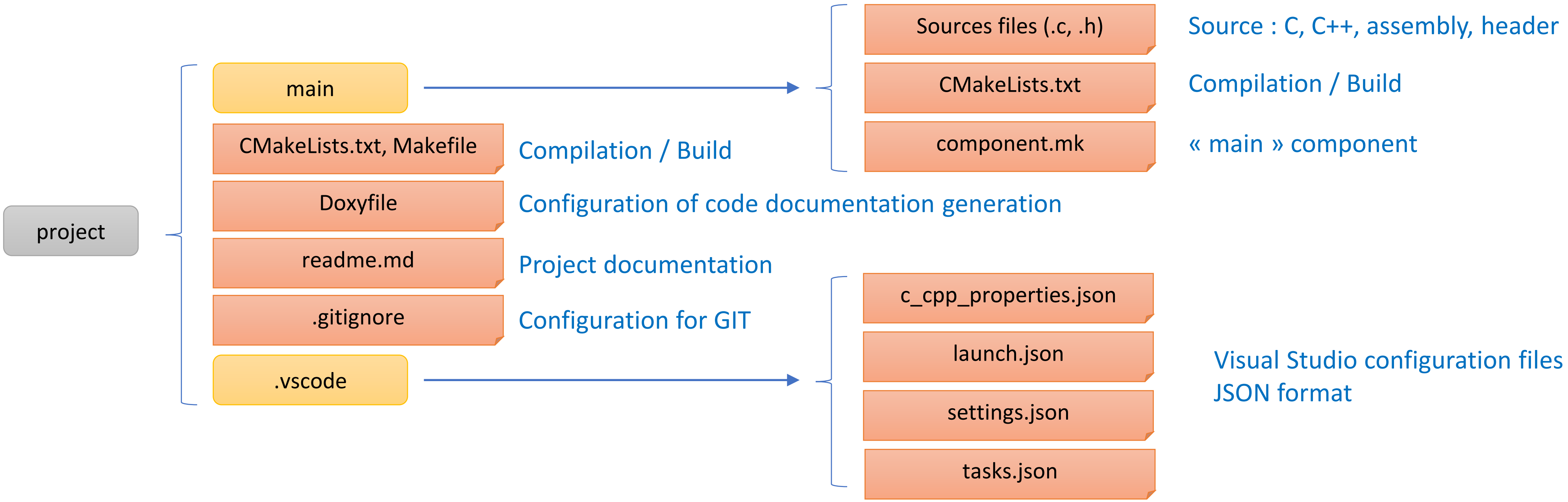
ESP32 project template

- For Visual Studio Code
- Located in « esp32-vscode-project-template » project
  - https://github.com/fmuller-pns/esp32-vscode-project-template



- project
  - main
    - Sources files (.c, .h) — Source : C, C++, assembly, header
    - CMakeLists.txt — Compilation / Build
    - component.mk — « main » component
  - CMakeLists.txt, Makefile — Compilation / Build
  - Doxyfile — Configuration of code documentation generation
  - readme.md — Project documentation
  - .gitignore — Configuration for GIT
  - .vscode
    - c_cpp_properties.json
    - launch.json
    - settings.json
    - tasks.json

    Visual Studio configuration files
    JSON format

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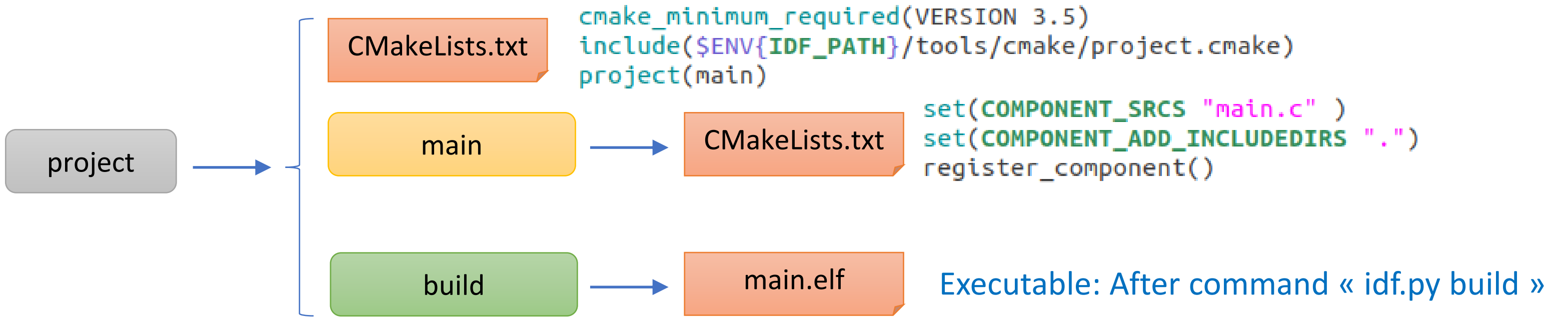
CMakeLists.txt & CMake

- CMake (cmake.org)
  - Cross-platform family of tools
  - Designed to build, test and package software
  - Used to control the software compilation process using simple platform and compiler independent configuration files
  - Generate native makefiles
  - Open-source
- File configuration : *CMakeLists.txt*
- ESP32 guide
  - https://docs.espressif.com/projects/esp-idf/en/latest/esp32/api-guides/build-system.html#project-cmakelists-file
- idf.py (Python script) is a wrapper around CMake
  - idf.py build



```
cmake_minimum_required(VERSION 3.5)
include($ENV{IDF_PATH}/tools/cmake/project.cmake)
project(main)
```

```
set(COMPONENT_SRCS "main.c" )
set(COMPONENT_ADD_INCLUDEDIRS ".")
register_component()
```

Executable: After command « idf.py build »

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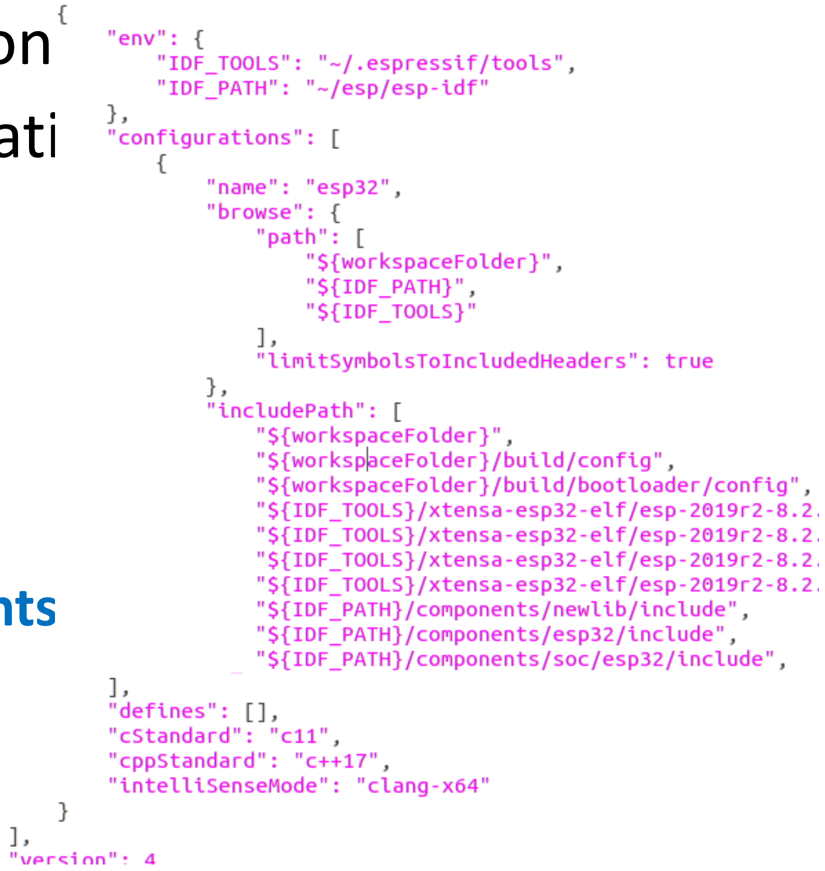
Visual Studio Code

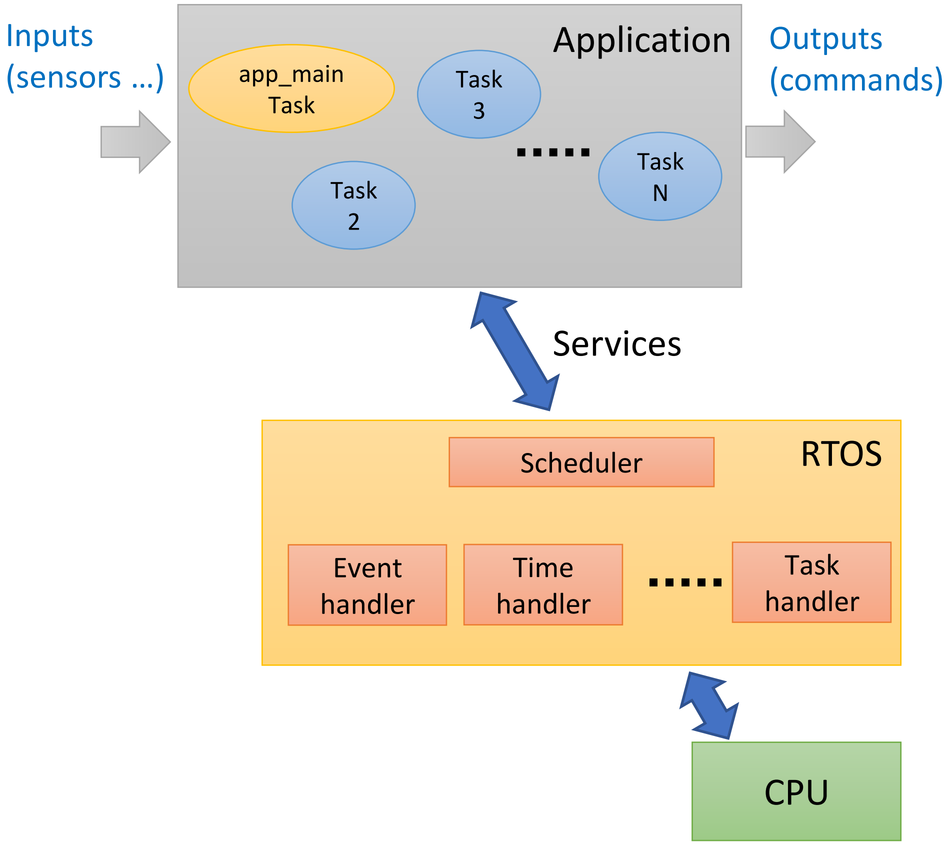
- *.vscode* folder including configuration
- JSON format (JavaScript Object Notati
- Environment
  - IDF_TOOLS
  - IDF_PATH
- Configuration : esp32
  - name, browse
  - **includePath: important for components**
- Miscellaneous
  - cStandard : c11 (ISO/IEC 9899:2011)
  - cppStandard : c++17 (ISO/IEC 14882)



```
    {
        "env": {
            "IDF_TOOLS": "~/.espressif/tools",
            "IDF_PATH": "~/esp/esp-idf"
        },
        "configurations": [
            {
                "name": "esp32",
                "browse": {
                    "path": [
                        "${workspaceFolder}",
                        "${IDF_PATH}",
                        "${IDF_TOOLS}"
                    ],
                    "limitSymbolsToIncludedHeaders": true
                },
                "includePath": [
                    "${workspaceFolder}",
                    "${workspaceFolder}/build/config",
                    "${workspaceFolder}/build/bootloader/config",
                    "${IDF_TOOLS}/xtensa-esp32-elf/esp-2019r2-8.2.
                    "${IDF_TOOLS}/xtensa-esp32-elf/esp-2019r2-8.2.
                    "${IDF_TOOLS}/xtensa-esp32-elf/esp-2019r2-8.2.
                    "${IDF_TOOLS}/xtensa-esp32-elf/esp-2019r2-8.2.
                    "${IDF_PATH}/components/newlib/include",
                    "${IDF_PATH}/components/esp32/include",
                    "${IDF_PATH}/components/soc/esp32/include",
        ],
        "defines": [],
        "cStandard": "c11",
        "cppStandard": "c++17",
        "intelliSenseMode": "clang-x64"
    }
],
"version": 4
```

Using FreeRTOS on ESP32 boards

- RTOS = Real Time Operating System
- Starting point
  - *app_main()* task
- Input/output management
  - Input/output handler
  - Interrupt handler
- Task scheduling
  - Organization of functioning in tasks
  - Scheduling policy
  - Time handler
- Inter task communications
  - Synchronization (event)
  - Communication (data)
  - Access to a shared resource (data)
  - Time (counter, watchdog)



Coding Style

Base Types

- Define in *portmacro.h* header file
- Most efficient data type for the architecture
  - UBaseType_t, BaseType_t
  - 32-bit type on a 32 bit architecture, 16-bit type on a 16 bit architecture …
- Specific types
  - portCHAR, portLONG, portSHORT
  - portFLOAT, portDOUBLE
  - portBASE_TYPE
- Useful Constants
  - pdTRUE, pdFALSE
  - pdPASS, pdFAIL

Variable prefix names

Base prefix names

- c : char
- s : short
- l : long
- x : portBASE_TYPE

Other prefix names

- p : pointer
- u : unsigned
- v : void

```
BaseType_t uxMyBoolVar = pdTRUE;          // u: unsigned, x: Base Type
portSHORT *psMyVar1;                      // p: pointer, s: short
const portCHAR *pcTaskName = "Task 1\r\n";// p: pointer, c: char
```

Function prefix names

Like variable name

- c, s, l, x
- p, u, v

+

File name where it defined

- Task : task.c
- Semaphore : semphr.h
- Queue : queue.c
- Timer : timers.c
- …

```
// Function, v: function returns void
void vInit(UBaseType_t uxPriority) {    // u: unsigned, x: base type

  vTaskPrioritySet(vTask1, uxPriority); // return (v: void), Task: task.c
  BaseType_t xVar = xQueueReceive(...); // return (x: base type), Queue: queue.c
  void *pvId = pvTimerGetTimerID(...);  // return (p: pointer, v: void), Timer: timer.c
  vSemaphoreCreateBinary(...);          // return (v: void), Semaphore: semph.c
  ...
}
```

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Macro Names

- Most macros
  - Written in upper case
  - Prefixed with lower case letters

Prefix	Location	Example
port	portable.h / portmacro.h	portMAX_DELAY, portDOUBLE, portINLINE
task	task.h	taskENTER_CRITICAL(), taskENABLE_INTERRUPTS()
pd	projdefs.h	pdFALSE, pdMS_TO_TICKS, errQUEUE_EMPTY
config	FreeRTOSConfig.h	configUSE_PREEMPTION, configUSE_IDLE_HOOK
err	projdef.h	errQUEUE_BLOCKED, errQUEUE_FULL
…	…	…

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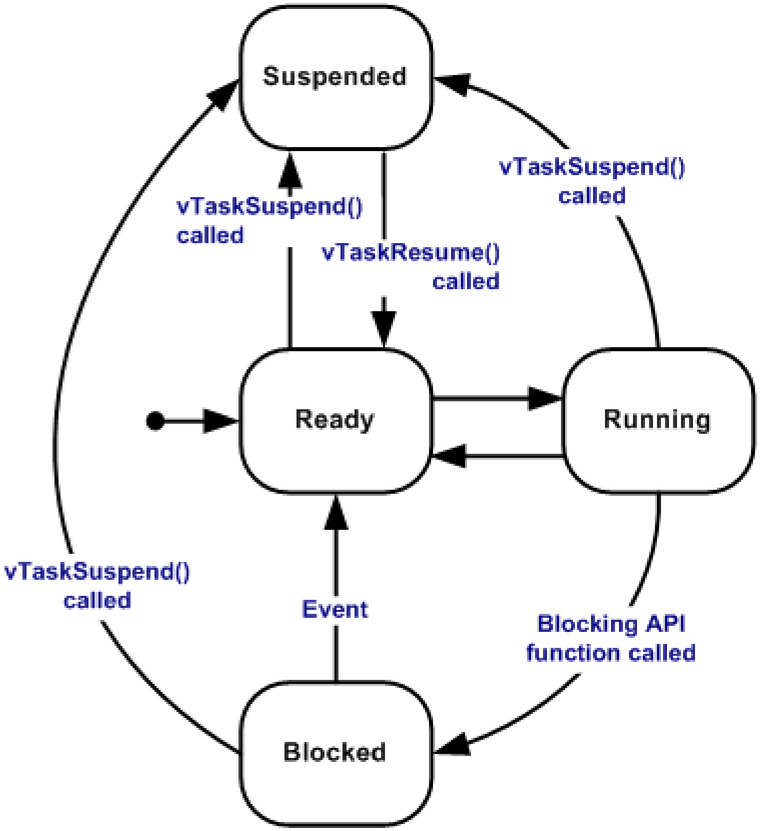
Task Management

Task States

- Running
  - Task is actually executing
- Ready
  - Tasks are those that are able to execute (Ready list)
- Blocked
  - Tasks are currently waiting for either a temporal or external event (delay, queue, semaphore …)
  - Tasks normally have a timeout period and be unblocked
- Suspended
  - Tasks only enter or exit this state when explicitly commanded to do so through the vTaskSuspend() and xTaskResume()
  - Tasks do not have a time out



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Task implementation – infinite loop

```c
void vMyTask(void *pvParameters)
{
  const char *pcTaskName = "Task is running\r\n";
  volatile uint32_t ul;

  for (;; ) {

    vPrintString(pcTaskName);
    /* Simulate a cpu usage */
    for (ul = 0; ul < 0xffffff; ul++);

  }
}
```

Declaration

Application code inside the infinite loop

- When a task is in blocked, suspended or ready state, the context of the task (variables …) is saved in the TCB (Task Control Block)

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Task implementation – task exit

- The application code comes out of the infinite loop
- Must delete the task properly

Declaration

Application code inside the infinite loop

Delete

```
void vMyTask(void *pvParameters)
{
  const char *pcTaskName = "Task is running\r\n";
  volatile uint32_t ul;
  int counter = 50;

  for (;; ) {
    vPrintString(pcTaskName);
    /* Simulate a cpu usage */
    for (ul = 0; ul < 0xffffff; ul++);
    /* Exit ? */
    if (counter-- == 0) break;
  }
  /* to ensure its exit is clean */
  vTaskDelete(NULL);
}
```

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Task creation

- xTaskCreate() function
- Return pdFAIL or pdPASS

```
BaseType_t xTaskCreate(
        TaskFunction_t pvTaskCode,     /* Pointer to the function that implements the task. */
        const char * const pcName,     /* Text name for the task. */
        uint16_t usStackDepth,         /* Stack depth */
        void *pvParameters,            /* Task parameter. */
        UBaseType_t uxPriority,        /* Task priority. */
        TaskHandle_t *pxCreatedTask); /* Task handle to reference the task in API calls */
```

Simple Task instance

- Without parameter (NULL)
- Without Task handle (NULL)

```
int main( void ) {

  /* Create task with No parameter, No task handle */
  xTaskCreate(vMyTask, "My Task", 1000, NULL, 1, NULL);

  /* Start the scheduler to start the tasks executing. */
  vTaskStartScheduler();

  for (;; );

  return 0;
}
```

Task instance with parameter

- Parameters is a pointer of void type (void *)

```c
void vMyTask(void *pvParameters) {
  char *pcTaskName;
  volatile uint32_t ul;

  pcTaskName = (char *)pvParameters;

  for (;; )
  {
    vPrintString(pcTaskName);

    for (ul = 0; ul < 0xffffff; ul++);
  }
}
```

Cast

```c
const char *pcMyTaskName = "MyTask is running\r\n";

int main(void) {
  /* Create task without task handle */
  xTaskCreate(vMyTask, "My Task",
              1000,
              (void*)pcMyTaskName,
              1,
              NULL);

  /* Start the scheduler. */
  vTaskStartScheduler();

  for (;; );
  return 0;
}
```

Cast

Task instance with task handler

- Task handler is used to access on the API
- Useful to change parameters dynamically (priority …)

```
TaskHandle_t xHandleMyTask = NULL;

int main( void ) {
  /* Create task. */
  xTaskCreate(vMyTask, "My Task",
              1000,
              NULL,
              1,
              &xHandleMyTask);

  vTaskStartScheduler();

  for (;; );
  return 0;
}
```

```
void vMyTask(void *pvParameters)
{
  volatile uint32_t ul;
  int count;

  for (;; ) {
    /* Simulate a cpu usage */
    for (ul = 0; ul < 0xffffff; ul++);

    /* Change priority from handler */
    if (count++ > 50)
      vTaskPrioritySet(xHandleMyTask, 4);
    else
      vTaskPrioritySet(xHandleMyTask, 1);
  }
}
```

Change priority dynamically

Multiple Instances of a same task

- Each instance
  - Independent (1 TCB & 1 stack per instance)
  - Own local variables
- If they are declared *static*, the variable is shared between the different instances of the task

```
int main( void ) {
  /* Create 2 task instances of vMyTask() */
  xTaskCreate(vMyTask, "My Task1",
              1000, NULL, 1, NULL);
  xTaskCreate(vMyTask, "My Task2",
              1000, NULL, 1, NULL);

  vTaskStartScheduler();
  for (;; );
  return 0;
}
```

```
void vMyTask(void *pvParameters) {
  volatile uint32_t ul;
  static int count;

  for (;; ) {
    /* Simulate a cpu usage */
    for (ul = 0; ul < 0xffffff; ul++);

    /* count is a shared variable of the task */
    count++;
    vPrintStringAndNumber("Count = ", count);
    }
}
```

ul is a local variable

count is shared by 2 instances

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Idle Task

- To ensure there is always at least one task that is able to run
- Idle task is created automatically with the lowest possible priority (tskIDLE_PRIORITY = 0)
- Idle task is responsible for freeing memory allocated by the RTOS to tasks that have since been deleted
- Idle task hook (callback)
  - Idle task hook is a function that is called during each cycle of the idle task
  - Does not call any API functions that might cause the idle task to block
  - Set *configUSE_IDLE_HOOK = 1* to use it

```
void vApplicationIdleHook(void) {
    ...
}
```

Approximated Periodic task

- *vTaskDelay(TickNumber)* to blocked task during TickNumber ticks
- ***pdMS_TO_TICKS*** macro converts time to tick number
- Period depends on execution time of the task
  - Keep the blocked state is relative to the time at which vTaskDelay() was called

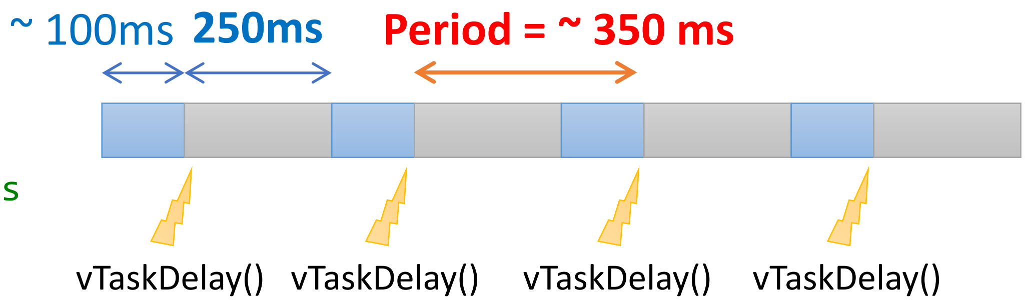
Convert 250ms to tick number

```
void vMyTask(void *pvParameters) {
  char *pcTaskName;
  const TickType_t xDelay250ms = pdMS_TO_TICKS(250UL);

  /* parameter : Task name */
  pcTaskName = (char *)pvParameters;

  for (;; ) {
    vPrintString(pcTaskName);
    calculationFct();    // duration: 100ms
    vTaskDelay(xDelay250ms);
  }
}
```

100 ms

Task blocked for 250 ms

Period = 100 ms + **250 ms** = **~ 350 ms**



Exactly Periodic task

- Should be used when a fixed execution period is required
- *vTaskDelayUntil(LastTickNumber, TickNumber)* to blocked task during TickNumber ticks relative to last call of *vTaskDelayUntil()*
- Use *xTaskGetTickCount()* function to initialize *LastTickNumber* variable

```
void vMyTask(void *pvParameters) {
  char *pcTaskName;
  TickType_t xLastWakeTime;
  const TickType_t xDelay250ms = pdMS_TO_TICKS(250UL);
  volatile uint32_t ul;

  pcTaskName = (char *)pvParameters;
  xLastWakeTime = xTaskGetTickCount();

  for (;; ) {
    vPrintString(pcTaskName);
    calculationFct();    // duration: 100ms
    vTaskDelayUntil(&xLastWakeTime, xDelay250ms);
  }
}
```

100 ms

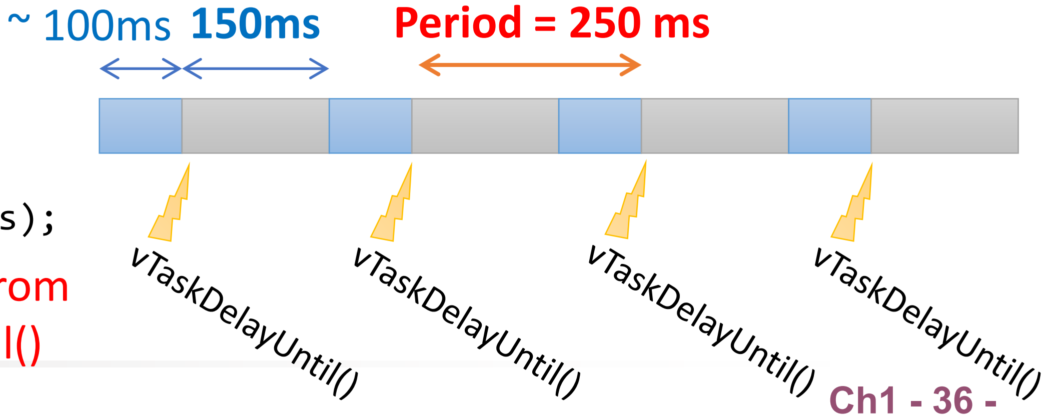
Updated by the vTaskDelayUntil()

Initialize for the first use

Task blocked for 250 ms from last call of vTaskDelayUntil()

Right period !

Period = 100 ms + **150 ms** = **<u>250 ms</u>**



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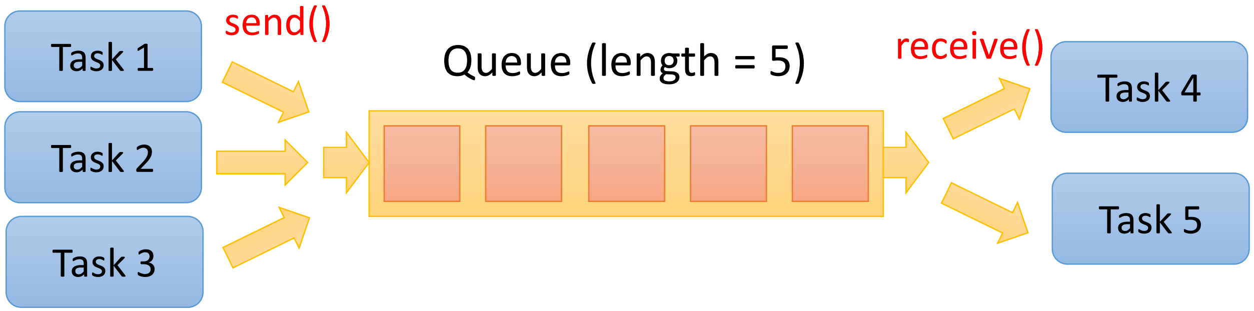
Message Queue

Introduction

- FIFO behavior: First in First out
- Length: maximum number of items per queue
- Fixed size data items
- Queue by copy : data sent to the queue is copied byte for byte into the queue
- Classical functions: FIFO behavior
  - Send: written to the end of the queue (Tail)
  - Receive: removed from the front of the queue (Head)
- Extra functions: No FIFO behavior
  - Write item to the front (Head) of a queue
  - Overwrite item that is already at the front of a queue



Example of behavior

Global declaration

```
QueueHandle_t xQueue1;
```

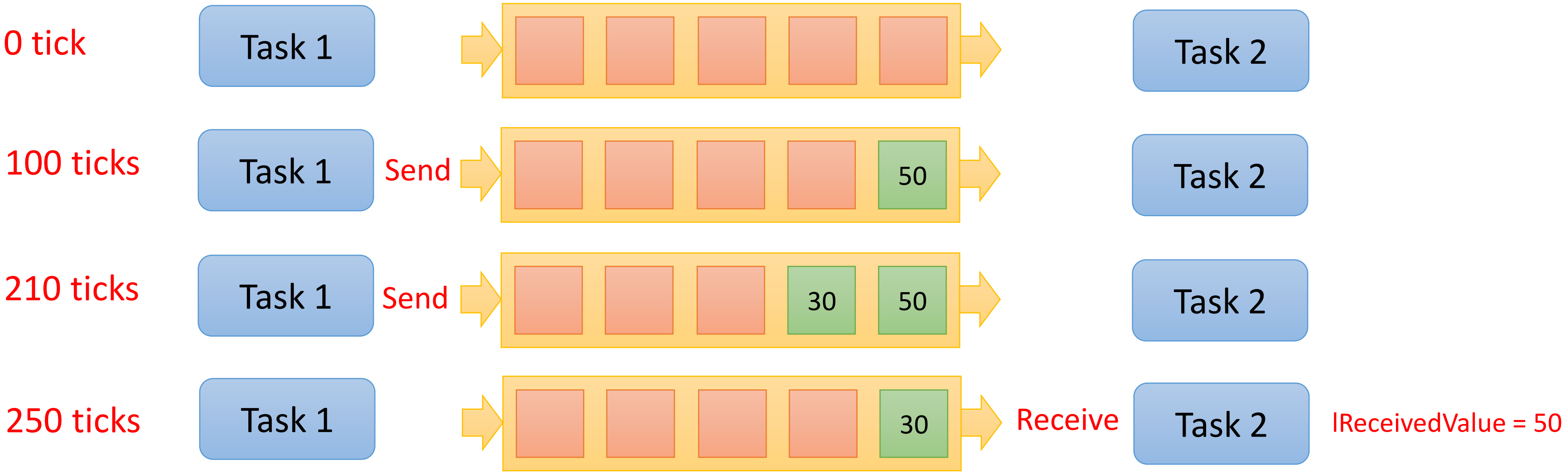
In main()

```
xQueue2 = xQueueCreate(1, sizeof(uint32_t));
```

```
void Task1(void *pvParameters) {
  int32_t lSentValue;
  for (;; ) {
    vTaskDelay(100);
    lSentValue = 50;
    xQueueSend(xQueue1, &lSentValue, 0);
    vTaskDelay(110);
    lSentValue = 30;
    xQueueSend(xQueue1, &lSentValue, 0);
  }
}
```

```
void Task2(void *pvParameters) {
  int32_t lReceivedValue;
  BaseType_t xStatus;
  for (;; ) {
    vTaskDelay(250);
    xStatus = xQueueReceive(xQueue1,
                &lReceivedValue,
                portMAX_DELAY);
   }
}
```

xQueue1



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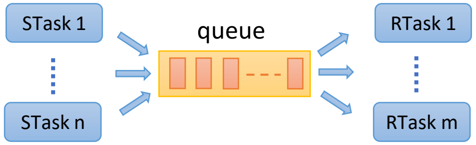
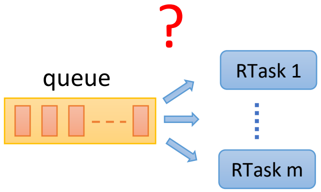
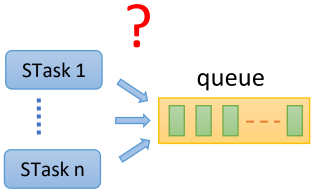
Blocking on single Queue

- Access by Multiple Tasks
  - Any number of tasks can write to the same queue
  - Any number of tasks can read from the same queue
- Blocking on Queue Reads : Empty Queue
  - Specify block time or Time out (optional)
  - More than one task blocked on waiting for data
  - Only one task will be unblocked when data becomes available
    - Highest priority task
    - Same priority : the longest blocked task
- Blocking on Queue Writes : Full Queue
  - Specify block time or Time out (optional)
  - More than one task blocked on it waiting to complete a send operation
  - Only one task will be unblocked when space on the queue becomes available
    - Highest priority task
    - Same priority : the longest blocked task

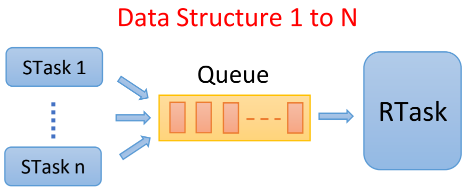


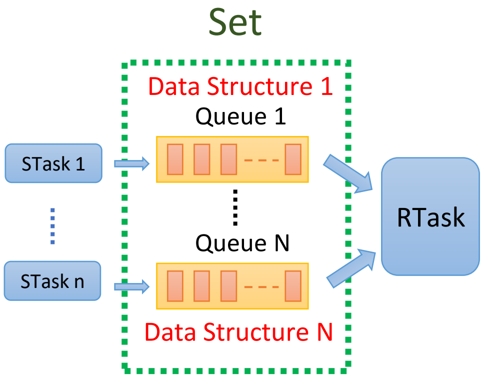




Blocking on multiple Queues (1)

- 2 solutions
  - (1) Using a single queue that receives structures
  - (2) Using separate queues for some data sources
- Second solution
  - Set configUSE_QUEUE_SETS = 1
  - Creating a queue set
  - Adding queues to the set*
  - Reading from the queue set to determine which queues within the set contain data





```
QueueHandle_t xQueue1 = NULL, xQueue2 = NULL;
QueueSetHandle_t xQueueSet;

int main(void) {
  xQueue1 = xQueueCreate(1, sizeof(char *));
  xQueue2 = xQueueCreate(1, sizeof(uint32_t));

  /* Create the queue setwith 2 events */
  xQueueSet = xQueueCreateSet(2);

  /* Add the two queues to the set. */
  xQueueAddToSet(xQueue1, xQueueSet);
  xQueueAddToSet(xQueue2, xQueueSet);
  ...
}
```

Example with N = 2

* Semaphores can also be added to a queue set

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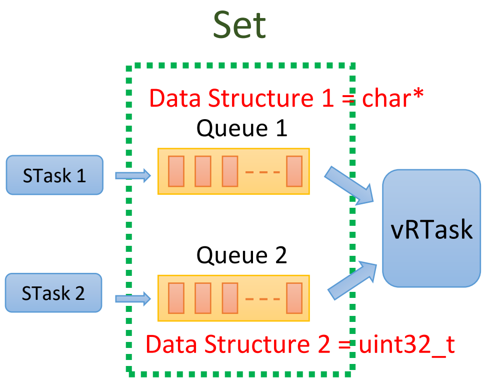
Blocking on Multiple Queues (2)

Example with N = 2

```
void vRTask(void *pvParameters)
{
   QueueSetMemberHandle_t xHandle;
   QueueHandle_t xQueueThatContainsData;
   char *pcReceivedString;
   uint32_t ulRecievedValue;

   for (;; ) {
      /* Block on the queue set for a maximum of 100ms */
      xHandle = xQueueSelectFromSet(xQueueSet, pdMS_TO_TICKS(100));

      if (xHandle == NULL) {
         /* The call to xQueueSelectFromSet() timed out. */
         ...
      }
      else if (xHandle == (QueueSetMemberHandle_t)xQueue1) {
         xQueueReceive(xQueue1, &pcReceivedString, 0);
         ...
      }
      else if (xHandle == (QueueSetMemberHandle_t)xQueue2) {
         xQueueReceive(xQueue2, &ulRecievedValue, 0);
         ...
      }
   }
}
```



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Resource management

Introduction

- **Shared/guarded resource**
- Critical section
  - Protection of a region of code from access by other tasks and by interrupts
- Binary semaphore
  - Used for synchronization : tasks/tasks or tasks/interrupts
  - Task notification is also a good alternative for synchronization
- Counting semaphore
  - Used for counting events or resource management
- Mutual exclusion (Mutex)
  - Binary semaphore
  - Included a priority inheritance mechanism
  - Can be a Recursive Mutex

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Critical section / region

- Code segment executed as an atomic action
  - No preemption, surrounded by P()/V() operations
  - Only interrupts may still execute whose logical priority is above the value assigned to the configMAX_SYSCALL_INTERRUPT_PRIORITY
- Execution of the critical section must be as short as possible
- Primitives
  - taskENTER_CRITICAL(), taskENTER_CRITICAL_FROM_ISR()
  - taskEXIT_CRITICAL(), taskEXIT_CRITICAL_FROM_ISR()

Task

Critical section

```
void vPrintString(const char *pcString) {
  taskENTER_CRITICAL();
  {
    printf("%s", pcString);
    fflush(stdout);
  }
  taskEXIT_CRITICAL();
}
```

Interrupt

Critical section

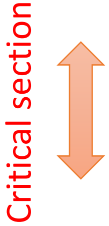
```
void vAnInterruptServiceRoutine(void) {
  UBaseType_t uxSavedIsrStatus;
  ...
  uxSavedIsrStatus =  taskENTER_CRITICAL_FROM_ISR();
  {
    ...
  }
  taskEXIT_CRITICAL_FROM_ISR(uxSavedIsrStatus);
  ...
}
```

Critical section / region

Suspended Scheduler

- Suspending/locking the scheduler
- No preemption but interrupts enabled
  - If an interrupt requests a context switch while the scheduler is suspended, then the request is held pending, and is performed only when the scheduler is resumed.
- FreeRTOS API functions must not be called while the scheduler is suspended
- Primitives
  - vTaskSuspendScheduler()
  - xTaskResumeScheduler()

```
void vPrintString(const char *pcString) {
  vTaskSuspendScheduler();
  {
    printf("%s", pcString);
    fflush(stdout);
  }
  xTaskResumeScheduler();
}
```



Critical section

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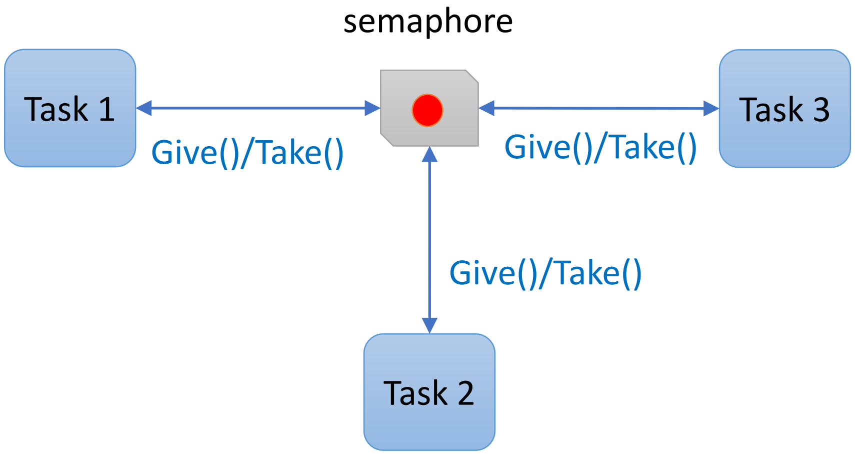
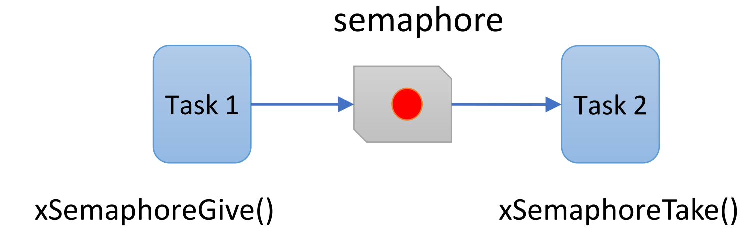
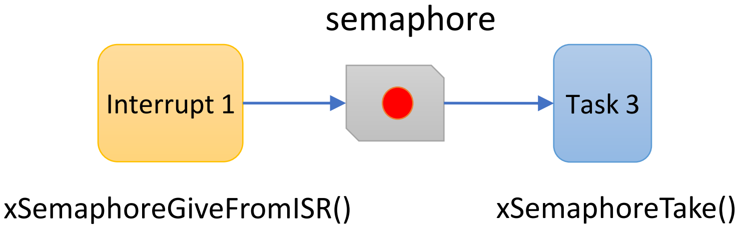
Binary semaphore

- Queue with one item (called token)
- Full / Empty queue = binary
- Highest priority task will be unblocked when the semaphore becomes available







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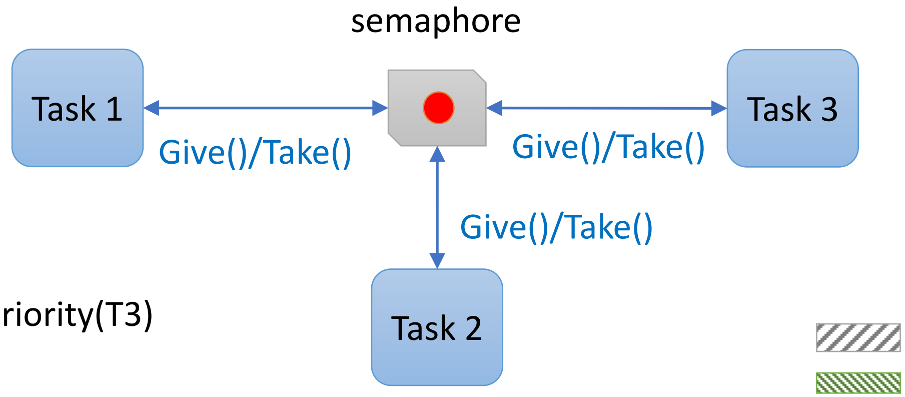
Binary semaphore example



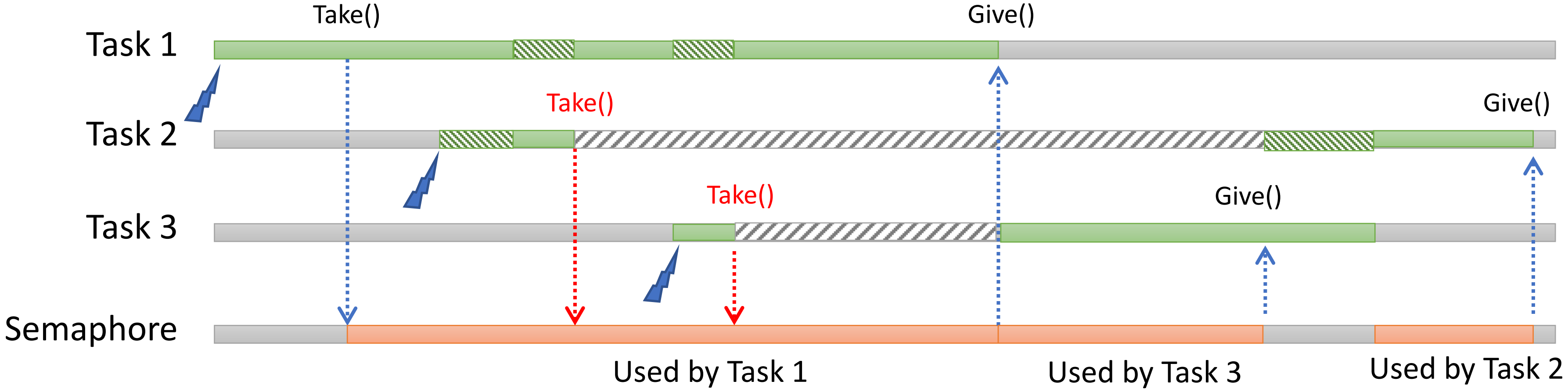
Round Robin

Priority(T1) = Priority(T2) < Priority(T3)

▨ Blocked (waiting for resource)

▨ Ready

🟩 Running



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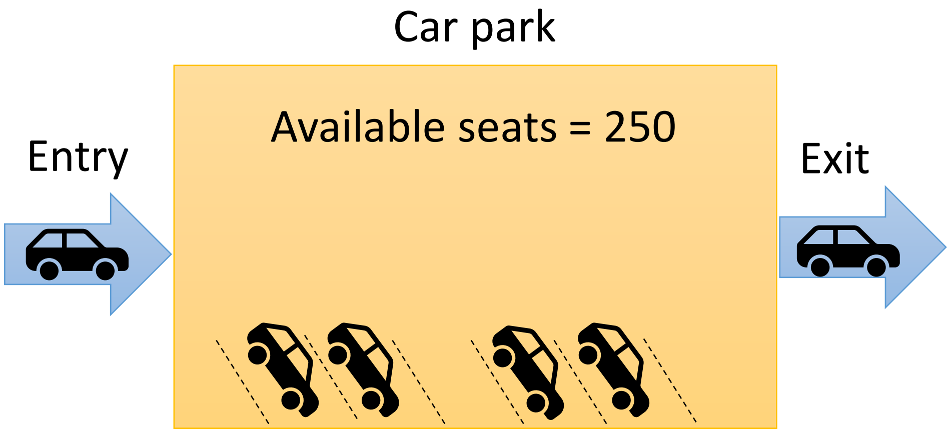
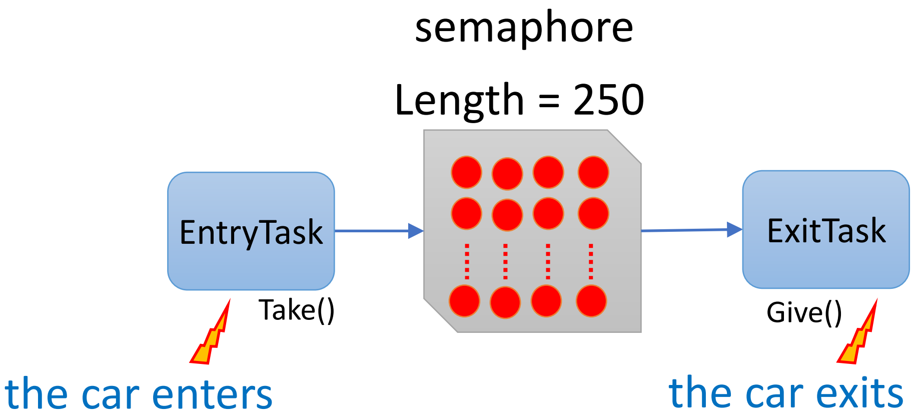
Counter semaphore

- Queue with length of more than one item (token)
- Count the number of items in the queue
- Set configUSE_COUNTING_SEMAPHORES
- Example: Resource management
  - Count value indicates the number of resources available





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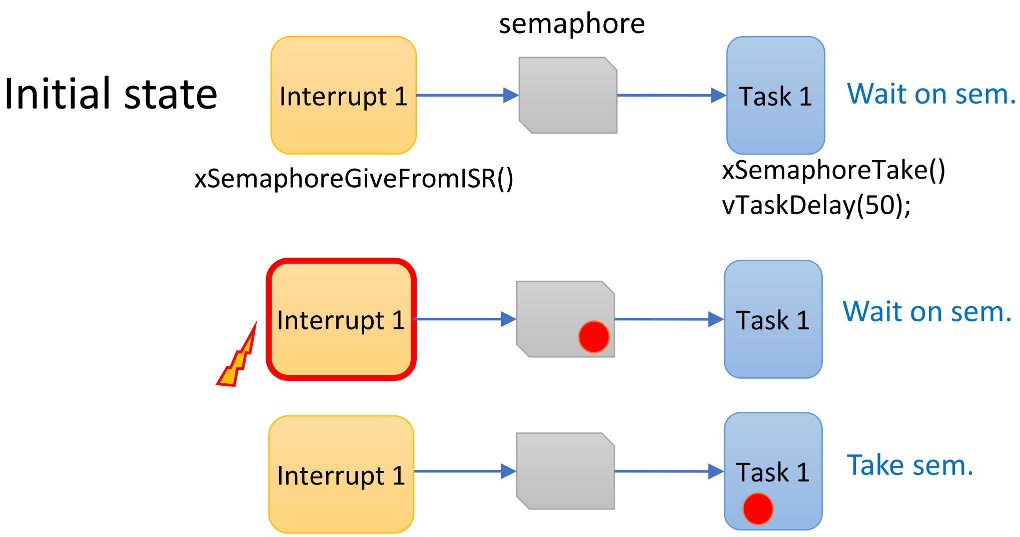
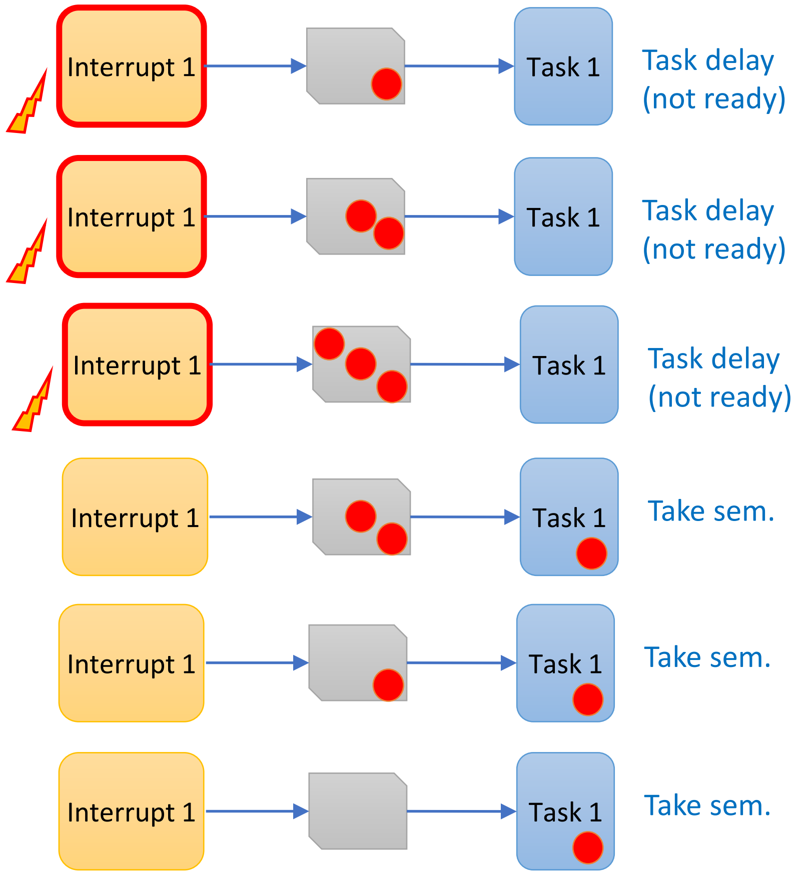
Counter semaphore

Counting event example

- Count value indicates the number of events that have occurred but have not been processed
- Will allow events to be processed by the task even if it is not ready





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Mutex – Mutual Exclusion

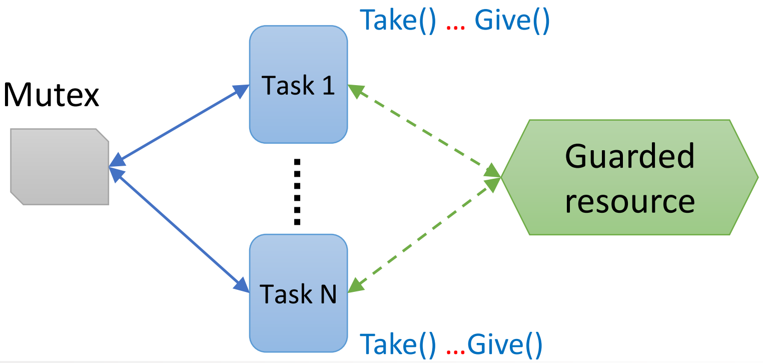
- Used to control access to a resource shared between tasks
- A task should never (or the least possible!) get blocked by a lower priority task
- Included a priority inheritance mechanism
- Set configUSE_MUTEXES = 1

Task X

Take()

Access to the guarded resource

Give()



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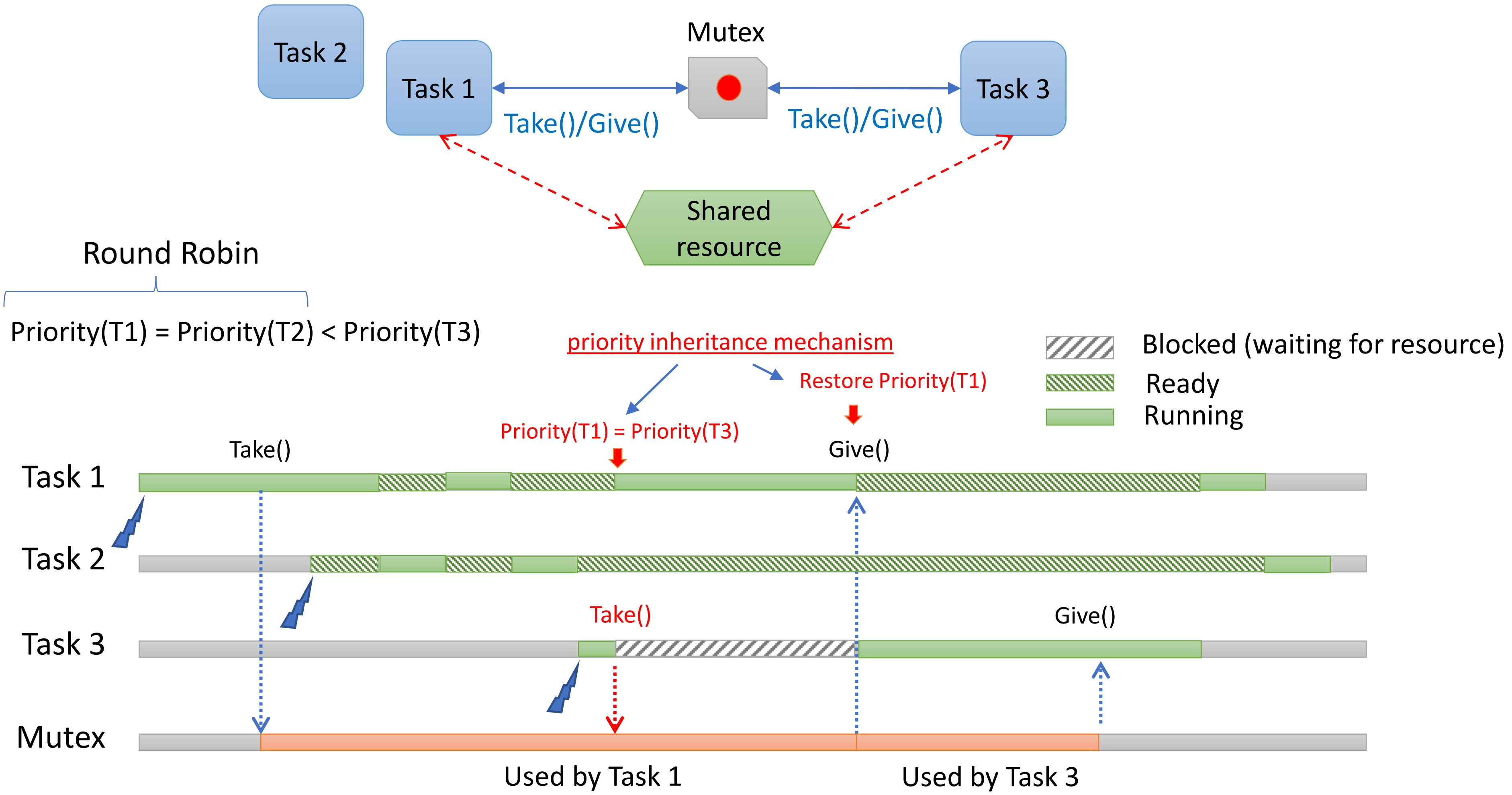
Mutex example



Task 2

Task 1

Mutex

Task 3

Take()/Give()

Take()/Give()

Shared resource

Round Robin

Priority(T1) = Priority(T2) < Priority(T3)

priority inheritance mechanism

Priority(T1) = Priority(T3)

Restore Priority(T1)

▨ Blocked (waiting for resource)

▨ Ready

🟩 Running

Take()

Give()

Task 1

Task 2

Task 3

Take()

Give()

Mutex

Used by Task 1

Used by Task 3

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Recursive Mutex

- Possible for a task to deadlock with itself
- Attempts to take the same mutex more than once
- Scenario
  - Task 1 successfully obtains a mutex
  - While holding the mutex, the task 1 calls a library function
  - Library function attempts to take the same mutex
  - The task 1 is in blocked state ! (deadlock)
- Avoided by using a recursive mutex
  - Can “take” more than one by the same task
  - Just call once “give”

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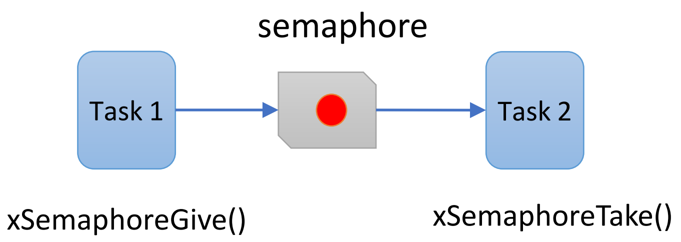
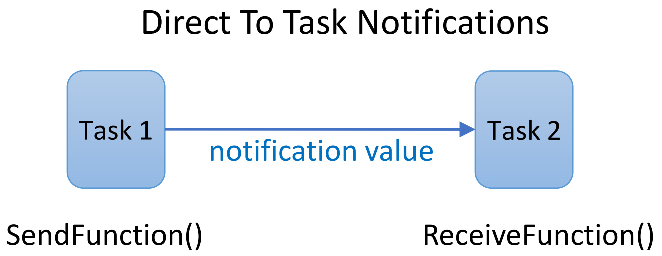
Direct To Task Notifications

Introduction

- Tasks communicate through intermediary objects
  - Queues, Semaphore …
  - Data are not sent directly to a receiving task/ISR
- Another solution: Using Direct To Task Notifications
- Advantages
  - Faster than using a queue, semaphore or event group
  - RAM Footprint Benefits : less RAM than using a queue, semaphore or event group
- Set configUSE_TASK_NOTIFICATIONS = 1





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Limitations

- Task notification cannot be used
  - Sending an event or data <u>to</u> an ISR
  - Enabling more than one receiving task
  - Buffering multiple data items
    - Task notifications send data to a task by updating the receiving task's notification value.
  - Broadcasting to more than one task
    - Task notifications are sent directly to the receiving task
  - Waiting in the blocked state for a send to complete
    - If a task attempts to send a task notification to a task that already has a notification pending

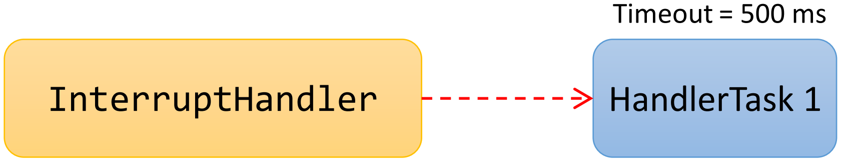
First Example
processing all at once

```
TaskHandle_t xHandlerTask = NULL;

int main(void) {
  xTaskCreate(vHandlerTask, "Handler", 1000, NULL, 3, &xHandlerTask);
  vPortSetInterruptHandler(3, ulInterruptHandler);
  vTaskStartScheduler();
  for (;; );
  return 0;
}

void vHandlerTask1(void *pvParameters) {
  uint32_t ulEventsToProcess;
  for (;; ) {
    ulEventsToProcess = ulTaskNotifyTake(pdTRUE, pdMS_TO_TICKS(500));
    if (ulEventsToProcess != 0) {
      while (ulEventsToProcess > 0) {
        vPrintString("Handler task - Processing event.\r\n");
        ...
        ulEventsToProcess--;
      }
    }
    else {
      ...
    }
  }
}
```

notification value = 0

Time out

All at once



```
uint32_t ulInterruptHandler(void) {
  BaseType_t xHigherPriorityTaskWoken;
  vTaskNotifyGiveFromISR(xHandlerTask, &xHigherPriorityTaskWoken);
  portYIELD_FROM_ISR(xHigherPriorityTaskWoken);
}
```

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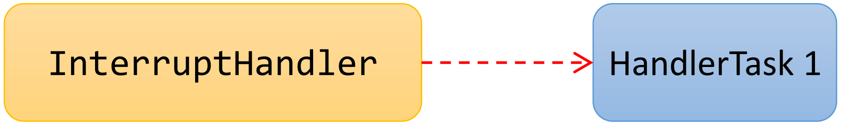
Second Example
Processing one by one

```
TaskHandle_t xHandlerTask = NULL;

int main(void) {
  xTaskCreate(vHandlerTask, "Handler", 1000, NULL, 3, &xHandlerTask);
  vPortSetInterruptHandler(3, ulInterruptHandler);
  vTaskStartScheduler();
  for (;; );
  return 0;
}
```

Timeout = 500 ms



One by one

notification value = notification value - 1

```
void vHandlerTask1(void *pvParameters) {
  for (;; ) {

    if (ulTaskNotifyTake(pdFALSE, pdMS_TO_TICKS(500)) != 0) {
      vPrintString("Handler task - Processing event.\r\n");
      ...
    }
    else {
      ...
    }
  }
}
```

```
uint32_t ulInterruptHandler(void) {
  BaseType_t xHigherPriorityTaskWoken;
  vTaskNotifyGiveFromISR(xHandlerTask, &xHigherPriorityTaskWoken);
  portYIELD_FROM_ISR(xHigherPriorityTaskWoken);
}
```

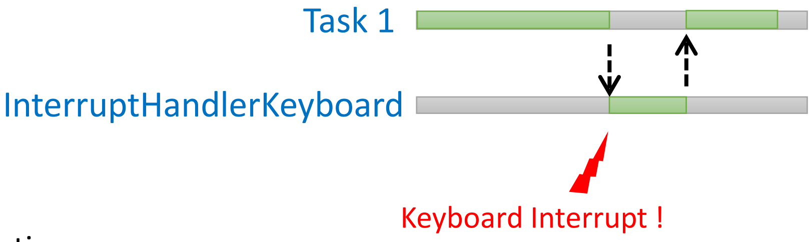
Advanced functions

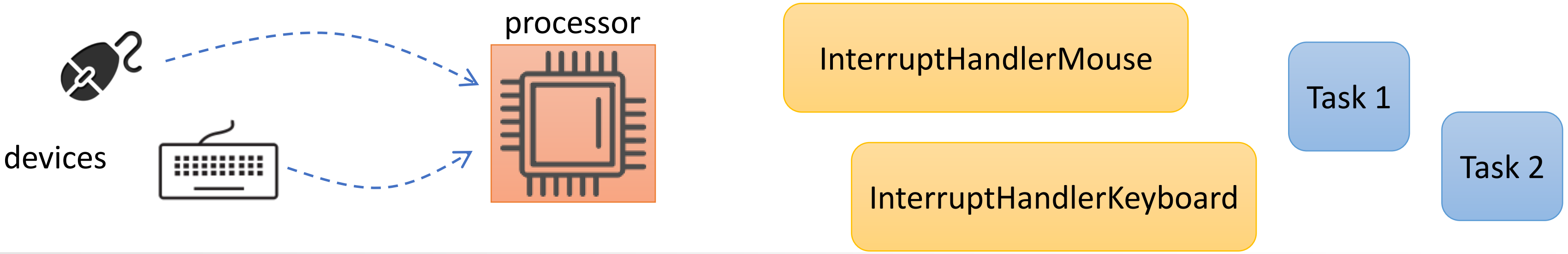
- xTaskNotify(), xTaskNotifyFromISR()
  - More flexible and powerful than xTaskNotifyGive()
  - Can be used to update the receiving task's notification value
    - Increment
    - Set one or more bits in the receiving task's notification value
    - Write a completely new number into the receiving task's notification value
- xTaskNotifyWait()
  - More powerful than ulTaskNotifyTake()
  - Allows a task to wait, with an optional timeout
  - To be cleared in the calling task's notification value
    - entry to the function
    - on exit from the function

Interrupt Management

What is an interrupt ?

- Signal sent from a device/program
- Request for the processor to interrupt the current program execution
- Associated with a interrupt handler
- Hardware interrupt - Interrupt ReQuest (IRQ)
  - IRQ is an electronic signal issued by an external hardware device
  - GPIO, Timer, UART, USB, Mouse, keyboard …
- Software interrupt
  - Requested by the processor itself
    - executing particular instructions
    - when certain conditions are met
    - triggered by program execution errors, called traps or exceptions
- Interrupt can be disabled or maskable, some are non-maskable interrupts (NMI)





Interrupt & task

- Distinction between the priority of a task & an interrupt
  - Tasks will only run when there are no ISRs running
  - The lowest priority interrupt will interrupt the highest priority task
  - No way for a task to pre-empt an ISR
- Interrupt Service Routine (ISR) API
  - One version for use from tasks
  - One version for use from ISRs with <u>no blocked state</u>
  - Never call a FreeRTOS API function that does not have “FromISR” in its name from an ISR
  - Allows task/ISR code to be more efficient

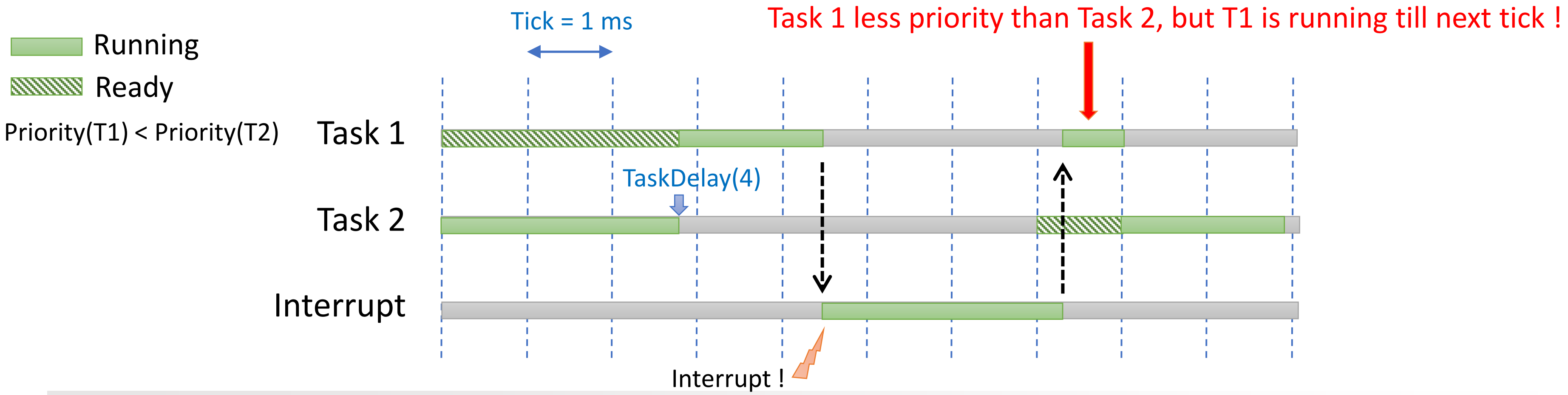
Context Switch - Problematic

- The task running when the interrupt exits might be different to the task that was running when the interrupt was entered

```
void vTask1(void *pvParameters) {
  for (;; ) {
    vPrintString("Task 1 running ...\r\n");
  }
}
```

```
uint32_t ulInterruptHandler(void) {
  vPrintString("Interrupt wake up !\r\n");
}
```

```
void vTask2(void *pvParameters) {
  for (;; ) {
    vTaskDelay(4);
    vPrintString("Task 2 running ...\r\n");
  }
}
```



Task 1 less priority than Task 2, but T1 is running till next tick !

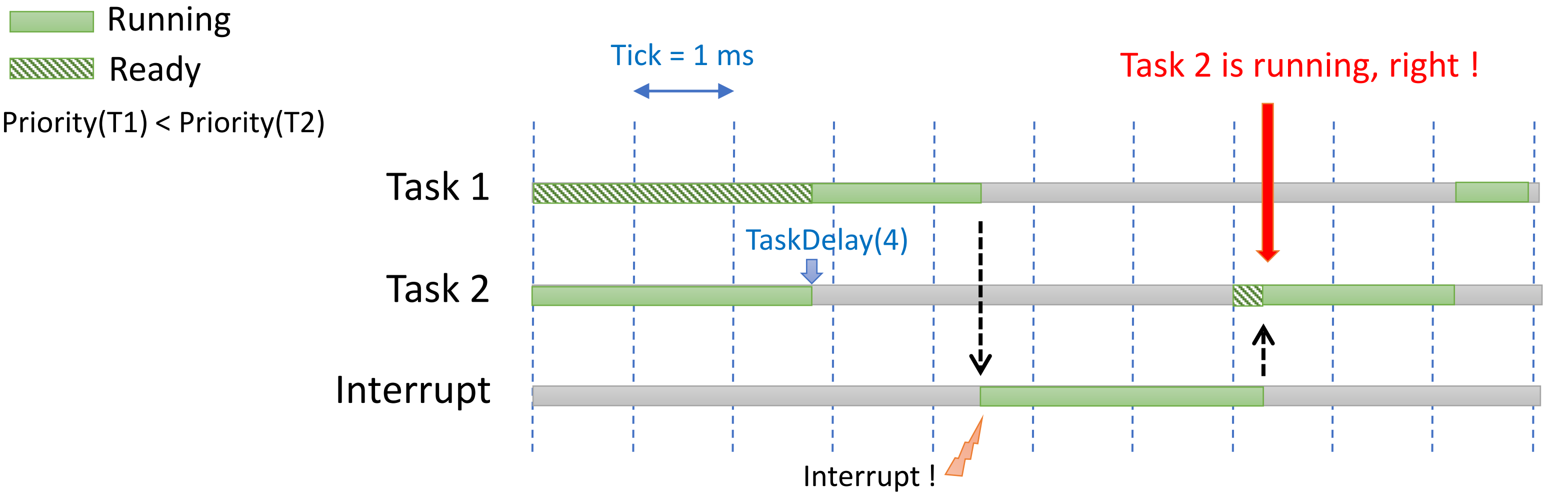
Context Switch - Solution

- Called a API function to request a context switch if necessary
- portYIELD_FROM_ISR(pxHigherPriorityTaskWoken)
  - pxHigherPriorityTaskWoken = true : could have a context switch
  - pxHigherPriorityTaskWoken = true : do nothing

```
uint32_t ulInterruptHandler(void) {

   vPrintString("Interrupt wake up !\r\n");

   portYIELD_FROM_ISR(pdTRUE);
}
```



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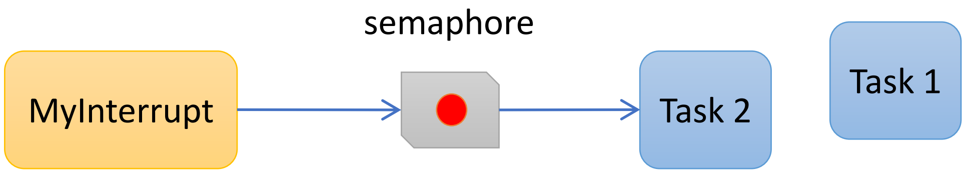
Example with semaphore

Priority(T1) < Priority(T2)

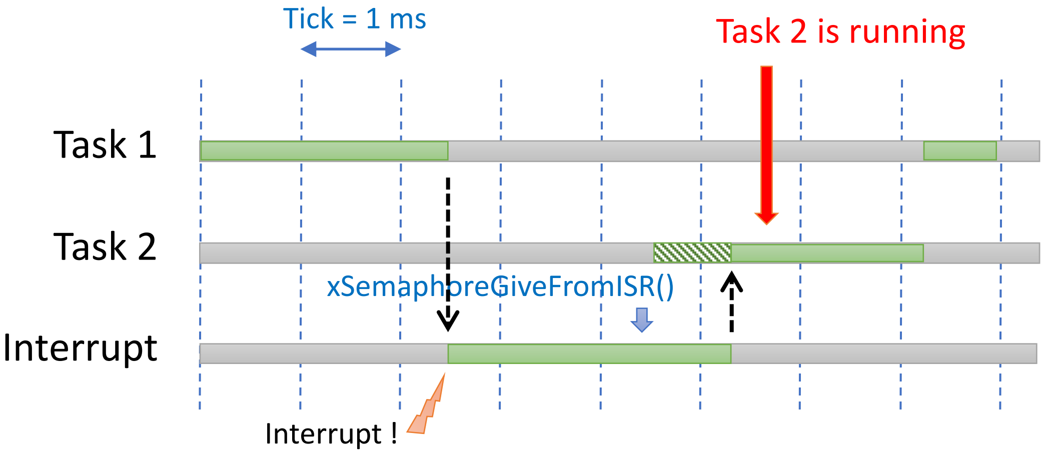


```
uint32_t ulInterruptHandler(void) {
  BaseType_t xHigherPriorityTaskWoken= pdFALSE;

  xSemaphoreGiveFromISR(xBinarySemaphore,
                        &xHigherPriorityTaskWoken);

  vPrintString("Interrupt wake up !\r\n");
  portYIELD_FROM_ISR(xHigherPriorityTaskWoken);
}
```

```
void vTask2(void *pvParameters) {
  for (;; ) {
    xSemaphoreTake(xCountingSemaphore,
                   portMAX_DELAY);
    vPrintString("Task 2 running ...\r\n");
  }
}
```



Using an interrupt on Windows port

```
#define mainINTERRUPT_NUMBER 3
```

Numbers 0 to 2 are used by the FreeRTOS Windows port itself
3 is the first number available to the application.

```
int main(void) {
  vPortSetInterruptHandler(mainINTERRUPT_NUMBER, ulInterruptHandler);
  ...
}

uint32_t ulInterruptHandler(void) {
  BaseType_t xHigherPriorityTaskWoken= pdFALSE;
  ...
  portYIELD_FROM_ISR(xHigherPriorityTaskWoken);
}
```

Somewhere else (in a task)

```
 vPortGenerateSimulatedInterrupt( mainINTERRUPT_NUMBER );
```

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