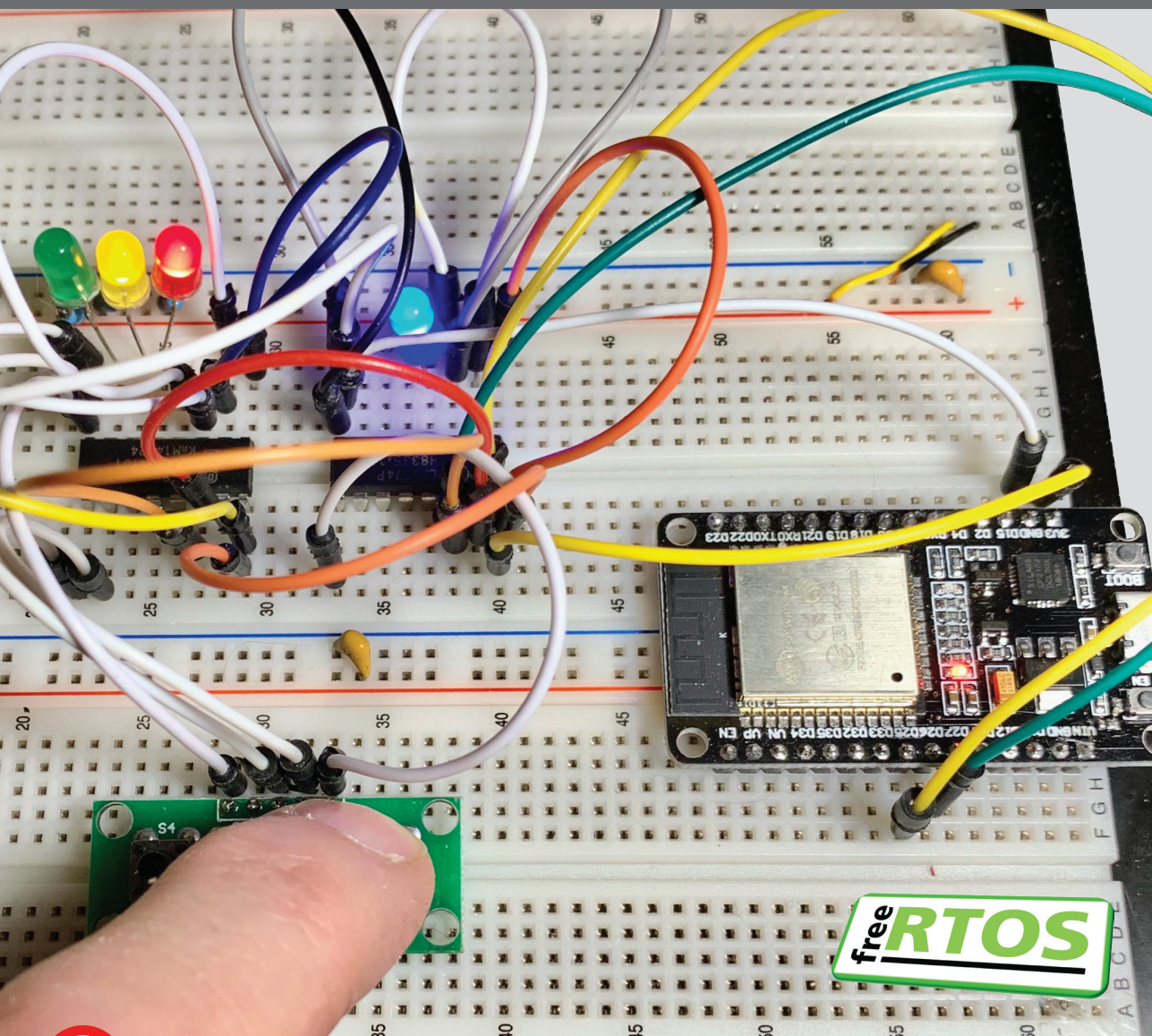
FreeRTOS for ESP32-Arduino

Practical Multitasking Fundamentals



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Warren Gay

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Chapter 1 • Introduction

In recent times, the development of System on a Chip (Soc) has lead to the popular use of microcontrollers. Many products sold today will have one or more microcontrollers found inside. Their small size, low cost, and increasing capabilities make them very compelling. Beginning in 2005, the Arduino project made microcontrollers more accessible to students by simplifying the programming environment.[1] Since then, hobbyists and engineers alike have exploited its capabilities.

More recently, FreeRTOS within the Arduino software framework has been introduced on some platforms. Why is FreeRTOS beneficial? What problems does it solve? How can FreeRTOS be leveraged by your project? These are some of the questions answered in this book with demonstrations.

Not all Arduino hardware platforms support FreeRTOS. The RTOS (Real-Time Operating System) component requires additional resources like SRAM (Static Random Access Memory) and a stack for each task. Consequently, very small microcontrollers won't support it. For larger microcontrollers that do, a rich API (Application Programming Interface) is available to make writing your application easier and more powerful.

The Need for RTOS

The general approach used on small AVR (ATmel) devices is to poll for events and respond. A program might test for button presses, incoming serial data, take temperature readings, and then at the right time, produce a result like closing relays or sending serial data. That polling approach works well enough for small projects.

As the number of input events and conditions increases, the complexity tends to multiply. Managing events by polling requires an ever-increasing management of state. Well designed programs may, in fact, implement a formal "state machine" to organize this complexity.

If instead, the same program was split into independently executing subprograms, the problem becomes much simpler to manage. Within FreeRTOS, these are known as tasks. The button press task could examine the GPIO input and debounce it. It becomes a simple loop of its own, producing an event only when the debounced result indicates that the button was pressed. Likewise, the serial input task operating independently can loop while receiving characters until an end of line character was encountered. Once the serial data was decoded, the interpreted command could signal an event. Finally, the master task, receiving both the button press and command events from other tasks can trigger an action event (like the closing of relays). In this manner, a complex application breaks down into smaller tasks, with each task focusing on a subset of the problem.

How are tasks implemented? In the early years of computing, mainframes could only run one program at a time. This was an expensive way to use a computer that occupied the size of a room. Eventually, operating systems emerged, with names like the Time Sharing Option (TSO), which made it possible to share that resource with several users (all running

different programs). These early systems gave the illusion of running multiple programs at the same time by using a trick: after the current time slice was used up, the program's registers were saved, and another program's registers were reloaded, to resume the suspended program. Performed many times per second, the illusion of multiple programs running at once was complete. This is known as *concurrent execution* since only one program is running at any one instant.

A similar process happens today on microcontrollers using an RTOS. When a task starts, the scheduler uses a hardware timer. Later, when the hardware timer causes an interrupt, the scheduler suspends the current task and looks for another task to resume. The chosen task's registers are restored, and the new (previously suspended) task resumes. This concurrent execution is also known as *preemptive scheduling* because one task preempts another when the hardware timer interrupts.

Preemptive scheduling is perhaps the main reason for using FreeRTOS in today's projects. Preemptive scheduling permits concurrent execution of tasks, allowing the application designer to subdivide complex applications without having to plan the scheduling. Each component task runs independently while contributing to the overall solution.

When there are independent tasks, new issues arise. How does a task safely communicate an event to another task? How do you synchronize? How do interrupts fit into the framework? The purpose of this book is to demonstrate how FreeRTOS solves these multitasking related problems.

FreeRTOS Engineering

It would be easy to underestimate the design elegance of FreeRTOS. I believe that some hobbyists have done as much in forums. Detractors talk about the greater need for efficiency, less memory, and how they could easily implement their routines instead. While this may be true for trivial projects, I believe they have greatly underestimated the scope of larger efforts.

It is fairly trivial to design a queue with a critical section to guarantee that one of several tasks receives an item atomically. But when you factor in task priorities, for example, the job becomes more difficult. FreeRTOS guarantees that the highest priority task will receive that first item queued. Further, if there are multiple tasks at the same priority, the first task to wait on the queue will get the added item. Strict ordering is baked into the design of FreeRTOS.

The mutex is another example of a keen FreeRTOS design. When a high priority task attempts to lock a mutex that is held by a lower priority task, the later's priority is increased temporarily so that the lock can be released earlier, to prevent deadlocks. Once released, the task that was holding the mutex returns to its original priority. These are features that the casual user takes for granted.

The efficiency argument is rarely the most important consideration. Imagine your application written for one flavour of RTOS and then in another. Would the end-user be able to

tell the difference? In many cases, it would require an oscilloscope measurement to note a difference.

FreeRTOS is one of several implementations that are available today. However, it's free status and its first-class design and validation make it an excellent RTOS to study and use. FreeRTOS permits you to focus on your *application* rather than to recreate and validate a home-baked RTOS of your own.

Hardware
To demonstrate the use of the FreeRTOS API, it is useful to concentrate on one hardware platform. This eases the requirements for the demonstration programs. For this reason, the Espressif ESP32 is used throughout this book, which can be purchased at a modest cost. These devices have enough SRAM to support multiple tasks and have the facilities necessary to support preemptive scheduling. Even more exciting, is the fact that these devices can also support WiFi and TCP/IP networking for advanced projects.

Dev Boards
While almost any ESP32 module could be used, the reader is encouraged to use the "dev board" variety for this book. The non-dev board module requires a TTL to serial device to program its flash memory and communicate with. Be aware that many TTL to serial devices are 5 volts only. To prevent permanent damage, these should *not* be used with the 3.3 volt ESP32. TTL to serial devices can be purchased, which do support 3.3 volts, usually with a jumper setting.

The dev boards are much easier to use because they include a USB to serial chip onboard. They often use the chip types CP2102, CP2104, or CH340. Dev boards will have a USB connector, which only requires a USB cable to plug into your desktop. They also provide the necessary 5 volts to 3.3-volt regulator to power your ESP32. GPIO 0 is sometimes automatically grounded by the dev board, which is required to start the programming. The built-in USB to serial interface makes programming the device a snap and permits easy display of debugging information in the Arduino Serial Monitor. Dev boards also provide easy GPIO access with appropriate labels and are breadboard friendly (when the header strips are added). The little extra spent on the dev board is well worth the convenience and the time it will save you.

One recommended unit is the ESP32 Lolin with OLED because it includes the OLED display. It is priced a little higher because of the display but it can be very useful for end user applications. Most ESP32 devices are dual-core (two CPUs), and the demonstrations in this book assume as much.

If you are determined to use the nondev board variety, perhaps because you want to use the ESP32CAM type of board, then the choice of USB to TTL serial converter might be important. While the FT232RL eBay units offer a 3.3-volt option, I found that they are problematic for MacOS (likely not for Windows). If the unit is unplugged or jiggled while the device is in use, you lose access to the device, and replugging the USB cable doesn't help. Thus it requires the pain of rebooting and is, therefore, best avoided.

Table 1-1 summarizes the major Espressif product offerings that will populate various development boards. When buying, zoom in on the CPU chip in the photo for identifying marks. There are other differences between them in terms of peripheral support etc., not shown in the table. Those details can be discovered in the Espressif hardware PDF datasheets. All examples in this book assume the dualcore CPU to run without modification. The demonstrations can be modified to work on a single core unit but when learning something new, it is best to use tested examples first.

Series	Cores	CPU Clock	SRAM + RTC	Marking
ESP32	2	80 to 240 MHz	520kB+16kB	ESP32-D0WD
				ESP32-D0WDQ6
				ESP32-D2WD
	1		520kB+16kB	ESP32-S0WD
ESP32-S2	1	240 MHz	320kB+16kB	

Table 1-1. Major Espressif Product Offerings

ESP8266

The hardware of the ESP8266 is quite capable of supporting FreeRTOS. If you use the Espressif ESP-IDF (Integrated Development Framework), you can indeed make use of the FreeRTOS API there. Unfortunately, the Arduino environment for the ESP8266 does not make this available, even though it has been used internally in the build.

To keep things simple for students familiar with Arduino therefore, this book is focused on the dualcore ESP32. What is described for FreeRTOS in this book can also be applied to the ESP-IDF for both the ESP8266 and the ESP32 devices.

FreeRTOS Conventions

Throughout this book and in the Arduino source code, I'll be referring to FreeRTOS function names and macros using their naming conventions. These are outlined in the FreeRTOS manual, which is freely available for download as a PDF file.[2] These are described in Appendix 1 of their manual.

While I am not personally keen on this convention, it is understood that the FreeRTOS authors were thinking about portability to many different platforms. Knowing their conventions helps when examining the reference API. The following two data types are used frequently:

- TickType_t – For the Espressif platform, this is a 32-bit unsigned integer (uint32_t), which holds the number of system ticks.

- BaseType_t – For the Espressif platform, this is defined as a 32-bit unsigned integer (uint32_t). The type is chosen to be efficient on the hardware platform being used.

Variable Names
The variable names used in FreeRTOS examples and arguments, use the following prefixes:

- ‘c’ - char type
- ‘s’ - short type
- ‘l’ - long type
- ‘x’ - BaseType_t and any other types not covered above

A variable name is further prefixed with a ‘u’ to indicate an unsigned type. If the value is a pointer, the name is prefixed with ‘p’. An unsigned character variable would use the prefix ‘uc’, while a pointer to a char type, would be ‘pc’.

Function Names
Function names are prefixed with two components:

- The data type of the value returned
- The file that the function is defined in

These are some of the examples they provide:

- vTaskPrioritySet() returns a void and is defined within FreeRTOS file task.c.
- xQueueReceive() returns a variable of type BaseType_t and is defined within FreeRTOS file queue.c.
- vSemaphoreCreateBinary() returns a void and is defined within FreeRTOS file semphr.h.

In this context, the prefix ‘v’ means that the function returns void.

Macro Names
Macro names are given in uppercase, except for a prefix that indicates where they are defined (Table 1-2).

Prefix	File	Example
port	portable.h	portMAX_DELAY
task	task.h	taskENTER_CRITICAL()
pd	projdefs.h	pdTRUE
config	FreeRTOSConfig.h	configUSE_PREEMPTION
err	projdefs.h	errQUEUE_FULL

Table 1-2. Macro name conventions used by FreeRTOS.

Header Files
Normally when using FreeRTOS there are #include statements required. Within the ESP32 Arduino programming environment, these are already provided internally. However, when you use the ESP-IDF or a different platform, you will need to know about the header files

listed in Table 1-3. Because they are not required in the Arduino code, they are only mentioned here.

Header File	Category	Description
FreeRTOS.h	First	Should be the first file included.
FreeRTOSConfig.h	Included by FreeRTOS.h	Not required when FreeRTOS.h has been included.
task.h	Tasks	Task support
queue.h	Queues	Queue support
semphr.h	Semaphores	Semaphore and mutex support
timers.h	Timers	Timer support

Table 1-3. FreeRTOS Include Files

Arduino Setup

This book uses the installed Arduino IDE rather than the newer web offering. If you've not already installed the Arduino IDE and used it, you might want to do so now. If you're using MacOS and recently upgraded to Catalina, you will also need to update your Arduino software. The IDE is downloadable from:

https://www.arduino.cc/en/main/software

Click the appropriate platform link for the install. At the time of writing, the website lists the following choices:

- Windows Installer, for Windows XP and up
- Windows Zip file for non-admin install
- Windows App. Requires Win 8.1 or 10.
- Mac OS X 10.8 Mountain Lion or newer.
- Linux 32 bits.
- Linux 64 bits.
- Linux ARM 32-bits.
- Linux ARN 64-bits.

Install guidance or troubleshooting is best obtained from that Arduino website. Normally, the IDE installs without problems.

ESP32 Arduino

To add ESP32 support to the Arduino IDE, open File->Preference (see Figure 1-1), Arduino->Preferences for MacOS, and add:

https://dl.espressif.com/dl/package_esp32_index.json

to your "Additional Boards Manager URLs" text box. If you already have something in there, then separate the addition with a comma (,).

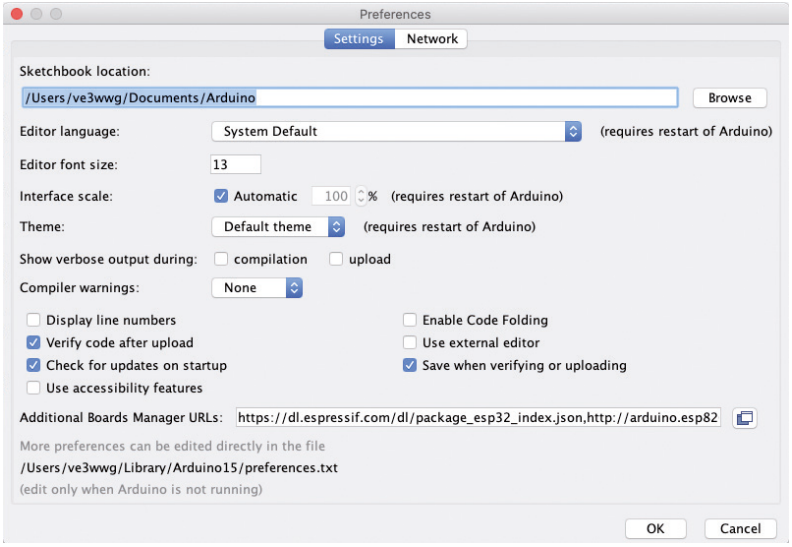

Figure 1-1. File->Preference dialog.

Next choose Tools->Board->Board Manager (Figure 1-2):

- Then search for "ESP32" and click install (or update), if supporting the ESP32.

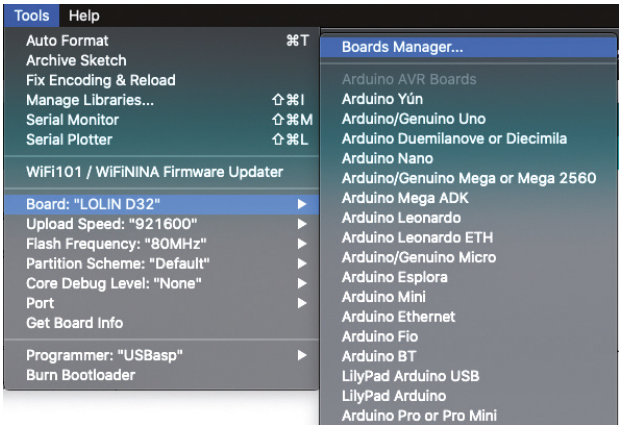

Figure 1-2. File->Board->Boards Manager menu selection.

Figure 1-3 shows the dialog after the ESP addition has been installed. That should be all you need to do, to add Espressif support to your Arduino IDE.

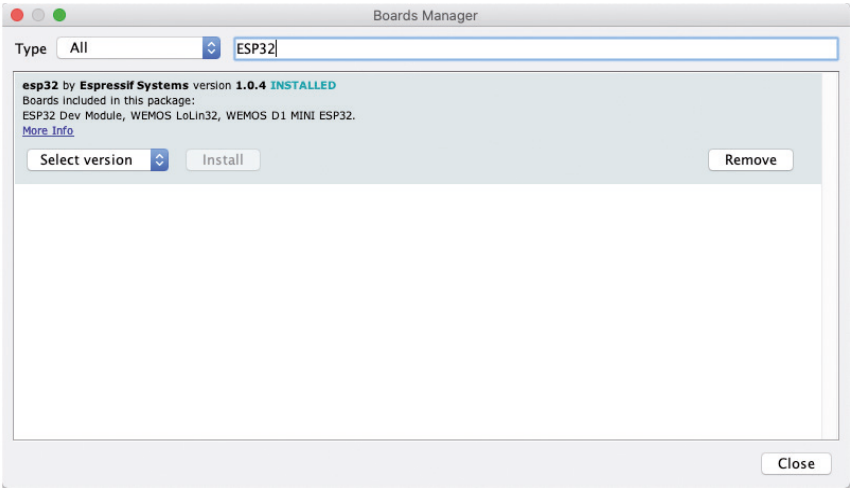

Figure 1-3. Boards Manager after the ESP addition is installed.

ESP Related Arduino Resources
If IDE issues arise, then search the resources found at

https://www.arduino.cc/

If the problem is Espressif related, then there is the following Arduino GitHub page:

https://github.com/espressif/arduino-esp32

C and C++
It surprises some to learn that the Arduino framework uses the C++ language. This may be deemphasized to prevent scaring prospective students – a common perception is that C++ is difficult. But C++ is increasingly finding its way into embedded programming circles because of its advantages of stronger type checking among other advantages. The career student is therefore encouraged to embrace it.

This book will use a dabbling of C++ language features when it is useful, instructive, or just plain preferred. One trivial example is the keyword nullptr is favoured over the old C macro NULL. Where C++ classes are used, they are simple objects. No C++ template programming is used in this book, so there is no need for fear and loathing.

There is one area that Arduino users will bump into when looking at Espressif provided example code. Most of their examples are written in C. The C language structure initialization *differs* from C++, although there are efforts working towards harmonization. Listing 1-1 shows a fragment of an Espressif C language wifi scan example. Notice the initialization syntax of the structure named wifi_config.

```
static void wifi_scan(void)
{
...
    wifi_config_t wifi_config = {
        .sta = {
            .ssid = DEFAULT_SSID,
            .password = DEFAULT_PWD,
            .scan_method = DEFAULT_SCAN_METHOD,
            .sort_method = DEFAULT_SORT_METHOD,
            .threshold.rssi = DEFAULT_RSSI,
            .threshold.authmode = DEFAULT_AUTHMODE,
        },
    };
...
}
```

Listing 1-1. Espressif examples/wifi/scan/main/scan.c fragment.

Members like .ssid are set to initialization values using the C language syntax. This style of initialization is not yet supported by C++. Given that Arduino code is C++, you cannot copy and paste C language structure initialization code into your program and expect it to compile.

Listing 1-2 shows *one* way it can be reworked in C++ terms (advanced users can also use the extern "C" approach). First, clear the structure completely to zero bytes by using the memset() function. Once cleared, the individual members can be initialized as required.

```
static void wifi_scan(void)
{
...
    wifi_config_t wifi_config;

    memset(&wifi_config,0,sizeof wifi_config);
    wifi_config.sta.ssid = DEFAULT_SID;
    wifi_config.sta.password = DEFAULT_PWD;
...
    wifi_config.sta..threshold.authmode = DEFAULT_AUTHMODE;
...
}
```

Listing 1-2. Function wifi_scan() Converted to C++ initialization.

FreeRTOS and C++

FreeRTOS is written in the C language to give it the greatest portability among microcontroller platforms and compiler tools. Yet it is quite useable from C++ code since the compiler is informed from the header files that the FreeRTOS API functions are C language dec-

larations. Because these are C language calls, some C++ restrictions naturally follow. For example, when using the FreeRTOS queue, you cannot add an item that is a C++ object, requiring constructors or destructors. The data item must be POD (Plain Old Data). This is understandable when you consider that the C language doesn't support class objects, constructors, or destructors.

Arduino FreeRTOS Config

The Arduino environment that is built for your ESP32 uses a predefined FreeRTOS configuration to declare the features that are supported and configure certain parameters. These macros are already included for the Arduino but other environments like ESP-IDF, require including the header file FreeRTOS.h. Many of the configured values for the ESP32 Arduino are provided in Table 1-4 for your convenience. The detailed meaning of these values is documented by the FreeRTOS reference manual, which is freely available online.

Macro	Value	Notes
configAPPLICATION_ALLOCATED_HEAP	1	ESP32 defined heap.
configCHECK_FOR_STACK_OVERFLOW	2	Check for stack overflow by initializing stack with a value at task creation time.
configESP32_PER_TASK_DATA	1	Per task storage facility
configEXPECTED_IDLE_TIME_BEFORE_SLEEP	2	
configGENERATE_RUN_TIME_STATS	0	Disabled
configIDLE_SHOULD_YIELD	0	Disabled
configINCLUDE_APPLICATION_DEFINED_PRIVILEGED_FUNCTIONS	0	Disabled
configMAX_TASK_NAME_LEN	16	Maximum name string length
configMINIMAL_STACK_SIZE	768	Idle task stack size (bytes)
configQUEUE_REGISTRY_SIZE	0	Queue registry not supported
configSUPPORT_DYNAMIC_ALLOCATION	1	Dynamic memory supported
configSUPPORT_STATIC_ALLOCATION	No support	
configTASKLIST_INCLUDE_COREID	0	Disabled
configUSE_ALTERNATIVE_API	0	Disabled
configUSE_APPLICATION_TASK_TAG	0	Disabled
configUSE_COUNTING_SEMAPHORES	1	Counting semaphores enabled
configUSE_MALLOC_FAILED_HOOK	0	Disabled
configUSE_MUTEXES	1	Mutexes enabled
configUSE_NEWLIB_REENTRANT	1	Reentrancy for newlib enabled
configUSE_PORT_OPTIMISED_TASK_SELECTION	0	Disabled
configUSE_QUEUE_SETS	1	Queue sets enabled
configUSE_RECURSIVE_MUTEXES	1	Recursive mutexes enabled
configUSE_STATS_FORMATTING_FUNCTIONS	0	Disabled

Macro	Value	Notes
configUSE_TASK_NOTIFICATIONS	1	Task notifications enabled
configUSE_TICKLESS_IDLE	No support	
configUSE_TIMERS	1	Timer support enabled
configTIMER_TASK_STACK_DEPTH	2048	Svc Tmr task stack size (bytes)
configTIMER_QUEUE_LENGTH	10	Depth of the command queue
configUSE_TIME_SLICING	1	Time slicing enabled (see reference manual)
configUSE_TRACE_FACILITY	0	Disabled FreeRTOS trace facilities

Table 1-4. Some ESP32 Arduino FreeRTOS configuration values.

A number of these are of special interest to Arduino users because we can determine that:

- The maximum string name for tasks and other FreeRTOS objects is 16 characters (configMAX_TASK_NAME_LEN).
- There is support for counting semaphores (configUSE_COUNTING_SEMAPHORES).
- There is support for mutexes (configUSE_MUTEXES).
- Mutex support includes recursive mutexes (configUSE_RECURSIVE_MUTEXES).
- There is support for queue sets (configUSE_QUEUE_SETS).
- There is support for task notification (configUSE_TASK_NOTIFICATIONS).
- There is support for FreeRTOS timers (configUSE_TIMERS).
- The Idle task uses a stack size of 768 bytes (configMINIMAL_STACK_SIZE).

For portability, the user can use these macros to determine the level of support available.

ESP32 Notes
This section provides a few brief reminders about ESP32 devices. The Espressif web resources and forums are the best places to get more detailed information.

Arduino GPIO References
Arduino maps "digital pin x" to a port and pin combination on some platforms. For example, digital pin 3 maps to pin PD3 on the ATmega328P. For the ESP32 Arduino environment, digital pin x maps directly to GPIO x.

Input Only
The ESP32 platform also has hardware limitations for GPIO. For example, GPIO 34 to 39 inclusive can only be used for *input.* These GPIO pins also lack the programmed pull-up resistor feature. For this reason, these inputs should always be used with external pull-up resistors for push button and switch inputs to avoid floating signals. A resistance of 10k to 50k ohm is sufficient.

Reserved GPIOs
Several ESP32 GPIO pins are reserved or are already in use by peripherals. For example, GPIO pins 6 through 11 are connected to the integrated SPI flash.

GPIO Voltage and Drive
The ESP32 device uses 3.3-volt GPIO ports and *none* are 5 volts tolerant. Inputs should never be subjected to above 3.3 + 0.6 volts (one silicon diode voltage drop). Voltages above 3.9 volts will subject the built-in protection diode to high currents and potentially destroy it. With the protective ESD (Electrostatic Discharge) diode damaged, the GPIO will be vulnerable to damage from static electricity (from the likes of the family cat). Alternatively, the ESD diode can short, causing a general malfunction of the port.

Output GPIOs have programmable current strengths, which default to strength 2. This is good for up to 20 mA.[3]

Programs
Arduino promotes the term "sketch" for their programs. I'll continue to refer to them as programs because this is the more widely accepted term. If the student pursues a career in embedded programming, he/she will most likely be using a non-Arduino framework for building *programs*. So I think it best to get comfortable with the term.

Many of the demonstrations written for this book are illustrated using the Wemos Lolin ESP32 dev board, which includes the built-in OLED. The OLED is only used by a few of the demonstration programs. Even then, some of those demonstrations can use the Serial Monitor instead. Otherwise, almost any "dev board" can be used if a reasonable complement of GPIOs is made available for you to use.

The serial interface brings with it a nagging problem for the Arduino ESP32. It would be desirable to have programs that run both with and without the USB serial interface plugged in. Yet it seems that the programs that make use of the serial interface will hang when not connected. Yet the Serial Monitor is too useful to forego for debugging and informational displays. Consequently, most demonstrations use the serial interface as provided by the ESP32 inclusion of the newlib library.[4] The first printf() call encountered, will assume a serial interface at 115,200 baud, 8 bits, no parity, and 1 stop bit. By default, the Arduino IDE will provide this in its Serial Monitor.

It may be desirable in some cases to use a demonstration program without the Serial Monitor. In that case, comment out the printf() statements and re-flash the recompiled program. If it still hangs, look for remaining uncommented printf() calls.

Graphics/Drivers Used
The main graphic driver used is for the Wemos Lolin ESP32 that has the built-in OLED. This library is found by using the Arduino Tools -> Manage Libraries and searching for "ESP8266 and ESP32 Oled Driver for SSD1306 display" by ThingPulse, Fabrice Weinberg.

TTGO ESP32 T-Display
The graphics driver used for the TTGO ESP32 T-Display unit is the driver found by the Arduino Tools -> Manage Libraries and searching for "TFT_eSPI" by Bodmer (version 2.1.4 was tested). This driver requires further editing before it can be used (see Chapter 9, Interrupts).

M5Stack
M5Stack examples in this book require that you've installed the drivers found by the Arduino Tools -> Manage Libraries and searching for "M5Stack". Choose and install the library "M5Stack" by M5Stack. Version 0.2.9 was tested in this book.

Assumptions about the Reader
This book is targeted to new and advanced Arduino users alike. The new student will discover the benefits of FreeRTOS design by wading gently into RTOS concepts and the API. The advanced user looking to become familiar with FreeRTOS can quickly familiarize themselves with the API. The emphasis was placed on the practical but some background material is provided for the benefit of new students.

Because this book is focused upon FreeRTOS, the reader is assumed to have some familiarity with the ESP32 and the Arduino API. Activities like configuring and flashing the correct board from the Arduino IDE is assumed. Those encountering difficulties in these areas are encouraged to seek help from online documentation and forums for Arduino and Espressif.

Summary
At this point, I expect that you are champing at the bit to get started. By now, your Arduino IDE has been made ready and you have some ESP32 hardware ready to play with. Let's begin that journey of discovery into FreeRTOS!

Web Resources
[1] https://en.wikipedia.org/wiki/Arduino
[2] https://www.freertos.org/Documentation/FreeRTOS_Reference_Manual_V10.0.0.pdf
[3] https://www.esp32.com/viewtopic.php?t=5840
[4] https://sourceware.org/newlib/

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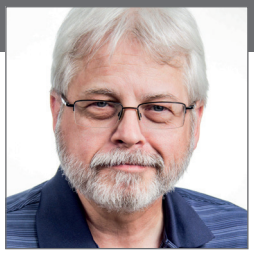
FreeRTOS for ESP32-Arduino

Practical Multitasking Fundamentals

Warren Gay



Warren Gay is a datablocks.net senior software developer, writing Linux internet servers in C++. He got involved with electronics at an early age, and since then he has built microcomputers and has worked with MC68HC705, AVR, STM32, ESP32 and ARM computers, just to name a few.

Programming embedded systems is difficult because of resource constraints and limited debugging facilities. Why develop your own Real-Time Operating System (RTOS) as well as your application when the proven FreeRTOS software is freely available? Why not start with a validated foundation?

Every software developer knows that you must divide a difficult problem into smaller ones to conquer it. Using separate preemptive tasks and FreeRTOS communication mechanisms, a clean separation of functions is achieved within the entire application. This results in safe and maintainable designs.

Practicing engineers and students alike can use this book and the ESP32 Arduino environment to wade into FreeRTOS concepts at a comfortable pace. The well-organized text enables you to master each concept before starting the next chapter. Practical breadboard experiments and schematics are included to bring the lessons home. Experience is the best teacher.

Each chapter includes exercises to test your knowledge. The coverage of the FreeRTOS Application Programming Interface (API) is complete for the ESP32 Arduino environment. You can apply what you learn to other FreeRTOS environments, including Espressif's ESP-IDF. The source code is available from github.com. All of these resources put you in the driver's seat when it is time to develop your next uber-cool ESP32 project.

What you will learn:

- How preemptive scheduling works within FreeRTOS
- The Arduino startup "loopTask"
- Message queues
- FreeRTOS timers and the IDLE task
- The semaphore, mutex, and their differences
- The mailbox and its application
- Real-time task priorities and its effect
- Interrupt interaction and use with FreeRTOS
- Queue sets
- Notifying tasks with events
- Event groups
- Critical sections
- Task local storage
- The gatekeeper task

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