# Embedded Systems and Advanced Computing

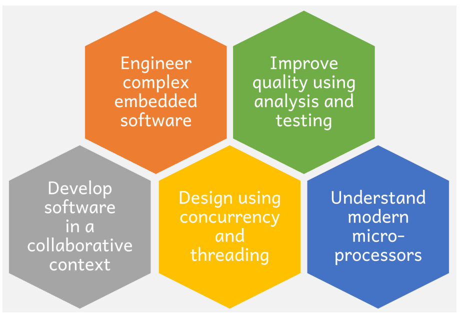
*ENCE464*

Andy Ming / Quelldateien

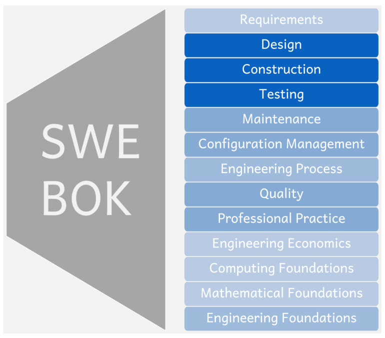
## Table of contents

## How to work code

Remember that software engineering is 50-70% maintenance. Because modern machines heavily rely on microcontrollers there is great demand.

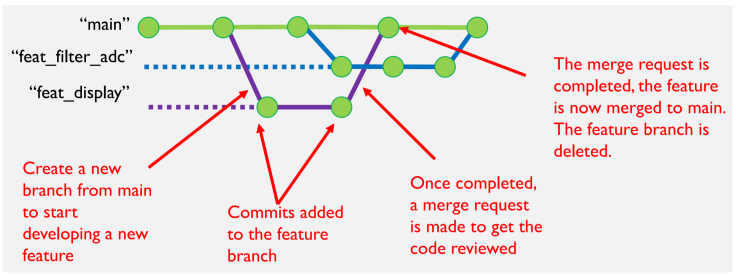

Engineer complex embedded software
Improve quality using analysis and testing
Develop software in a collaborative context
Design using concurrency and threading
Understand modern micro-processors

Software engineering has many different aspects (the dark blue ones are focused on here), find out more here.



### Feature Branches

To implement different features, use a branch per feature, this guarantees that the main is always in working condition.


"main"
"feat_filter_adc"
"feat_display"
Create a new branch from main to start developing a new feature
Commits added to the feature branch
Once completed, a merge request is made to get the code reviewed
The merge request is completed, the feature is now merged to main. The feature branch is deleted.

**! Branching Rules**

- Feature branches are **temporary** branches for new features, improvements, bug fixes or refactorings.
- Don't push directly to **master/main**.
- Each feature branch is owned by **one** developer.
- Only do merge requests on **complete** changes i.e. don't break main.
- Thoroughly test your change prior to **starting** AND prior to **completing** a merge request.
- Use your commit messages to tell the **story** of your development process.

To minimise integration issues:

- A feature branch should only hold a small increment of change
- If main is updated during feature development, merge the new main into your feature branch **locally**, **before** making a merge request

### Clean Code

**Smells of Bad Code**

- *Rigidity*: Changing a single behaviour requires changes in many places
- *Fragility*: Changing a single behaviour causes malfunctions in unconnected parts
- *Inseparability*: Code can't be reused elsewhere
- *Unreadability*: Original intent can't be derived from code

### Reveal Intent

```
// BAD
uint16_t adcAv;  // Average Altitude ADC counts
// GOOD
uint16_t averageAltitudeAdc;
```

### Don't Repeat Yourself (DRY)

Avoid duplicate code → Put it into a function. Can you put it in a function? Then you should!

### Consistent Abstraction

**High-Level** ideas shouldn't get lost in **Low-Level** operations.

```
// Bad Example
deviceState.newGoal = readADC() * POT_SCALE_COEFF;
↪  // low-level
deviceState.newGoal = (deviceState.newGoal /
↪  STEP_GOAL_ROUNDING)*STEP_GOAL_ROUNDING;  //
↪  high-level
```

### Encapsulation

- *Hide* as much as possible
- *Public* Interface: Header File, only declare what other modules need to know
- *Private* / Inner Workings: Source File
- *Avoid* global variables → Use *getter* & *setter*

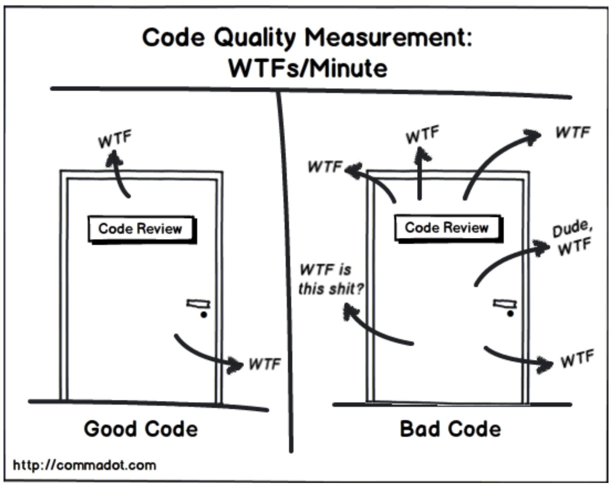
### Comments

More comments ≠ better quality. Use comments only to:

1. Reveal intent after you tried everything else
2. Document public APIs - sometimes

### Code Reviews

Use *merge requests*, label feeback as *bug, code, quality, preference*.



## SOLID

How to make designs **flexible**.

## Legacy / Vererbt / Veralteter Code

If handed bad quality (no tests, no encapsulation, no good practices, . . . ) and you have to add features you can either (1) *add to the mess by hacking in new features* or (2) *rewrite code from scratch*.

The issues are (1) will *reduce productivity* and it's *easy to introduce bugs* but (2) is very *time consuming*, it's *difficult to maintain two versions* (there might still be old versions in the field which have to be maintained) and there will be a *new set of bugs* to deal with.

So we try to refactor until it's easy to make changes. To preserve functionality we iterate *in small increments* with **Trageted Tests** *(allows changes and new features to happen at the same time)*:

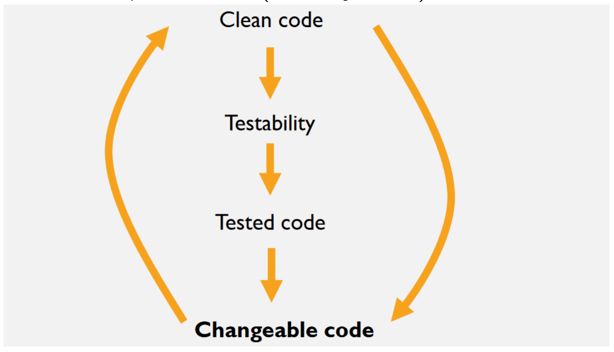
1. **Write tests** of the code you need to change
2. **Test drive** changes to legacy code
3. **Test drive** new code
4. **Refactor** tested area

Also add **Characterisation Tests** where understanding is required. *Tests are a living documentation*.

To make sure *key functionality* isn't altered, add **Strategic Tests**. (e.g. control algorithm, safety-critical error detection, . . . )

**Putting Code Under Test**

1. Identify are of code to test (targeted, characterisation, strategic)
2. Find test points (function calls, global variables → encapsulate ASAP, serial)
3. Break dependencies (Solitary tests)



# Embedded Software Design

## Architecture

Architecture are "important" structures, every structure is important for a specific part of the software. There are several different structures in embedded software systems.

**Architecture Goals**

- *Understandability* - In Development & Maintenance
- *Modifiability* - Through "best practices"

- *Performance* - Reduce Overheads

Other possible requirements: Portability, Testability, Maintainability, Scalability, Robustness, Availability, Safety, Security

**Static Structures:** Conceptual abstraction a developer works with

| Structure | Elements | Relationships |
|---|---|---|
| Decomposition | Modules, functions | Submodule of |
| Dependency | Modules | Depends on |
| Class | Classes | Inheritance, association |

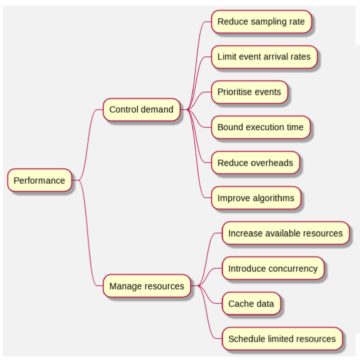
**Dynamic Structures:** Relationships that exist in executing software

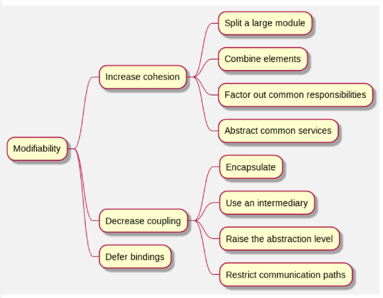
| Structure | Elements | Relationships |
|---|---|---|
| Collaboration | Components | Connections |
| Data-flow | Processes, stores | Flows of data |
| Task | Tasks, objects | Interactions |

**Allocation Structures:** Assignment of software elements to external things

| Structure | Elements | Relationships |
|---|---|---|
| Memory Map | Data, addresses | Allocated to |
| Implementation | Modules, files | Allocated to |
| Deployment | Software, hardware | Allocated to |

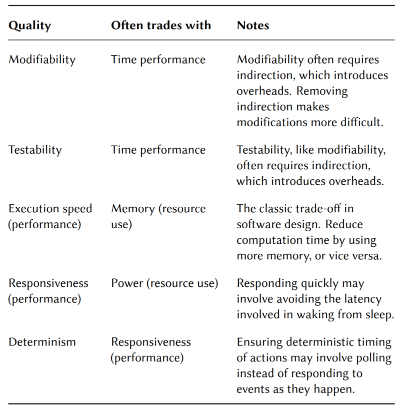
Patterns are always a combination of tactics, depending on what you're trying to achieve.





**Trade-Offs**

Quality attributes can conflict with each other. For example:



| Quality | Often trades with | Notes |
|---|---|---|
| Modifiability | Time performance | Modifiability often requires indirection, which introduces overheads. Removing indirection makes modifications more difficult. |
| Testability | Time performance | Testability, like modifiability, often requires indirection, which introduces overheads. |
| Execution speed (performance) | Memory (resource use) | The classic trade-off in software design. Reduce computation time by using more memory, or vice versa. |
| Responsiveness (performance) | Power (resource use) | Responding quickly may involve avoiding the latency involved in waking from sleep. |
| Determinism | Responsiveness (performance) | Ensuring deterministic timing of actions may involve polling instead of responding to events as they happen. |

**Keep Record of Decisions**

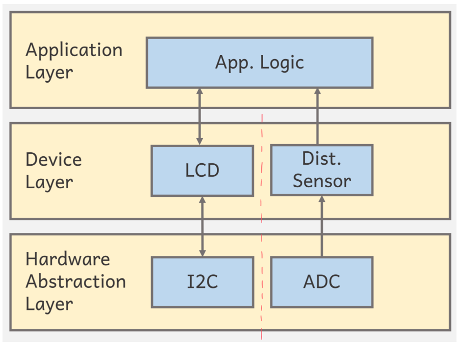
To keep record of decisions and to not loose the overview use tools like:

- *Architecture Haikus*: A onepager overview of your document see here or in the appendix folder.
- *Architecture Decision Records*: A incremental document to record decisions on the go either in a tool or a markdown file.

## Layered

Each layer is is providing services to the above layer through well-defined interfaces. Each layer can only interact with the layer directly above or below.

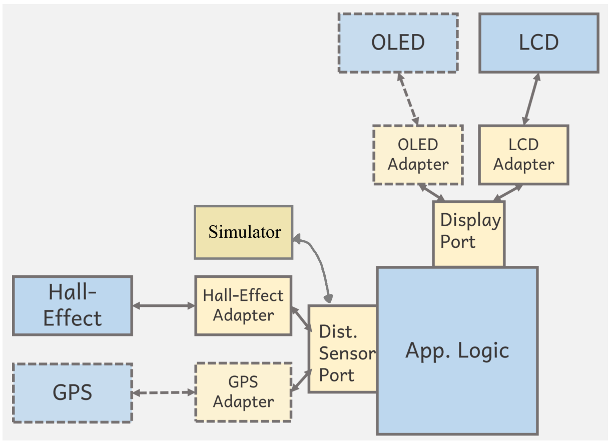
Supports portability and modifiability by allowing internal changes to be made inside a layer without impacting other layers, and isolating changes in layer-to-layer interfaces from more distant layers.



## Ports-and-Adapters (or *Hexagonal*)

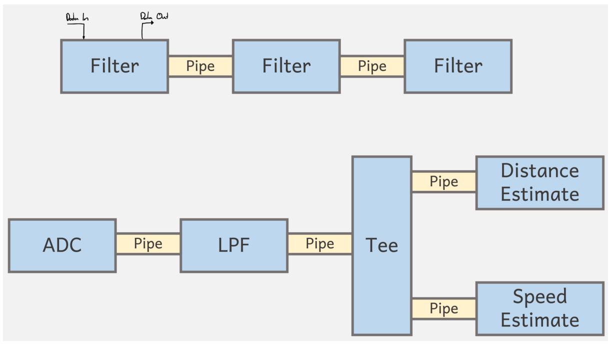
Introduces a single core logic which communicates through abstraction interfaces (**Ports**) to different modules. The **Adapters** map the external interactions to the standard interface of the port.

Supports portability and testability by making the inputs to the ports independent of any specific source, and supports modifiability by creating a loose coupling between components.



## Pipes-and-Filters

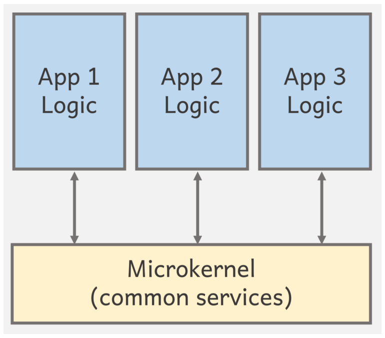
Supports modifiability through loose coupling between components, and performance by introducing opportunities for parallel execution.



## Microkernel

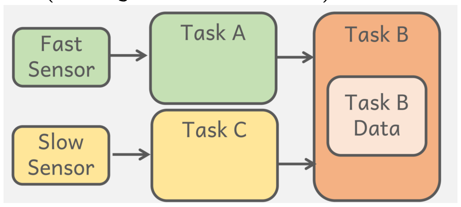
RTOS is a implementation of a Microkernel Architecture. The **Microkernel** includes a set of common core services. Specific services (**Tasks**) can be plugged into the kernel.

Supports modifiability and portability.



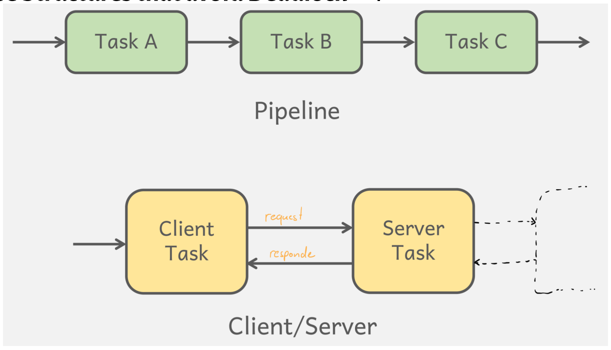
**Tasks for Priority and Modularity**

+ Control Priority
+ Control Response Time
+ Modularity
- Concurrency Issues
- Overhead (Scheduler)
- Starvation (Task gets no CPU time)



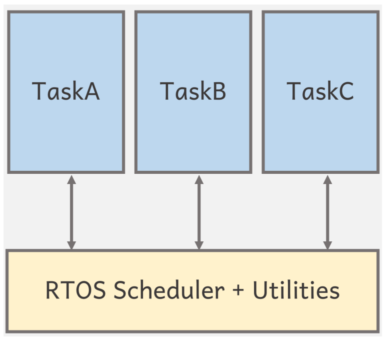
Use **just enough** tasks.

**Choose Structures that avoid Deadlock**

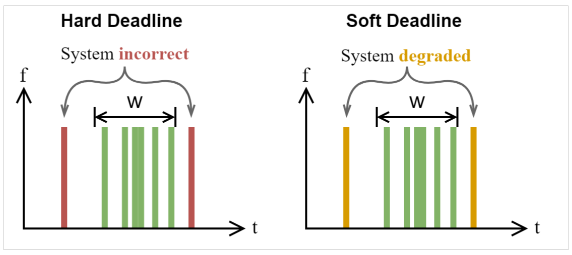


## RTOS

To improve **Performance** we introduce **Concurrency** (Run tasks in parallel).



Preemptive approach: *Separation* of concerns, *Scalability*, State is *Managed*.
Do the **right thing** at the **right time** *W*



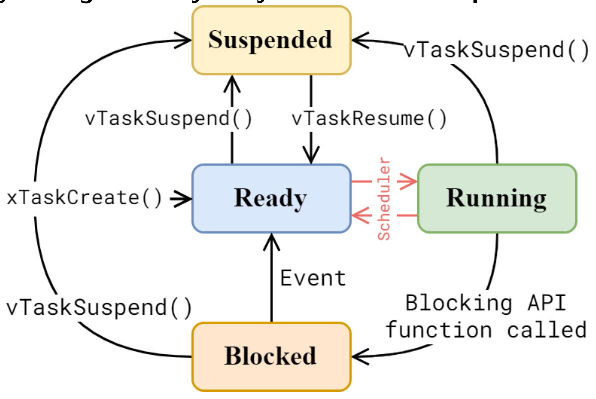
**RTOS vs. Desktop OS**

- Desktop OSs don't try to achieve *hard* real-time performance
- In a Desktop OS, programs can be loaded in runtime
- RTOS is compiled as part of the application, to add a new "program" the application has to be recompiled

## Tasks

```
xTaskCreate(
    BlinkTask,    // Function that defines task
    "Blink Task", // Task name (used in debugging)
    STACK_SIZE,   // No. of 4-byte words for stack
    NULL,        // Optional pointer to task argument
    PRIORITY,     // Higher number = higher priority
    NULL);        // Optional pointer to task handle
```

Taskswitches happen at *scheduling points* which occur when a **task is blocked**, **interrupt causes a task**, **priority change**, **higher priority task gets ready** or **system tick interrupt**.



**Stack Size**

**Stack Size Value**

The stack size value passed in `xTaskCreate` is measured in **4-Byte** words.
Set high margins, something like **300%**

- Minimal: `configMINIMAL_STACK_SIZE`
- Maximal: Device *RAM*
- Actually: Analyse
  - Dynamic: Set something and see if it works / use `uxTaskGetStackHighWaterMark` to measure
  - Static: Use tools (e.g. GCC `-fstack-usage`) to attempt reading on how much stack is needed per function

**Priority** Task priority has a strong influence on when a task is run and thus on the overall behaviours of the application.

**Assign priority based on importance**

1. Separate tasks into "critical" (hard deadline) and "non-critical" (soft deadline)
2. Assign low priority to non-critical tasks
3. To be sure about critical tasks meeting their deadlines, apply scheduling theory

**Assign non-critical tasks to low priorities**

1. Either apply the same priority for all non-critical tasks
2. Or prioritise by *importance*, which depends on
   a. Shortness of Deadline
   b. Frequency of Execution
   c. Need for Precessor time

**Assign critical tasks deadline monotonic priorities**

Apply priority based on the size of it's deadline.

1. Highest ← shortest deadline
2. Lowest ← longest deadline

**Deadline / Rate Monotonic Priorities**

Deadlines $D_i$ and Period $T_i$ for each task $i$
**Deadline Monotonic**: $D_i \leq T_i$
**Rate Monotonic**: $D_i = T_i$
Futhermore, following assumptions are made:

- Fixed-priority preemptive scheduling
- Hard-Deadline tasks are either:
  - *Periodic* (fixed interval)
  - *Sporadic* (known minimum time between triggering events)

**Check Schedulability of Critical Tasks** To check if deadlines can be met (schedulable) we calculate the **response time upper bound** $R_i^{ub}$ for each task $i$. This has to be less than the task deadline $D_i$

$$R_i^{ub} \leq D_i$$

The tasks are ordered after priority from $i = 1$ (highest priotity) and so on. Then Calculate the upper bound for every task through

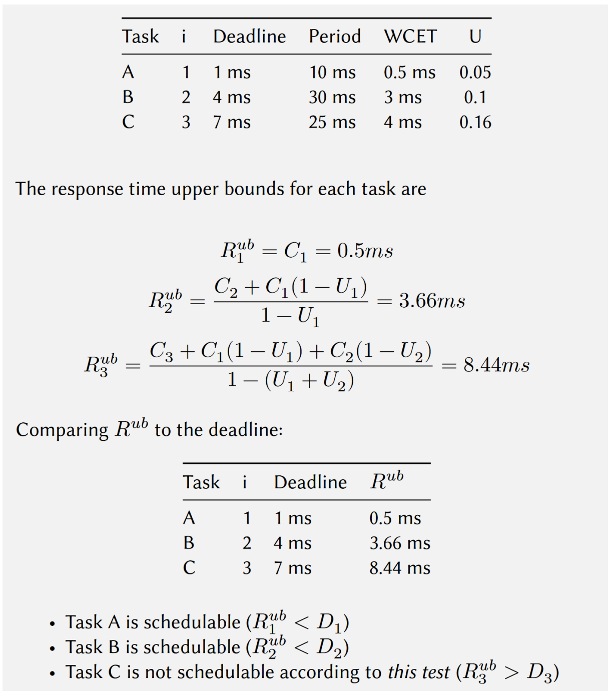
$$R_i^{ub} = \frac{C_i + \sum_{j=1}^{i-1} C_j(1 - U_j)}{1 - \sum_{j=1}^{i-1} U_j}$$

$C_i$ worst case execution time (WCET)
$U_i$ utilisation $U_i = \frac{C_i}{T_i}$
$T_i$ task period

Thus $R_1^{ub} = C_1$ ans each lower priority task has a response time that depends on the utilisation of the tasks above it.

**Response Time Upper Bound**

- If task $R_i^{ub} \leq D_i$ checks, task is practically schedulable
- If task fails test, there is still chance for it to work, as there've been many assumptions
- Response times tests don't account for task interactions and os overhead
- Tests depend on some kind of worst case execution time per task



| Task | i | Deadline | Period | WCET | U |
|---|---|---|---|---|---|
| A | 1 | 1 ms | 10 ms | 0.5 ms | 0.05 |
| B | 2 | 4 ms | 30 ms | 3 ms | 0.1 |
| C | 3 | 7 ms | 25 ms | 4 ms | 0.16 |

The response time upper bounds for each task are

$$R_1^{ub} = C_1 = 0.5ms$$
$$R_2^{ub} = \frac{C_2 + C_1(1 - U_1)}{1 - U_1} = 3.66ms$$
$$R_3^{ub} = \frac{C_3 + C_1(1 - U_1) + C_2(1 - U_2)}{1 - (U_1 + U_2)} = 8.44ms$$

Comparing $R^{ub}$ to the deadline:

| Task | i | Deadline | $R^{ub}$ |
|---|---|---|---|
| A | 1 | 1 ms | 0.5 ms |
| B | 2 | 4 ms | 3.66 ms |
| C | 3 | 7 ms | 8.44 ms |

- Task A is schedulable ($R_1^{ub} < D_1$)
- Task B is schedulable ($R_2^{ub} < D_2$)
- Task C is not schedulable according to *this test* ($R_3^{ub} > D_3$)

**Estimating WCET** To estimate **W**orst **C**ase **E**xecution **T**ime, there are two basic approaches

**Static Analysis** (Analysis of the source code)

- Relies on good processor model
- Good for simple code & MCU
- Difficult for complex code & MCU

**Dynamic analysis** (Measurement at runtime)

- Common in industry
- Must be able to exercise worst-case path
- Simple: Toggle GPIO

## Concurrency / Gleichzeitigkeit

Tasks "logically happen" at the same time, either physically (multicore) or through context switches (single-core). This should improve **Responsiveness**.

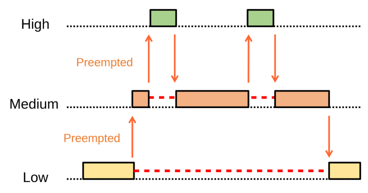


Figure 0.1: Tasks of different priority in a preemptive RTOS

- **Cooperative** multi-tasking: Tasks determine whether they give control back or not
- **Preemptive** multi-tasking: A scheduler takes control of what task gets how much time and also pulls tasks from executing

**Important Properties**

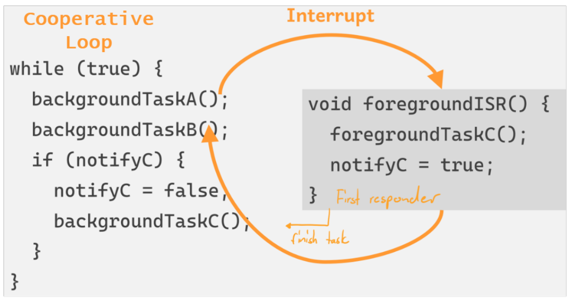
**Safety**: Nothing bad ever happens
**Liveness**: Something useful eventually happens
**Responsiveness**: Eventually is a reasonable amount of time

**Cooperative Round-Robin**

+ Simple
- No priorities
- Worst case response = sum of all task times
- Scheduling can be deterministic, but task periods must be harmonic

- Must manually manage state of long-running tasks
- Any change may alter response times

**Preemptive: Fore-/Background**



```
while (true) {
  backgroundTaskA();
  backgroundTaskB();
  if (notifyC) {
    notifyC = false;
    backgroundTaskC();
  }
}
```

```
void foregroundISR() {
  foregroundTaskC();
  notifyC = true;
}
```

+ Prioritise tasks
+ Separation of tasks and scheduling eases change
- Worst case response = interrupt time + longest task time
- Time-triggered scheduling deterministic, task harmonic

- Complex task handling / 3rd-party microkernel
- Race conditions for interrupts
- Manual managing of long-running tasks

**Preemptive: RTOS Impelementation** Each task is written as if it is a *single main loop*.

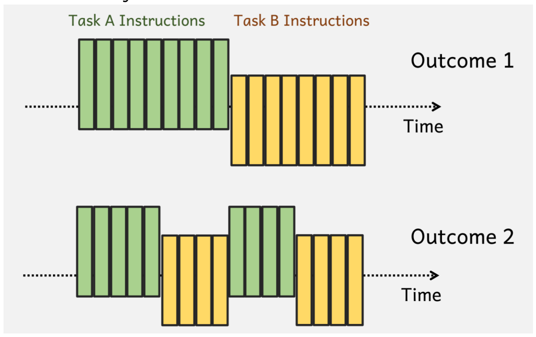
```
// Main Setup
#include <FreeRTOS.h>
#include <task.h>
void main() {
    xTaskCreate(BlinkTask, "BlinkA", STACK_SIZE, NULL,
↪   BLINK_PRIO, NULL);
    xTaskCreate(BlinkTask, "BlinkB", STACK_SIZE, NULL,
↪   BLINK_PRIO, NULL);
    vTaskStartScheduler();
}

// The Task
void BlinkTask(void* pvParameters) {
    while(true) {
        ledInvert();
        vTaskDelay(pdMS_TO_TICKS(500));
    }
}
```

+ Prioritise tasks and responses
+ Separation of tasks and scheduling eases change
+ Long-running tasks are scheduler managed
+ Scheduling is flexible
+ Usefull features (timing-services, protocol stacks, multi-processors,...)
- Worst-case response = interrupt time + scheduler context switch

- Depending on 3rd-party microkernel
- Must manage raceconditions on recourses
- OS overhead costs recources

**Concurrency Issues**

**Race Condition**: Outcome depends on timing → Occur when task modify **shared data**



**Containment**: Keep data within a task
**Immutability**: Use unchanging data
**Atomic Data**: Only share data which can be changed atomically
**Critical Section**: Section of code must execute *atomically* (in one run)
**Synchronisation**: Concurrency Control

**Mutex (Mutual Exclusion)** Only one task can take / lock the mutex at a time. Other task trying to acquire the mutex are blocked until the mutex is released. A mutex can only be **released** *by the task that* **acquired** *it.*
If two or more tasks **share a recource**, use a mutex for protection.

```
#include <semphr.h>
SemaphoreHandle_t mutex = xSemaphoreCreateMutex();
...
// in a task
for (int32_t i = 0; i < 1000000; i++) {
    xSemaphoreTake(mutex, portMAX_DELAY);
    counter = counter + 1;
    xSemaphoreGive(mutex);
}
```

**Encapsulate Synchronization**

- Avoid scattering mutexes around the code
- Prevent client tasks of accessing mutexes directly

- Ensure only a single mutex is hold at a time

```
// counter_manipultor.c
static SemaphoreHandle_t mutex;
static int32_t counter = 0;

void counterAdd(int32_t value) {
    xSemaphoreTake(mutex, portMAX_DELAY);
    counter = counter + value;
    xSemaphoreGive(mutex);
}
int32_t counterGetValue() {
    xSemaphoreTake(mutex, portMAX_DELAY);
    int32_t local = counter;
    xSemaphoreGive(mutex);
    return local;
}

// counter_task.c
void CounterTask(void* pvParameters) {
    for (int32_t i = 0; i < 100; i++) {
        counterAdd(1);
    }
    int32_t final = counterGetValue();
    printf“(%”d, final);
    vTaskSuspend(NULL);
}
```

**Semaphore** A semaphore can be **given** *by any task*. To receive and wait for a signal use `xSemaphoreTake(...)`.
If two or more tasks need to **coordinate actions**, use a semaphore to send signals.

```
SemaphoreHandle_t signal = xSemaphoreCreateBinary();
void TaskA(void* pvParameters) {
    for (;;) {
        printf("Ready!");
        xSemaphoreGive(signal);
        vTaskSuspend(NULL);
    }
}
void TaskB(void* pvParameters) {
    for (;;) {
        xSemaphoreTake(signal, portMAX_DELAY);
        printf("Go!");
        vTaskSuspend(NULL);
    }
}
```

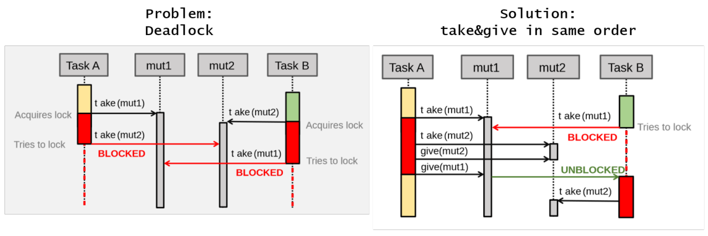
**Task Notification** Task notifications are FreeRTOS specific and offer a *light weight* alternative to a semaphore.

**Queues** Used to send data from one task to the other. Data is written to a queue **as copy**.

```
// create queue
#include <queue.h>
QueueHandle_t msgQueue = xQueueCreate(QUEUE_SIZE,
↪  sizeof(msg_t));

// send a message
xQueueSend(msgQueue, &toSend, 0);

// receive a message
xQueueReceive(msgQueue, &received, portMAX_DELAY);
```

`xQueueReceive(..., portMAX_DELAY)` is blocking until something is put into the queue. The time can be adjusted by the last argument, usually `portMAX_DELAY`, veeeeery long.

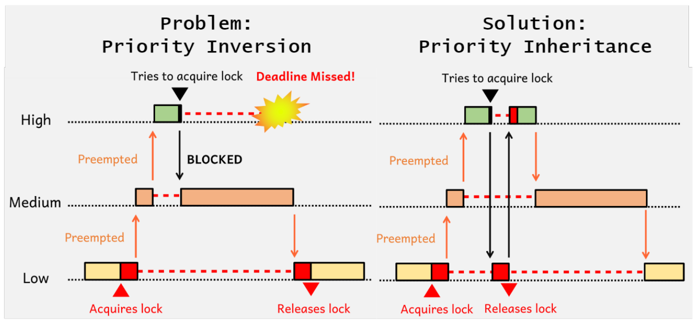
**Deadlock** .



We can also design tasks to only block in one place and thus deadlocks are less likely

```
void Task(void* pvParameters) {
    for (;;) {
        xQueueReceive(...); // single block
        switch (received.msgType) {
            case MSG_A: // Handle A events
            case MSG_B: // Handle B events
            case TIMER_1: // Handle timer
            case default: // Assert?
        }
    }
}
```

**Priority Inversion** .



## Resources

## Performance

## Testing

Testing is for *Finding Bugs*, *Reduce risk to user* **and** *business*, *reduce development costs*, *keep code clean*, *improve performance* and to *verify that* **requirements are met**. There are different test which can be performed:

- *Unit Testing*: Verify behaviour of individual units (modules)
- *Integration Testing*: Ensure that units work together as intended
- *System Testing*: Test **end-to-end** functionality of application
- *Acceptance Testing*: Verify that the requirements are met (whole system)
- *Performance Testing*: Evalutate performance metrics (e.g. execution time)
- *Smoke Testing*: Quick test to ensure major features are working

To make testing efficient, we implement automatic testing routines. They act as a **live** documentation. Allows for **refactoring with confidence**.

### Unit Test

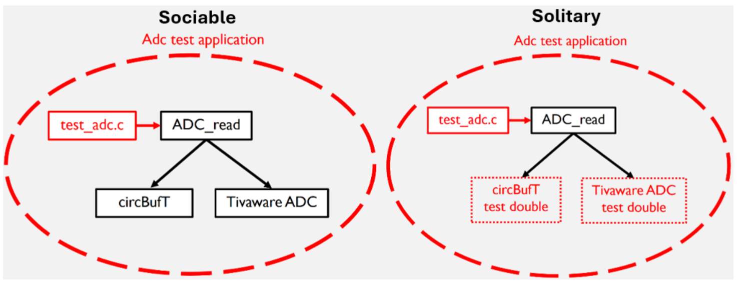
A good test case checks **one behaviour** under **one condition**, this makes it easier to localise errors.

```
void test_single_element_in_single_element_out(void)
↪ {
    // Arrange: given buffer has a single element
    writeCircBuf(&buff, 11);
    // Act: when buffer is read
    uint32_t value = readCircBuf(&buff);
    // Assert: then the same value is returned
    TEST_ASSERT_EQUAL(11, value);
}
```

Testing Frameworks

- Unit Test Framework Unity
- Test Double Framework fff

### Unit Test with Collaborators



### Test Doubles

Implement test doubles through the fake function framework (fff). There are different variations of test doubles:

**Stub**: Specify a return value - *Arrange*

```
// Set single return value
i2c_hal_register_fake.return_val = true;
// Set return sequence
uint32_t myReturnVals[3] = { 3, 7, 9 };
SET_RETURN_SEQ(readCircBuf, myReturnVals, 3);
```

**Spy**: Capture Parameters - *Arrange* / *Assert*

```
// Arrange, e.g. get passed function
adc_hal_register(ADC_ID_1, dummy_callback);
void (*isr) (void) = ADCIntRegister_fake.arg2_val;
// Assert Parameter
TEST_ASSERT_EQUAL(3,
↪   ADCSequenceDataGet_fake.arg1_val);
```

**Mock**: Can act as a *Stub*, *Spy*, and much more (from fff). Implemented as follows:

```
// in some_mock.h
VALUE_FUNC(uint32_t *, initCircBuf, circBuf_t *,
↪   uint32_t);
VOID_FUNC(writeCircBuf, circBuf_t *, uint32_t);
```

**Fake**: Provide a custom fake function - *Arrange*

```
// Define Fake Function
int32_t ADCSequenceDataGet_fake_adc_value(uint32_t
↪   arg0, uint32_t arg1, uint32_t *arg2) {
    *arg2 = FAKE_ADC_VALUE;
    return 0;
}
// Apply Fake Function - Arrange
ADCSequenceDataGet_fake.custom_fake =
↪   ADCSequenceDataGet_fake_adc_value;
```

### Continuous Integration

*CI* is used to automate the integration of code changes. These are automated scripts running all the tests. This is usually implemented in the code hoster (e.g. *GitLab*) and is executed after every push. It also runs before every merge and **blocks a merge** if one of the tests fails.