Embedded and Real-Time Systems course

Zephyr Project:
RT Services Introduction

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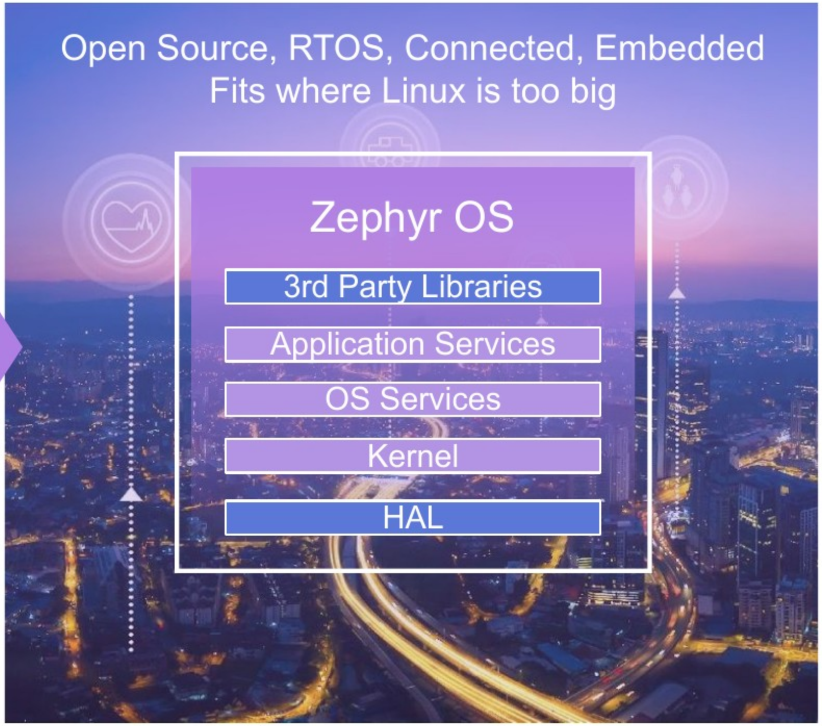
Vision

Quoted from the Linux Foundation documentation:

“The Zephyr Project strives to deliver the best-in-class RTOS for connected resource-constrained devices, built to be secure and safe.”

Zephyr Project Overview

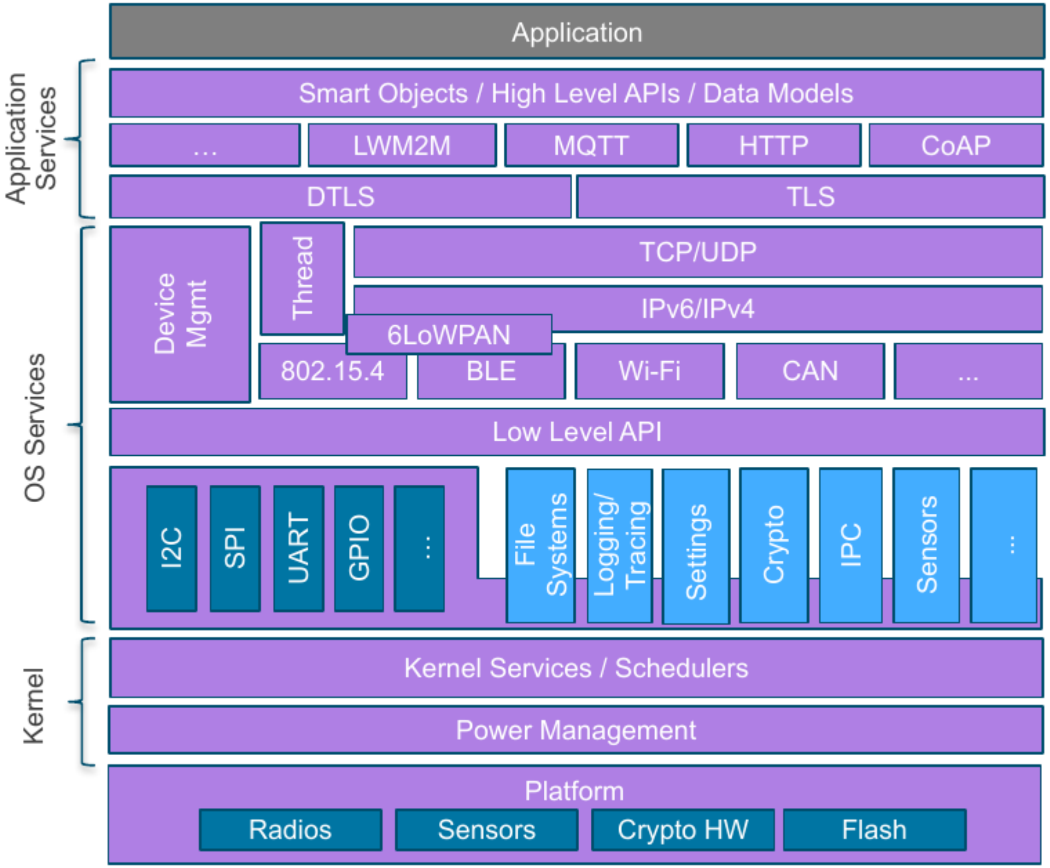
- **Open source real time operating system**
- Vibrant **Community** participation
- Built with **safety** and **security** in mind
- **Cross-architecture** with broad SoC and development board support.
- **Vendor Neutral governance**
- **Permissively licensed** - Apache 2.0
- **Complete, fully integrated, highly configurable and modular (for flexibility)**
- Product development ready using **LTS** includes **security updates**
- **Auditable codebase,** for certification



Architecture

Main characteristics

- Highly Configurable and Modular
- Cooperative and Preemptive Threading
- Memory and Resources are typically statically allocated
- Integrated device driver interface
- Memory Protection: Stack overflow protection, Kernel object and device driver permission tracking, Thread isolation
- Bluetooth® Low Energy (BLE 5.1) with both controller and host, BLE Mesh
- 802.15.4 OpenThread
- Native, fully featured and optimized networking stack



Some products using Zephyr


Grush Gaming Toothbrush

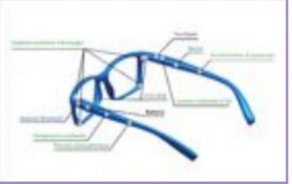

Proglove

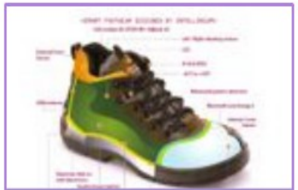

Rigado IoT Gateway


Adero Tracking Devices


Distancer


OB-4


Ellcie-Healthy Smart Connected Eyewear


Intellinium Safety Shoes


GNARBOX 2.0 SSD


HereO Core Box


Safety Pod


Oticon More


hereO Smartwatch


Point Home Alarm


RUUVI Node


Anicare Reindeer Tracker


Sentrius


See.Sense AIR

Zephyr vs other RTOS

- There are many other RTOS
- Selecting the "best one" depends on the criteria used (i.e. the user, the application, the context, ...).
- Among the most popular "competitors"
  - FreeRTOS (one of my favorites)
    - Provides essentially scheduling services and IPC
    - Much lower abstraction level regarding peripherals and comm stacks when compared with Zephyr
    - Backed by Amazon ...
  - Mbed OS
    - Also aims at IoT, complete ecosystem, etc.,
    - But it is owned by ARM and supports only ARM Cortex-M hardware
  - Azure RTOS (ThreadX)
    - Also aims at IoT, complete ecosystem, etc.,
    - But backed/controlled by Microsoft

Focusing on Kernel and scheduling

Kernel services for development:

- **Multi-threading Services** for cooperative, priority-based, non-preemptive, and preemptive threads with optional round robin time-slicing. Includes POSIX pthreads compatible API support.
- **Interrupt Services** for compile-time registration of interrupt handlers.
- **Memory Allocation Services** for dynamic allocation and freeing of fixed-size or variable-size memory blocks.
  - Note that for **Real-Time static memory allocation is preferred**
- **Inter-thread Synchronization Services** include binary semaphores, counting semaphores, and mutex semaphores.
- **Inter-thread Data Passing Services** include basic message queues, enhanced message queues, and byte streams.
- **Power Management Services** such as tickless idle and an advanced idling infrastructure.

Focusing on Kernel and scheduling

Zephyr provides a comprehensive set of thread scheduling choices:

- Cooperative and Preemptive Scheduling
- Earliest Deadline First (EDF)
- Meta IRQ scheduling implementing “interrupt bottom half” or “tasklet” behavior
- Timeslicing:
  - Enables time slicing between preemptible threads of equal priority
- Multiple ready-queue management strategies:
  - Simple linked-list ready queue: unsorted, small # of tasks
  - Red/black tree ready queue (self-balanced binary tree. Some memory and overhead. Use for 20+ tasks and scales well)
  - Traditional multi-queue ready queue (array of lists, one per priority)

Threads/Tasks

- **In Zephyr any number of threads can be defined by an application**
  - Limit is the available RAM.
  - Each thread is referenced by a thread id that is assigned when the thread is created
- **Main properties of a thread**
  - A (private) stack area. Size should be adapted according to the space required by thread local variables
  - A thread control block for private kernel bookkeeping of the thread's metadata (e.g. the current state)
  - An entry point (a C function), that corresponds to the work to be carried out
  - A scheduling priority
  - A set of thread options (depend on architecture, e.g. Floating Point Unit)
  - A start delay (how long the kernel should wait before starting the thread)
  - Execution mode (supervisor or user mode).
    - By default threads run in supervisor mode (access to privileged CPU instructions, the entire memory address space, and peripherals). User mode threads have a reduced set of privileges.
      Support to User Mode threads is optional (CONFIG_USERSPACE)

Threads/Tasks

- **Thread lifecycle and states**
  - A thread must be created before use
  - Threads typically execute forever, but they can also be terminated
    - A thread terminates if it returns form its C function
    - In such case it must release any shared resources owned (e.g. mutexes, dynamically allocated memory), as the the kernel does not reclaim them automatically.
    - A thread can be aborted if triggers a fatal condition (e.g. dereferencing a null pointer) or by an explicit call to k_thread_abort() (by itself or other thread)

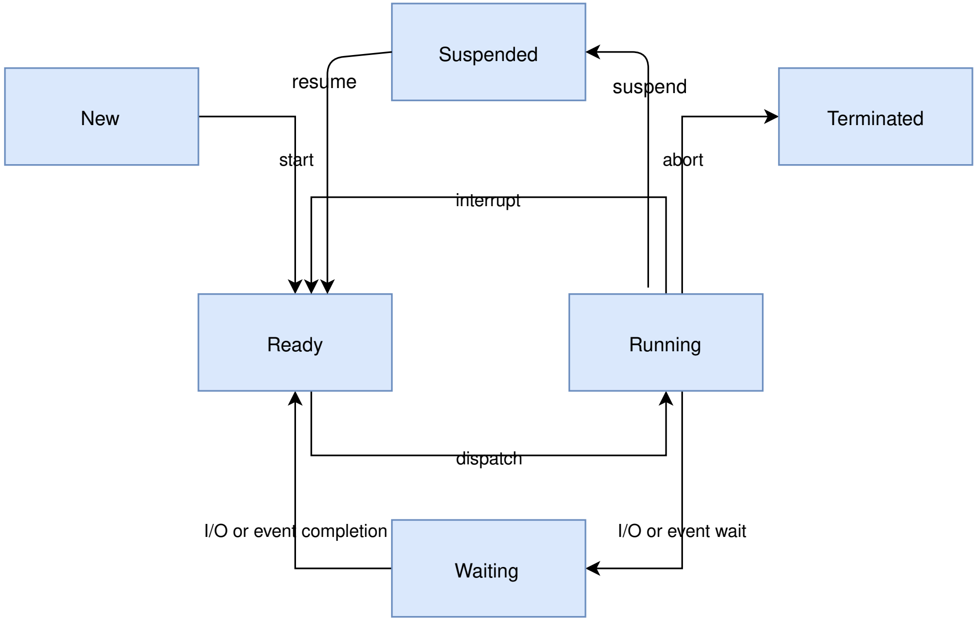


Image from: https://developer.nordicsemi.com/nRF_Connect_SDK/doc/latest/zephyr/reference/kernel/threads/index.html

Threads/Tasks

- **Thread lifecycle and states**
  - A task is **Ready** if it is eligible for execution
    - The scheduler decides which ready tasks are granted with the CPU
    - Preemption can occur
  - A **Suspended** task is prevented from executing for an indefinite time.
    - Calls to k_thread_suspend() and k_thread_resume() mange the Suspended state
  - A task is on the **Waiting** state if is waiting for event, e.g. a semaphore that is unavailable or a timeout to occur

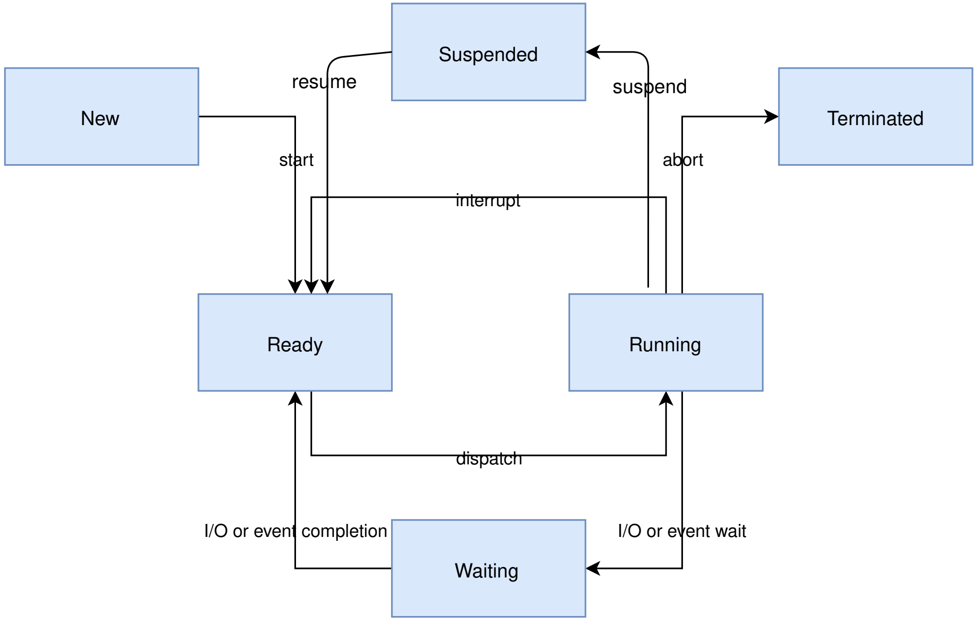


Image from:
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Threads/Tasks

Thread Stack objects

- Each thread requires its own stack buffer for the CPU to push context. Depending on configuration, there are several constraints that must be met:
  - Additional memory may be reserved for memory management structures
  - If guard-based stack overflow detection is enabled, a small write-protected memory management region must immediately precede the stack buffer to catch overflows.
  - If userspace is enabled, a separate fixed-size privilege elevation stack must be reserved to serve as a private kernel stack for handling system calls.
  - If userspace is enabled, the thread’s stack buffer must be appropriately sized and aligned such that a memory protection region may be programmed to exactly fit.
- Moreover alignment constraints can be quite restrictive, for example some MPUs require their regions to be of a power of two in size and word-aligned.
- Because of this, **portable code can’t simply pass an arbitrary character buffer to k_thread_create()**. Special macros exist to instantiate stacks, prefixed with K_KERNEL_STACK and K_THREAD_STACK.

Threads/Tasks

Thread Stack objects

- **Kernel-only Stacks**
  - If it is known that a thread will never run in user mode, or the stack is being used for special contexts like handling interrupts, it should be defined via K_KERNEL_STACK macros
  - These stacks minimize memory use (e.g. the kernel doesn’t need need to reserve additional room for the privilege elevation stack)
  - Attempts from user mode to use stacks declared in this way will result in a fatal error for the caller.
- **Thread stacks**
  - If it is known that a stack will need to host user threads, or if this cannot be determined, define the stack with K_THREAD_STACK macros. This may use more memory but the stack object is suitable for hosting user threads.

If CONFIG_USERSPACE is not enabled, K_THREAD_STACK and K_KERNEL_STACK macros become equivalent.

Threads/Tasks

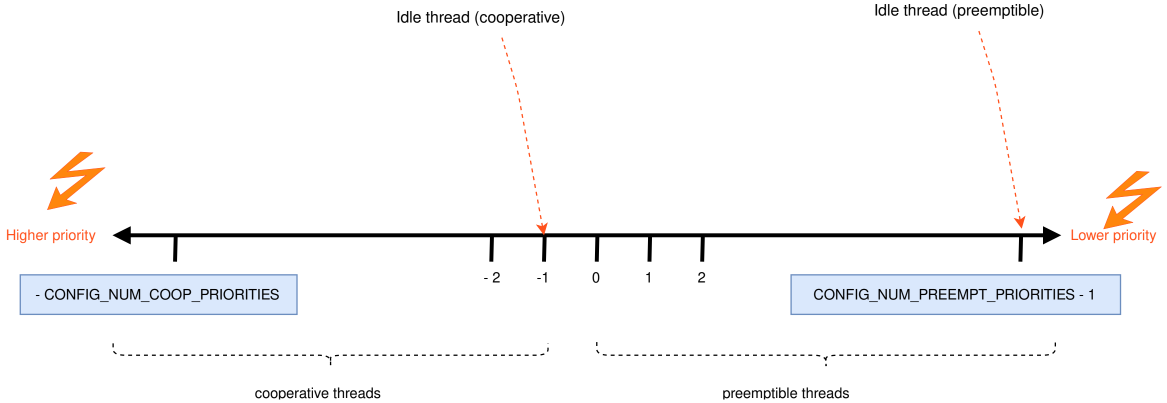
Thread Priorities

- Thread **priority** is an **integer value** (negative or non-negative).
  - Lower priority numbers correspond to higher priority levels
- The scheduler allows **two classes of threads**, based on priority:
  - A **cooperative** thread has a **negative priority value**.
    - Once it becomes the current thread, a cooperative thread remains the current thread until it performs an action that makes it not ready (Suspended or Waiting).
    - **Not well suited for real-time**
  - A **preemptible** thread has a **non-negative priority value**.
    - Once it becomes the current thread, a preemptible thread may be preempted at any time if a cooperative thread, or a preemptible thread of higher or equal priority, becomes ready.
- A thread’s initial priority value can be altered dynamically. In particular, a preemptible thread may become a cooperative thread, and vice versa, by changing its priority.

Threads/Tasks

Thread Priorities

- The kernel supports a virtually unlimited number of thread priority levels.
- The configuration options **CONFIG_NUM_COOP_PRIORITIES** and **CONFIG_NUM_PREEMPT_PRIORITIES** specify the number of priority levels for each class, resulting in the following usable priority ranges:
  - Cooperative threads: (-CONFIG_NUM_COOP_PRIORITIES) to -1
  - Preemptive threads: 0 to (CONFIG_NUM_PREEMPT_PRIORITIES - 1)



Threads/Tasks

Implementing tasks/threads

```
#define TASK1_STACK_SIZE 500
#define TASK1_PRIORITY 5
...
void Task1_Code(void *arg1, void *arg2, void *arg3)
{
     /* Task code here */
}
...

K_THREAD_STACK_DEFINE(Task1_stack_area, TASK1_STACK_SIZE);
struct k_thread Task1_thread_data;
k_tid_t Task1_tid;
...

Task1_tid = k_thread_create(&Task1_thread_data, Task1_stack_area,
                          K_THREAD_STACK_SIZEOF(Task1_stack_area),
                          Task1_Code,         /* Pointer to code, i.e. the function name */
                          NULL, NULL, NULL,   /* Three optional arguments */
                          Task1_PRIORITY,
                          0,                  /* Thread options. Arch dependent */
                          K_NO_WAIT);         /* or delay in milliseconds */
```

Threads/Tasks

Implementing tasks/threads

- **Typical structure of a task/thread**

```
void Task1_Code(void *arg1, void *arg2, void *arg3)
{
      /* Initializations (executed only once) */
      ...

      /* Task body – usually never ends */
      while (1) {
            ...
            Do Computations();
            ...
            Some form of Suspend or Wait(); /* Tasks usually don’t run all the time */

      }

     /* Thread terminates if execution reaches this point */
}
```

Threads/Tasks

Implementing tasks/threads

- **Periodic tasks** are common in RT systems
- Simple (but poor, why?) method:

```
void Task1_Code(void *arg1, void *arg2, void *arg3)
{
      /* Initializations (executed only once) */
      ...

      /* Task body – usually never ends */
      while (1) {
            ...
            Do Computations();
            ...
            k_msleep(TASK1_PERIOD);
      }

    /* Thread terminates if execution reaches this point */
}
```

Threads/Tasks

Implementing tasks/threads

- **Sporadic tasks** are also common in RT systems
  - Usually there is a primitive that puts the thread in Waiting/Suspend state

```
void Task1_Code(void *arg1, void *arg2, void *arg3)
{
      /* Initializations (executed only once) */
      ...

      /* Task body – usually never ends */
      while (1) {
            ...
            Do Computations();
            ...
            Blocking call to a semaphore/mutex/event/condition_variable/...
      }

    /* Thread terminates if execution reaches this point */
}
```

Threads/Tasks

Thread runtime statistics

- Runtime statistics can be gathered and retrieved if CONFIG_THREAD_RUNTIME_STATS is enabled
- Example of statistics is the total number of execution cycles of a thread.
- By default runtime statistics are gathered using the default kernel timer. Some platforms have higher resolution timers. The use of these timers can be enabled via CONFIG_THREAD_RUNTIME_STATS_USE_TIMING_FUNCTIONS.
- Example:

```
k_thread_runtime_stats_t rt_stats_thread;

...

k_thread_runtime_stats_get(k_current_get(), &rt_stats_thread);

printk("Cycles: %llu\n", rt_stats_thread.execution_cycles);

...
```

Bibliography

- Kate Stewart, “Zephyr Project: Unlocking Innovation with an Open Source RTOS”, The Linux Foundation, 2022.
- Nordic documentation for kernel services
  - https://developer.nordicsemi.com/nRF_Connect_SDK/doc/latest/zephyr/kernel/index.html#kernel
  - https://developer.nordicsemi.com/nRF_Connect_SDK/doc/latest/zephyr/kernel/services/scheduling/index.html
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