Threads Overview

✅ Thread 1: Sleeping & Suspended

- **Function**: thread1_fn
- **Behavior**:
  - Sleeps for 2 seconds repeatedly using k_sleep(), which puts it in the **sleeping state**.
  - Can be **suspended** by Thread 3 using k_thread_suspend(), which halts its execution regardless of its sleep state.
  - Later **resumed** by Thread 3 using k_thread_resume().

✅ Thread 2: Pending

- **Function**: thread2_fn
- **Behavior**:
  - Waits indefinitely on a semaphore using k_sem_take(&sync_sem, K_FOREVER).
  - This puts it in the **pending state** until another thread gives the semaphore.
  - Once the semaphore is given by Thread 3, it prints a message and loops back to wait again.

✅ Thread 3: Running & Controller

- **Function**: thread3_fn
- **Behavior**:
  - Runs continuously and **controls the other two threads**.
  - Suspends Thread 1, waits 3 seconds, then resumes it.
  - Gives the semaphore to Thread 2 to unblock it.
  - Sleeps for 5 seconds before repeating.
- This thread is always **running** when active and demonstrates how a thread can manage others.

🧠 Thread Priorities

- **Thread 1**: Priority 1 (highest)
- **Thread 3**: Priority 4
- **Thread 2**: Priority 5 (lowest)

In Zephyr, **lower numbers mean higher priority**. So Thread 1 will preempt others unless it's sleeping or suspended.

🔄 Execution Flow Summary

1. **Startup**:
   - All three threads are created and start running.
2. **Thread 1**:
   - Sleeps for 2 seconds → enters **sleeping state**.
   - May be **suspended** by Thread 3 during this time.
3. **Thread 2**:
   - Waits on a semaphore → enters **pending state**.
   - Remains blocked until Thread 3 gives the semaphore.

4. **Thread 3**:
    - Suspends Thread 1 → Thread 1 enters **suspended state**.
    - Sleeps for 3 seconds.
    - Resumes Thread 1 → Thread 1 can now run again.
    - Gives semaphore to Thread 2 → Thread 2 wakes up.
    - Sleeps for 5 seconds and repeats the cycle.

📊 Thread States Demonstrated

Thread	State(s) Demonstrated	How?
Thread 1	Sleeping, Suspended	k_sleep(), k_thread_suspend()
Thread 2	Pending	k_sem_take()
Thread 3	Running	Actively controls other threads

Here's a detailed breakdown of the core concepts from the Zephyr Project documentation on **Threads and Thread Services**, based on the official page:
🔗 Zephyr Thread Services Documentation

🧵 Core Concepts of Threads in Zephyr

✅ 1. Thread Basics

- **Thread**: The smallest unit of execution in Zephyr.
- Each thread has:
    - Its own **stack**
    - A **priority**
    - A **state** (e.g., ready, running, suspended)
- Threads are scheduled by the **Zephyr kernel** based on priority and system configuration.

✅ 2. Thread Lifecycle

- **Creation**: Threads can be created statically at compile time or dynamically at runtime.
- **States**:
    - READY: Eligible to run
    - RUNNING: Currently executing
    - PENDING: Waiting for an event/resource
    - SUSPENDED: Not eligible to run
    - DEAD: Terminated

✅ 3. Thread Priorities

- Zephyr uses **cooperative** and **preemptive** scheduling.
- Priority range:

    - Lower numerical value = higher priority
    - CONFIG_NUM_COOP_PRIORITIES and CONFIG_NUM_PREEMPT_PRIORITIES control the range
- Cooperative threads must yield explicitly.

✅ 4. Thread Creation APIs

- **Static creation**: Using K_THREAD_DEFINE()
- **Dynamic creation**: Using k_thread_create()
- Parameters include:
    - Stack size
    - Priority
    - Entry function
    - Arguments
    - Options (e.g., start immediately or not)

✅ 5. Thread Control APIs

- k_thread_suspend(): Suspend a thread
- k_thread_resume(): Resume a suspended thread
- k_thread_abort(): Terminate a thread
- k_thread_yield(): Yield CPU voluntarily
- k_sleep(): Put thread to sleep for a duration

✅ 6. Thread Stack

- Each thread requires a **dedicated stack**.
- Stack size must be carefully chosen to avoid overflow.
- Zephyr provides tools like CONFIG_THREAD_STACK_INFO to monitor stack usage.

✅ 7. Thread Entry Function

- The function that a thread runs when it starts.
- Signature: void thread_entry(void *p1, void *p2, void *p3)
- Accepts up to 3 arguments.

✅ 8. Thread Options

- Flags passed during thread creation:
    - K_ESSENTIAL: Marks thread as essential (kernel panic if it exits)
    - K_FP_REGS: Enables floating-point context saving
    - K_USER: Marks thread as user mode

✅ 9. Thread Sleeping and Delays

- k_sleep(K_MSEC(ms)): Sleep for milliseconds
- k_msleep(ms): Alias for k_sleep()
- k_busy_wait(us): Busy-wait for microseconds (CPU-consuming)

✅ 10. Thread Monitoring

- Zephyr supports **thread monitoring**via:
    - k_thread_name_set() and k_thread_name_get()
    - k_thread_stack_space_get(): Check remaining stack
    - k_thread_state_str(): Get human-readable state

✅ 11. Thread Local Storage (TLS)

- Zephyr supports **TLS** for storing data unique to each thread.
- Useful for reentrant code and thread-specific configurations.

✅ 12. Thread Safety

- Use **mutexes**, **semaphores**, and **message queues** to protect shared resources.
- Avoid race conditions and deadlocks by careful design.

Would you like a visual diagram or code examples for any of these concepts (e.g., thread creation, suspension, or stack monitoring)?

Here's a crisp, bullet-point summary of Zephyr's Kernel Thread Services, highlighting all important points:

- **Core Concept: Threads**
  - Fundamental unit of execution, enabling **concurrency**.
  - Independent path of execution with its own **stack** and **CPU context**.
  - Managed by the Zephyr **RTOS kernel**.
  - Ideal for complex, blocking, or extensive processing unsuitable for ISRs.
  -
- **Thread Properties:**
  - **Unique ID:** k_tid_t.
  - **Dedicated Stack:** Configurable size, for local data and context.
  - **Thread Control Block (TCB):** Kernel metadata.
  - **Entry Point Function:** Where thread execution begins, accepts 3 arguments.
  - **Priority:** Controls scheduling (-ve for cooperative, 0+ve for preemptive).
  - **Options:** Flags for special kernel treatment.
  - **Start Delay:** Optional initial delay before execution.
  -
- **Thread Modes:**
  - **Supervisor Mode:** Full privileges, full memory access (kernel, drivers).
  - **User Mode:** Reduced privileges, limited memory access (requires CONFIG_USERSPACE). Enhances security/stability.
  -
- **Thread Lifecycle:**
  - **Created:** Initialized via **k_thread_create(**) or macros.
  - **States:** Ready, Running, Suspended, Waiting/Blocked, Stopped, Dead.
  - **Termination:**
    - **Synchronous:** Returns from entry function (preferred).
    - **Asynchronous (Abort):** k_thread_abort() or kernel on fatal error.
  - **Suspension:** k_thread_suspend() (indefinite pause), resumed by k_thread_resume().
  -
- **Thread Stack Management:**
  - Each thread needs its own stack buffer.
  - **Stack Overflow Detection:** Available (if configured) via guard-based mechanisms.
  - **Static Definition:**

    - K_KERNEL_STACK_DEFINE: For kernel-only threads (memory efficient).
    - K_THREAD_STACK_DEFINE: For both kernel and user threads.
  - **Dynamic Allocation:** k_thread_stack_alloc(), k_thread_stack_free().
  -
- **Thread Priorities & Preemption:**
  - **Priority:** Lower numerical value = Higher precedence (e.g., 0 > 1).
  - **Cooperative Threads (-ve priorities):**
    - Run until they **yield (k_yield())** or **block**.
    - **NOT preempted** by higher-priority preemptive threads.
  - **Preemptive Threads (0+ve priorities):**
    - Can be **preempted** by any higher-priority ready thread.
  - **Configurable Levels:** Number of cooperative (CONFIG_NUM_COOP_PRIORITIES) and preemptive (CONFIG_NUM_PREEMPT_PRIORITIES) levels can be set.
  - **Meta-IRQ Threads:** Highest cooperative priorities, can preempt all others (used for interrupt bottom-halves).
- **Thread Options (Examples):**
  - K_ESSENTIAL: Thread termination is a fatal system error.
  - K_FP_REGS/K_SSE_REGS: Enable saving/restoring floating-point/SSE registers.
  - K_USER: Creates thread in user mode (requires CONFIG_USERSPACE).
- **Thread Custom Data:**
  - CONFIG_THREAD_CUSTOM_DATA: Enables a 32-bit private data area per thread.
  - Accessible only by the thread itself.
- **Thread Spawning & APIs:**
  - **Creation:** Define stack/TCB, then k_thread_create().
  - **Convenience Macro:** K_THREAD_DEFINE for compile-time declaration.
  - **User Mode Thread Creation:** Requires specific permissions and K_USER option for child thread.
  - **Runtime Statistics:** CONFIG_THREAD_RUNTIME_STATS for performance analysis.

Here's a **detailed explanation** of the k_thread_create() function in Zephyr RTOS, including **all parameters and options**:

🔧 Function Signature

```
struct k_thread *k_thread_create(
  struct k_thread *new_thread,
  k_thread_stack_t *stack,
  size_t stack_size,
  k_thread_entry_t entry,
  void *p1, void *p2, void *p3,
  int prio,
  uint32_t options,
```

k_timeout_t delay

);

📌 Parameter Breakdown

1. **new_thread**

- Type: struct k_thread *
- Description: Pointer to a k_thread structure that Zephyr will initialize to represent the new thread.
- You must allocate this structure (usually statically or globally).

2. **stack**

- Type: k_thread_stack_t *
- Description: Pointer to the memory region used as the thread's stack.
- Must be defined using K_THREAD_STACK_DEFINE() or K_THREAD_STACK_ARRAY_DEFINE().

3. **stack_size**

- Type: size_t
- Description: Size of the stack in bytes.
- Must match the size used in K_THREAD_STACK_DEFINE().

4. **entry**

- Type: k_thread_entry_t
- Description: Function pointer to the thread's entry function.
- Signature of the function:
- void thread_entry(void *p1, void *p2, void *p3);

5. **p1, p2, p3**

- Type: void *
- Description: Up to three arguments passed to the thread entry function.
- Can be used to pass context or configuration data.

6. **prio**

- Type: int
- Description: Thread priority.
  - Lower number = higher priority.
  - Use CONFIG_NUM_COOP_PRIORITIES and CONFIG_NUM_PREEMPT_PRIORITIES to configure.
  - Negative values are for **cooperative** threads.
  - Zero and above are for **preemptive** threads.

7. **options**

- Type: uint32_t
- Description: Bitmask of thread options. Common flags include:

Option	Description
K_ESSENTIAL	Marks thread as essential (kernel panic if it exits)
K_FP_REGS	Enables saving of floating-point registers
K_USER	Starts thread in user mode (if user mode is enabled)
K_INHERIT_PERMS	Inherit permissions from parent thread (used with memory domains)

8. **delay**

- Type: k_timeout_t
- Description: Delay before the thread is scheduled to run.
- Use macros like:
  - K_NO_WAIT: Start immediately
  - K_MSEC(ms), K_SECONDS(s): Delay for specified time

✅ Return Value

- Returns a pointer to the initialized **k_thread** structure.

🧪 Example Usage

```
K_THREAD_STACK_DEFINE(my_stack_area, 1024);

struct k_thread my_thread_data;



void my_thread(void *p1, void *p2, void *p3) {

    // Thread logic here

}



k_thread_create(&my_thread_data, my_stack_area, 1024,       my_thread, NULL, NULL, NULL,

              5, K_ESSENTIAL, K_NO_WAIT);
```

Would you like a **visual diagram** or **code walkthrough** for a real use case on QEMU or a specific board?

Core Concepts of Zephyr RTOS

Zephyr is a **lightweight, scalable, real-time operating system (RTOS)** designed for embedded systems. It supports multiple architectures and is highly modular, allowing developers to include only the components they need.

1. Kernel Architecture

- **Small-footprint kernel**: Designed for resource-constrained devices.
- **Supports multiple CPU architectures**: ARM, x86, RISC-V, ARC, MIPS, and more
-

2. Threading Model

Zephyr supports:

- **Cooperative threads**: Run until they yield or block.
- **Preemptive threads**: Can be interrupted by higher-priority threads.
- **Round-robin scheduling**: Among threads of equal priority.
- **POSIX pthreads API**: Optional compatibility layer.

3. Scheduling Algorithms

- **Cooperative and Preemptive Scheduling**
- **Earliest Deadline First (EDF)**
- **Meta IRQ scheduling**: For deferred interrupt handling.
- **Timeslicing**: Among equal-priority preemptible threads.

4. Memory Management

- **Heap and slab allocators**
- **Thread stacks**: Configurable per thread.
- **Custom memory regions**: For advanced use cases.

5. Inter-thread Communication

- **Semaphores**: Binary and counting.
- **Mutexes**: For mutual exclusion.
- **Message Queues and Pipes**: For data passing.

6. Power Management

- **System Power Management**: Application-defined policies.
- **Device Power Management**: Driver-level control.

7. Modularity

- Zephyr is **highly configurable** via Kconfig and device tree.
- Developers can enable/disable features to optimize footprint.

🧵 System Threads in Zephyr

System threads are **automatically spawned by the kernel** during system initialization. They are essential for basic OS operation.

Types of System Threads

1. Main Thread

- **Purpose**: Executes kernel initialization and then calls the user-defined main() function.
- **Priority**:
  - Highest preemptible priority (0) if preemption is enabled.
  - Lowest cooperative priority (-1) if not.
- **Behavior**:
  - If main() is defined and returns normally, the thread terminates without error.
  - If main() is missing or the thread aborts, a **fatal error** is raised.

2. Idle Thread

- **Purpose**: Runs when no other thread is ready.
- **Behavior**:
  - May invoke power-saving routines.
  - Otherwise, runs a “do-nothing” loop.
- **Priority**: Always the **lowest**.
- **Essential**: Cannot terminate; if it aborts, a fatal error occurs.

3. Workqueue Threads

- Spawned if the **system workqueue** is enabled.
- Handle deferred work items submitted by the application.

Writing a main() Function

Example:

Great question! Let's walk through the **flow of a Zephyr application** when running on the **QEMU x86** target, using your example build command:

west build -b qemu_x86 .

This command builds your Zephyr app for the qemu_x86 board. Here's a breakdown of what happens **from build to runtime**, and how the **Zephyr app flow** works:

🛠️ Build-Time Flow

1. **CMake Configuration**:
   - Zephyr uses **CMake** to configure the build system.
   - It identifies the board (qemu_x86), toolchain, and application source directory.
   - It loads the **Zephyr base modules**, board-specific files (qemu_x86.dts), and your app's CMakeLists.txt.
2. **Device Tree Processing**:
   - The board's .dts file is parsed to generate zephyr.dts and devicetree_generated.h.
   - This defines hardware configuration (e.g., memory, peripherals) for the virtual QEMU board.
3. **Kconfig Processing**:
   - Zephyr uses **Kconfig** to configure kernel features, drivers, and app-specific options.
   - This generates autoconf.h with all enabled features.
4. **Code Compilation**:
   - Your app code (e.g., main.c) and Zephyr kernel code are compiled.
   - The final ELF binary is linked with the Zephyr kernel and libraries.

🚀 Runtime Flow on QEMU x86

Once you run the app using:

west build -t run or **west build -t run -- -v**

Here's what happens:

1. **QEMU Emulation Starts**:
   - QEMU emulates an x86 CPU and memory.
   - It loads the Zephyr ELF binary into virtual memory and starts execution at the reset vector.
2. **Zephyr Boot Sequence**:
   - **Reset Handler**: Initializes CPU state and jumps to **z_cstart()**.
   - **Early Init**: Sets up memory, stacks, and clears BSS.
   - **Device Initialization**: Initializes devices in stages (PRE_KERNEL_1, PRE_KERNEL_2, POST_KERNEL).
   - **Scheduler Start**: Initializes the kernel scheduler and starts the main thread.
3. **Application Entry Point**:
   - Your app's main() function (or main_thread() if using CONFIG_MAIN_THREAD) is called.
   - From here, your logic runs—creating threads, using IPC (queues, mailboxes), etc.
4. **Thread Scheduling**:
   - Zephyr's **preemptive scheduler** manages thread execution based on priorities and states.
   - If you use k_thread_create(), k_msgq_put(), etc., the kernel handles context switching and IPC.

🧠 Example: What Happens in Your App

If your app has:

```
void main(void) {
    printk("Hello from main thread\n");

    k_thread_create(...); // create a system thread

}
```

Then the flow is:

- main() runs in the **main thread**.
- It prints to the console.
- It creates a new thread, which is scheduled and runs concurrently or after main() depending on priorities.

Would you like me to walk through a specific example from your app (e.g., using k_msgq, k_mbox, or k_thread_create) and show how the flow works in that case? You can also share your main.c or prj.conf if you'd like a more tailored explanation.

SYS_INIT(start_user_thread, POST_KERNEL, CONFIG_KERNEL_INIT_PRIORITY_DEFAULT);

This is a **macro** provided by Zephyr to register a function (start_user_thread) to be called during the system initialization phase. Here's what each part means:

🔍 Breakdown of SYS_INIT

✅ **start_user_thread**

This is the **function** that will be executed during system boot. It must match the signature:

```
int (*init_fn)(const struct device *dev)
```

Even if you don't use the dev parameter, it must be present.

✅ POST_KERNEL

This is the **initialization level**. Zephyr has several init levels:

Init Level	Description
PRE_KERNEL_1	Before kernel services are available (e.g., early hardware init)
PRE_KERNEL_2	After basic hardware init, still before kernel
POST_KERNEL	After kernel is initialized, before application starts
APPLICATION	After everything else, for app-level init

So POST_KERNEL means your function runs **after the kernel is ready**, but **before any threads (like main()) start**.

✅ CONFIG_KERNEL_INIT_PRIORITY_DEFAULT

This sets the **priority** of your init function **within the POST_KERNEL level**. Lower numbers run earlier. You can define your own priority or use Zephyr's default.

🧠 Why Use SYS_INIT?

- To **run code before main()** (or instead of main() if disabled).
- To **initialize threads, devices, or IPC** early.
- To **avoid using main()** when you want full control over thread startup.

🧪 Example Flow

With this macro, Zephyr will:

1. Boot and initialize hardware.
2. Initialize the kernel.
3. Call start_user_thread() during POST_KERNEL.
4. Your user thread starts running.
5. main() is skipped if CONFIG_MAIN_STACK_SIZE=0.

Would you like a visual diagram of the Zephyr boot/init sequence showing where SYS_INIT fits in?

==

Operation without Threads

Here are the important points from the selected text about Zephyr's 'Nothread' configuration, presented in bullet points:

- **Core Concept:** The "nothread" mode in Zephyr is enabled by setting CONFIG_MULTITHREADING = n, disabling full multithreading support.
- **Purpose:** It transforms Zephyr into a highly optimized, bare-metal-like framework for extremely resource-constrained devices, simple single-flow applications, and developers preferring bare-metal development.
- **Execution Model:**
  - **Single Execution Flow:** Applications run in a continuous "main loop" or "idle loop" without user-defined threads.
  - **No Preemption:** Code executes sequentially; no thread preemption occurs.
  - **No Kernel Objects:** Most kernel objects for inter-thread communication (semaphores, mutexes, queues) are unavailable or non-functional.
  - **Interrupt-Driven:** External events are primarily handled by Interrupt Service Routines (ISRs).
  - **Limited Context:** Operates with minimal CPU context, no separate thread stack management overhead.
- **Retained Functionalities:** Despite no multithreading, Zephyr still provides:
  - **Interrupt Management:** Robust interrupt handling framework.
  - **System Clock and Timers:** k_timer and time-based operations.
  - **Memory Management:** Basic allocation and protection services.
  - **Device Driver Support:** Many drivers (Flash, GPIO, UART) remain functional, allowing interaction with hardware via Zephyr's APIs.
- **Benefits:**
  - Ultra-low power consumption.
  - Suitable for simple sensor nodes and bootloaders.
  - Good for learning Zephyr's Hardware Abstraction Layer (HAL) and drivers.

- **Limitations:**
  - No concurrent tasks.
  - Requires manual event handling and state management.
  - No priority-based execution.
  - Can lead to more complex debugging for timing issues.

Here's a detailed explanation of the **"No Thread Context"** concept in Zephyr RTOS, based on the documentation at Zephyr Thread APIs [1].

🧠 What Is "No Thread Context" in Zephyr?

In Zephyr RTOS, **"no thread context"** refers to execution environments where **no thread is currently running**, such as:

- **Early boot** before the scheduler starts
- **Interrupt Service Routines (ISRs)**
- **Exception handlers**
- **Idle context** (when no threads are ready to run)

These contexts are **not associated with a k_thread object**, and therefore:

- Cannot use thread-specific APIs
- Cannot block or sleep
- Cannot yield or join threads

🧱 Core Concepts

1. **Thread Context vs No Thread Context**

Feature	Thread Context	No Thread Context
Associated with k_thread	✅ Yes	❌ No
Can call k_sleep()	✅ Yes	❌ No
Can access thread-local data	✅ Yes	❌ No
Can yield or join	✅ Yes	❌ No
Can use kernel objects	✅ Limited	⚠️ Only non-blocking

2. **Implications for Developers**

When writing code that runs in **no thread context**, such as in ISRs or early boot:

- Avoid APIs that **block or sleep**
- Use **non-blocking kernel APIs** (e.g., k_sem_give() is safe, k_sem_take() is not)
- Be cautious with memory allocation and thread management

3. **Common Scenarios**

- **Early Boot**: Before main() runs, the system is in no thread context.
- **Interrupts**: ISRs run outside of thread context.
- **Idle Loop**: When no threads are ready, the system may enter an idle state.

4. **Safe APIs in No Thread Context**

- k_sem_give()
- k_fifo_put()
- k_queue_append()
- k_poll_signal_raise()
- k_work_submit()

These are designed to be **safe and fast**, avoiding context switches or blocking behavior.

5. **Unsafe APIs in No Thread Context**

- k_sleep()
- k_thread_join()
- k_thread_suspend()
- k_mutex_lock()

These require a valid thread context and may cause faults if called improperly.

✅ Best Practices

Practice	Why It Matters
Use IS_ENABLED(CONFIG_ISR_CONTEXT)	Detect ISR context safely
Avoid blocking calls in ISRs	Prevent system crashes
Use deferred work (k_work)	Offload processing to thread context
Use k_thread_user_mode_enter() only in thread context	Ensures proper privilege drop

Would you like a **code example** showing how to safely use kernel objects in an ISR or early boot context?

References

[1] Zephyr API Documentation: Architecture thread APIs

System-Call

Here's a detailed explanation of the **Zephyr RTOS System Calls in User Mode**, based on the official documentation from the Zephyr Project:\ 🔗 System Calls — Zephyr Project Documentation

🧠 Core Concepts of Zephyr System Calls in User Mode

1. **User Mode vs Supervisor Mode**

- **User threads** run with **reduced privileges**:
  - Limited access to memory.
  - Restricted CPU instructions.
- **Supervisor threads** have full access to system resources.
- **System calls** allow user threads to request services from the kernel that they can't access directly.

2. **Why System Calls?**

- To **safely expose kernel functionality** to user threads.
- Prevent direct access to sensitive kernel data.
- Enforce **security and memory protection**.

3. **System Call Components**

Each system call in Zephyr has **four main components**:

a. **C Prototype**

- Declared with the **__syscall keyword.**
- Example:
- **__syscall void k_sem_init(struct k_sem *sem, unsigned int initial_count, unsigned int limit);**
- This is parsed by Zephyr's build scripts to generate the syscall interface.

b. **Implementation Function**

- The actual logic of the system call.
- Called directly in supervisor mode.
- In user mode, it's called **after validation**.

c. **Verification Function**

- Prefixed with **z_vrfy_**.
- Validates arguments passed from user mode.
- Ensures **type safety** and **memory access correctness**.

d. **Unmarshalling Function**

- Auto-generated.
- Handles **parameter unpacking** and **privilege elevation**.
- Ensures the syscall is routed correctly from user to kernel space.

4. **How System Calls Are Generated**

- Zephyr uses scripts like:
    - gen_syscalls.py — generates syscall stubs.
    - parse_syscalls.py — parses prototypes and generates metadata.
- These scripts ensure **consistency and safety** in syscall definitions.

5. **Best Practices**

- **Avoid exposing kernel internals** directly to user mode.
- **Do not expose APIs**that:
    - Use function pointers (unless typedef-ed).
    - Access private kernel data.
    - Register callbacks that run in supervisor mode.

6. **Limitations**

- Arrays must be passed as pointers (e.g., int *foo, not int foo[]).
- Function pointers must be typedef-ed before use in syscalls.
- Only certain kernel APIs are exposed to user mode.

7. **Security Considerations**

- All user-mode access is **validated**.
- Memory access is checked against **MPU (Memory Protection Unit)** settings.
- Only **safe, verified APIs** are exposed to user threads.

Zephyr RTOS provides a wide range of **system calls** that allow **user-mode threads** to safely interact with kernel services. While there isn't a single page listing *all* system calls in one place, the official documentation provides a comprehensive overview of how system calls are structured and used.

Here are the most useful resources and summaries:

📘 **Main Documentation Page**

🔗 System Calls — Zephyr Project Documentation\ This page explains:

- What system calls are.
- How to define and use them.
- How Zephyr generates syscall interfaces.
- Security and validation mechanisms.

🧰 **System Call API Reference**

🔗 User Mode and Syscall APIs — Zephyr API Docs\ This section includes:

- **Macros** like K_SYSCALL_VERIFY, K_SYSCALL_MEMORY_READ, etc.
- **Functions**like:
    - **k_object_validate()**
    - **k_thread_perms_set()**
    - **k_object_find()**
    - **k_thread_perms_clear()**

- These are used internally to **validate and manage access** to kernel objects from user mode.

🧾 Where Are All System Calls Listed?

All system calls are **enumerated** in the generated file:

include/generated/zephyr/syscall_list.h

This file is created during the build process and includes entries like:

K_SYSCALL_K_SEM_GIVE

K_SYSCALL_K_MUTEX_LOCK

K_SYSCALL_K_THREAD_START

These correspond to APIs like:

- k_sem_give()
- k_mutex_lock()
- k_thread_start()

🧪 Examples of Common System Calls

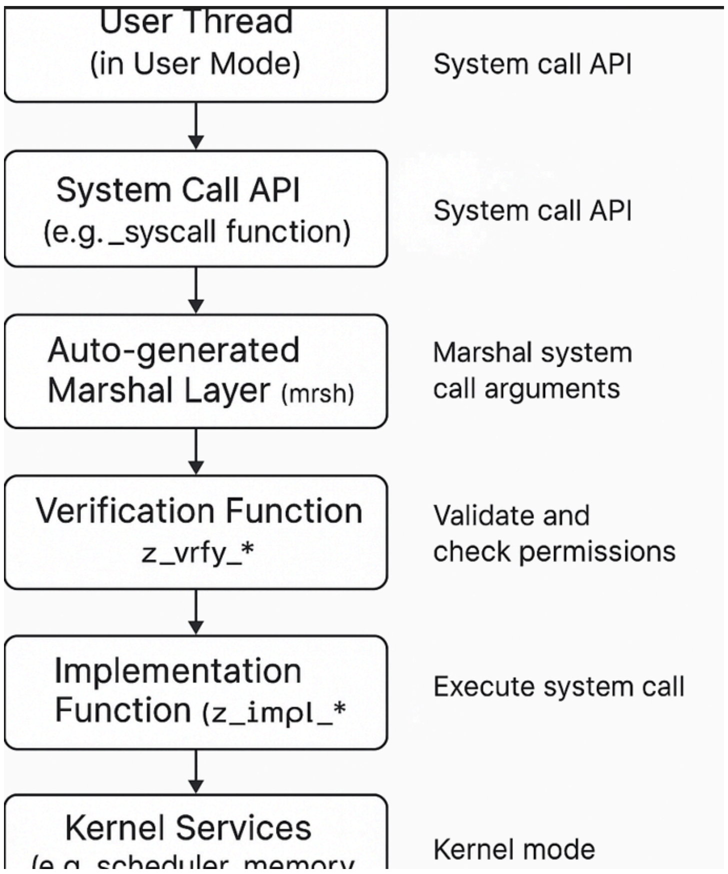
Here are some kernel APIs that are available as system calls:

System Call	**Description**
k_thread_create()	Create a new thread
k_thread_start()	Start a thread
k_sem_give()	Release a semaphore
k_sem_take()	Acquire a semaphore
k_mutex_lock()	Lock a mutex
k_mutex_unlock()	Unlock a mutex
k_msgq_put()	Put a message into a message queue
k_msgq_get()	Get a message from a message queue
k_timer_start()	Start a timer
k_timer_stop()	Stop a timer

Not all kernel APIs are exposed to user mode. Only those that are explicitly marked with __syscall and pass validation are available.

Would you like me to generate a **complete list of system calls from a Zephyr build directory** (e.g., from syscall_list.h) if you provide a build output? Or would you like a **script** to extract and list them from your own build?

```
(zephyr-venv)
root@inlen6239012112:/zephyrproject/zephyr/samples/Zaphyr_app/Thread_02# vi build/zephyr/include/generated/zephyr/syscall_list.h
```


User Thread (in User Mode)
System call API
System Call API (e.g._syscall function)
System call API
Auto-generated Marshal Layer (mrsh)
Marshal system call arguments
Verification Function z_vrfy_*
Validate and check permissions
Implementation Function (z_impl_*
Execute system call
Kernel Services
Kernel mode

Here's a detailed explanation of each step in the **Zephyr RTOS system call flow**, as illustrated in the diagram:

🧵 1. User Thread (User Mode)

- A thread running in **user mode** has limited privileges.
- It cannot directly access kernel memory or perform privileged operations.
- It calls a **system call API** (e.g., k_sem_give()), which is marked with __syscall.

🧩 2. System Call API (__syscall function)

- This is the **public-facing API** exposed to user threads.
- Declared with the __syscall keyword.
- It doesn't contain logic—it delegates the call to a **marshalling layer**.

🔄 3. Auto-generated Marshal Layer (*_mrsh.c)

- Generated during the build process.
- Responsible for:
  - **Unpacking arguments** from user space.
  - **Switching context** to supervisor mode.
  - Calling the **verification function**.
- Ensures safe transition from user to kernel space.

🔍 4. Verification Function (z_vrfy_*)

- Validates arguments passed from user mode.
- Checks:
  - Memory access permissions.
  - Object types and initialization.
  - Pointer validity.
- Prevents malicious or buggy user code from corrupting the kernel.

⚙️ 5. Implementation Function (z_impl_*)

- The actual kernel logic lives here.
- Called only after successful verification.
- Runs in **supervisor mode** with full privileges.
- Performs the requested operation (e.g., giving a semaphore, starting a thread).

🧠 6. Kernel Services

- The implementation function interacts with core kernel subsystems:
  - **Scheduler**
  - **Memory Manager**
  - **IPC mechanisms**
  - **Device drivers**
- These services are not directly accessible from user mode.

🔐 Security Summary

- This layered approach ensures:
  - **Memory safety**
  - **Access control**
  - **Isolation between user and kernel space**

Here's a detailed breakdown of the **Fatal Errors** mechanism in **Zephyr RTOS**, based on the official documentation:\ 🔗 Fatal Errors — Zephyr Project Documentation

🧠 What Are Fatal Errors in Zephyr?

A **fatal error** in Zephyr is a **non-recoverable condition** that causes the system to halt or reset. These errors are typically triggered by:

- Invalid memory access
- Stack overflows
- Assertion failures
- Unhandled exceptions
- Kernel bugs or misconfigurations

⚙️ Core Concepts

1. **Assertion Mechanism**

Zephyr provides runtime assertion macros to catch programming errors:

__ASSERT()

- Used to validate conditions at runtime.
- If the condition fails, a fatal error is triggered.
- Example:
- __ASSERT(foo == 0xF0CACC1A, "Invalid value of foo: 0x%x", foo);

__ASSERT_EVAL()

- A more flexible version of __ASSERT() that allows conditional evaluation of expressions.

Enabling Assertions

- Assertions are enabled using:
  - CONFIG_ASSERT=y
  - CONFIG_ASSERT_LEVEL=1 or 2
- Or by defining __ASSERT_ON in your build flags.

2. **Fatal Error Types**

Zephyr defines several fatal error codes, such as:

- K_ERR_CPU_EXCEPTION
- K_ERR_STACK_CHK_FAIL
- K_ERR_KERNEL_PANIC
- K_ERR_INVALID_TASK_EXIT

These codes help identify the cause of the failure.

3. **Fatal Error Handler**

k_sys_fatal_error_handler()

- This is the **default handler** invoked when a fatal error occurs.
- It is declared as a **weak symbol**, so you can override it in your application.
- Signature:
- void k_sys_fatal_error_handler(unsigned int reason, const z_arch_esf_t *esf);
- Parameters:
  - reason: The fatal error code.
  - esf: Exception stack frame (register state at the time of the error).

Default Behavior

- Halts the system.
- May enter an infinite loop or power off the hardware (depending on architecture).
- In QEMU, it typically exits the emulator.

4. **Customizing Fatal Error Handling**

You can override the default handler to:

- Log additional information.
- Attempt recovery (not recommended for kernel panics).
- Reboot the system.

Example:
[illegible]

```
void k_sys_fatal_error_handler(unsigned int reason, const z_arch_esf_t *esf) {
    printk("Custom fatal error handler: reason %d\n", reason);
    k_fatal_halt(reason);
}
```

5. **Debug Output**

When a fatal error occurs, Zephyr prints:

- The error code and message.
- The faulting instruction address.
- Register values.
- The name of the current thread.

Example output:

```
ASSERTION FAIL [foo == 0xF0CACC1A] @ main.c:42

Invalid value of foo, got 0xdeadbeef

>>> ZEPHYR FATAL ERROR 4: Kernel panic

Current thread: 0x20000414 (main)

Halting system
```

🧪 Best Practices

- Use __ASSERT() liberally during development to catch bugs early.
- Customize k_sys_fatal_error_handler() for better diagnostics.
- Avoid trying to recover from kernel panics unless you fully understand the implications.

Would you like a **sample project** that demonstrates triggering and handling a fatal error on QEMU x86? I can generate one for you.

The **Floating Point Services** in Zephyr RTOS provide mechanisms for managing floating point (FP) register usage by threads, depending on the hardware architecture and application needs.

🔧 **Purpose**

Zephyr allows threads to use floating point registers **only on supported architectures**, such as:

- ARM Cortex-M (with Floating Point Extension)
- Intel x86
- SPARC
- ARCv2 (with Floating Point Extension)

Note: Interrupt Service Routines (ISRs) are **not allowed** to use floating point registers.

🧠 Core Concepts

Zephyr supports **three modes** of floating point register usage:

1. **No FP Registers Mode**

- **Default mode**.
- No threads are allowed to use FP registers.
- If a thread tries to use them, the kernel **raises a fatal error** and aborts the thread.

2. **Unshared FP Registers Mode**

- Only **one thread** is allowed to use FP registers.
- On **x86**, the kernel initializes FP registers for use.
- On **ARM Cortex-M** and **ARCv2**, initialization is skipped.
- **No context switching** of FP registers is done.
- If multiple threads use FP registers, behavior is **undefined**.

3. **Shared FP Registers Mode**

- Multiple threads can use FP registers.
- The kernel:
  - Initializes FP registers.
  - Saves/restores FP context during context switches.
- Threads are categorized as:
  - **Non-user**: Cannot use FP registers.
  - **FPU user**: Can use standard FP registers.
  - **SSE user**: Can use both standard FP and SSE registers (x86 only).

On ARM Cortex-M, **Shared FP Registers Mode is the default** when FP is enabled.

⚙️ Implementation Details

- The kernel saves/restores FP context **only when needed**, minimizing overhead.
- Developers must **explicitly enable**FP support for threads using:
  - k_float_enable()
  - k_float_disable()

🧪 Suggested Use Cases

- Use **No FP mode** for performance if FP is not needed.
- Use **Unshared mode** for single-threaded FP applications.
- Use **Shared mode** for multi-threaded FP applications.

🔧 Configuration Options

You can configure FP support via Kconfig options:

- CONFIG_FLOAT
- CONFIG_FP_SHARING
- CONFIG_SSE

📘 API Reference

From the Floating Point API documentation:

k_float_enable(struct k_thread *thread, unsigned int options)

- Enables FP context preservation for a thread.
- optionscan be:
    - K_FP_REGS (x87/MMX)
    - K_SSE_REGS (SSE + x87/MMX)

k_float_disable(struct k_thread *thread)

- Disables FP context preservation for a thread.

Would you like a **code example** showing how to enable floating point support for a thread in Zephyr? Or perhaps a **comparison table** of the three modes?

Here's a detailed explanation of **Thread Local Storage (TLS)** in Zephyr RTOS, based on the official documentation:\ 🔗 Zephyr Thread Local Storage Documentation

🧠 What is Thread Local Storage (TLS)?

Thread Local Storage (TLS) allows each thread in Zephyr to have its **own private copy** of a variable. This is especially useful in multi-threaded applications where shared global variables could lead to race conditions or require synchronization.

🧩 Core Concepts

1. **Per-thread Variable Storage**

- TLS variables are stored in the **thread's stack**.
- Each thread gets its **own instance** of the variable.
- This ensures **data isolation** between threads.

2. **Toolchain and Architecture Support**

- TLS requires **toolchain support** (e.g., GCC, LLVM).
- The architecture must enable CONFIG_ARCH_HAS_THREAD_LOCAL_STORAGE.
- If not supported, CONFIG_THREAD_LOCAL_STORAGE will not be available.

⚙️ Configuration Options

To enable TLS in your Zephyr project, add the following to your prj.conf:

CONFIG_THREAD_LOCAL_STORAGE=y

Optional:

CONFIG_ERRNO_IN_TLS

```
CONFIG_ERRNO_IN_TLS=y
CONFIG_ERRNO=y
```

- **CONFIG_ERRNO_IN_TLS**: Makes errno thread-local, allowing user threads to access it without a system call.

🧾 Declaring and Using TLS Variables

✅ Declaration Syntax

Use the Z_THREAD_LOCAL macro:

In a header file:

```
extern Z_THREAD_LOCAL int my_tls_var;
```

In a source file:

```
Z_THREAD_LOCAL int my_tls_var;
```

With static (file-local scope):

```
static Z_THREAD_LOCAL int my_tls_var;
```

✅ Usage Example

```
void thread_func(void *p1, void *p2, void *p3){
  my_tls_var = 42;  // Each thread has its own copy
  printk("TLS value: %d\n", my_tls_var);
}
```

🧠 Why Use TLS?

- Avoids **data races** without needing mutexes.
- Simplifies **thread-safe** programming.
- Useful for **reentrant libraries**, **logging**, **error handling**, etc.

🧪 Architecture-Specific Behavior

Some architectures may require special handling for TLS setup. Zephyr provides an internal API:

```
size_t arch_tls_stack_setup(struct k_thread *new_thread, char *stack_ptr);
```

This sets up the TLS area in the thread's stack. It's handled internally by the kernel.

Would you like a **working code example** using TLS in a Zephyr thread, or help checking if your board/toolchain supports it?

Zephyr Kernel Version APIs, 🔗 Zephyr Version APIs Documentation

🧠 What Are Version APIs?

Zephyr's **Version APIs** allow developers to **programmatically retrieve and compare** the version of the Zephyr kernel being used. This is useful for:

- Ensuring compatibility with specific kernel features.
- Conditional compilation based on kernel version.
- Debugging and diagnostics.

🧩 Core Concepts

1. **Version Encoding**

Zephyr encodes its version as a **32-bit integer**, split into:

- **Major version** (8 bits)
- **Minor version** (8 bits)
- **Patch level** (8 bits)
- **Extra metadata** (8 bits, optional)

This encoding allows efficient version comparisons using bitwise operations.

2. **Macros and Functions**

🔹 KERNEL_VERSION(major, minor, patch)

- Encodes a version number into a 32-bit integer.
- Example:
- uint32_t v = KERNEL_VERSION(3, 2, 1); // Encodes version 3.2.1

🔹 KERNEL_VERSION_NUMBER

- A macro that expands to the **current kernel version** as a 32-bit integer.
- You can compare it with KERNEL_VERSION(...) to check compatibility.

🔹 **KERNEL_VERSION_MAJOR,**

KERNEL_VERSION_MINOR,

KERNEL_PATCHLEVEL

- Macros that expand to the current kernel's major, minor, and patch version numbers respectively.

✅ Example Usage

```
#include <zephyr/kernel_version.h>

#include <zephyr/sys/printk.h>


void main(void) {

    printk("Zephyr Kernel Version: %d.%d.%d\n",

           KERNEL_VERSION_MAJOR,
        KERNEL_VERSION_MAJOR,
        KERNEL_VERSION_MINOR,
        KERNEL_PATCHLEVEL);

    if (KERNEL_VERSION_NUMBER >= KERNEL_VERSION(3, 2, 0)) {
        printk("This feature is supported in Zephyr 3.2.0 or later.\n");
    } else {
        printk("This feature is not supported in your Zephyr version.\n");
    }
}
```

🧪 Why It Matters

- **Portability**: Helps maintain code across multiple Zephyr versions.
- **Feature Gating**: Enables or disables features based on kernel version.
- **Debugging**: Logs the kernel version for diagnostics.

Would you like a version of this example tailored for your current Zephyr project or a demo on qemu_x86?

==

The Zephyr Project kernel's user mode is designed to isolate untrusted user mode threads from each other and from the kernel itself. This isolation is crucial to prevent flawed or malicious user mode threads from compromising the system by leaking, modifying, or interfering with private data, resources, or the control of other threads or the kernel.

Here are the core concepts and details:

- **Isolation Goals**: The primary goal is to provide a robust security boundary between user applications and the kernel, as well as between different user applications.
- **Memory Protection**: User threads are limited to accessing only a subset of memory, including their stack, program text, read-only data, and specifically configured memory partitions. Access to other RAM areas is restricted and requires explicit grants from supervisor threads or through system calls.
- **Restricted Kernel Object Access**: User threads cannot directly access kernel object memory. All manipulations of kernel objects must be performed through validated system calls.
- **Device Driver Access Control**: Access to device drivers is restricted unless specifically granted, ensuring that user mode threads cannot directly control hardware without authorization.
- **API Call Validation**: The kernel rigorously validates all API calls made from user mode to prevent system crashes or data corruption.
- **Stack Overflow Protection**: The system is designed to detect and safely handle user mode stack overflows, typically by generating hardware faults.
- **Prevention of Unauthorized Actions**: User mode threads are prevented from making unauthorized system calls, tampering with memory protections, or introducing new executable code.
- **Inherited Permissions**: New threads can inherit permissions from their parent threads, simplifying the management of access rights.
- **Build-Time Definition Constraint**: All kernel objects, thread stacks, and device driver instances that are intended to be used from user mode must be defined at build time. This means that dynamically

loaded code has limitations, such as not being able to define new kernel objects or install interrupt handlers.

Limitations of the System:

- **Trusted Components**: The system does not provide protection against trusted components, including the kernel itself, supervisor mode threads, the toolchain, or the build system.
- **Kernel Mode Configuration Mistakes**: It does not protect against errors in memory domain configuration made in kernel mode that could inadvertently expose private kernel data.
- **Denial of Service (DoS) Attacks**: The system does not inherently protect against denial of service attacks that could occur through thread CPU starvation.

For more detailed information, you can refer to the Zephyr Project Kernel User Mode Overview.

Here's a **summary of the key points** from the Zephyr RTOS User Mode Overview, highlighting the core concepts:

🧠 Zephyr User Mode: Key Concepts

1. **Purpose of User Mode**

- Provides **memory and privilege isolation** for threads.
- Prevents user threads from accessing kernel memory or unauthorized resources.
- Enables **secure multi-threaded applications** in embedded systems.

2. **Thread Privilege Levels**

- **Supervisor Threads**: Full access to all system resources.
- **User Threads**: Restricted access, enforced by MPU/MMU.

3. **Memory Access Rules**

Memory Region	User Thread Access
Own Stack	✅ Yes
Other User Stacks	⚠️ Depends on MMU/MPU
Kernel Memory	❌ No
Read-Only Sections	✅ Read-only
Shared Memory Domains	✅ If granted

4. **Kernel Object Access**

- User threads **must be granted access** to kernel objects.
- Use:
- k_object_access_grant(&amp;my_sem, thread_id);
- k_object_access_all_grant(&amp;my_sem);

5. **System Call Interface**

- All user thread interactions with the kernel go through **validated system calls**.
- Ensures:
  - Correct object types
  - Valid memory access
  - Safe parameter usage

6. **Security Model**

- User threads are treated as **untrusted**.
- Isolation prevents:
  - Memory corruption
  - Privilege escalation
  - System crashes due to faulty user code

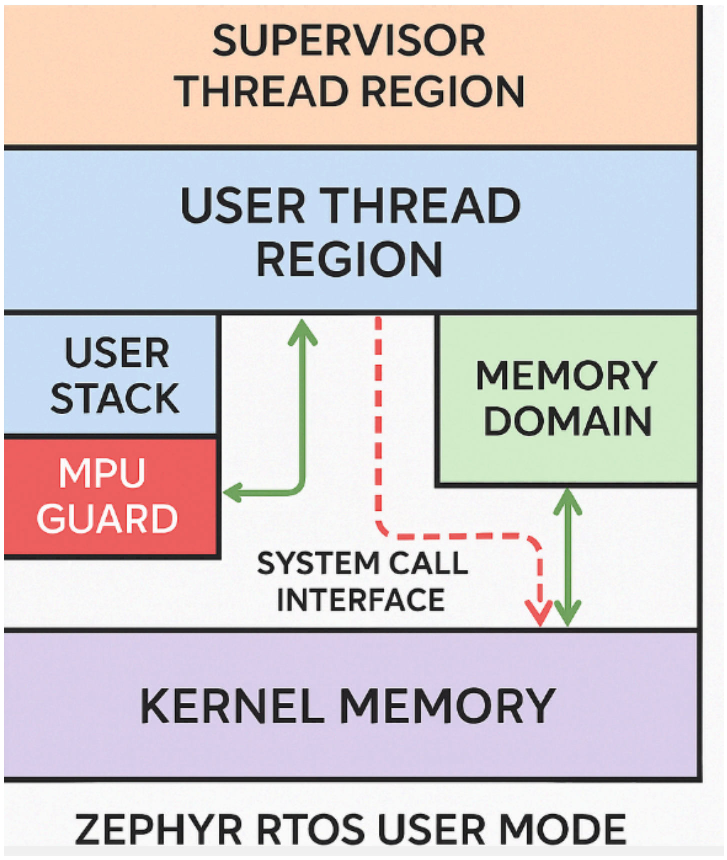
7. **Use Cases**

- Sandboxing third-party code
- Isolating application modules
- Building secure IoT firmware

✅ **Best Practices**

- Enable **CONFIG_USERSPACE**=y in prj.conf
- Use **K_THREAD_STACK_DEFINE()** for stack alignment
- Use memory domains for shared buffers
- Grant object access explicitly
- Validate all user input

Would you like a **code walkthrough** showing how to create a secure user thread with object access and memory domain setup?



Here's a detailed explanation of the **Zephyr RTOS Memory Domains** and **User Mode Memory Protection**, based on the official documentation: Zephyr Memory Domain Documentation [1].

🔐 Core Concepts of Memory Domains in Zephyr

1. **User Mode in Zephyr**

Zephyr supports running threads in **user mode**, which is a reduced privilege level. This is primarily designed for systems with a **Memory Protection Unit (MPU)** or **Memory Management Unit (MMU)**. The goal is to isolate user threads from critical kernel data and other threads, enhancing system security and stability.

2. **Memory Domains**

A **memory domain** is a logical grouping of memory regions that can be accessed by a set of threads. Each thread belongs to one memory domain, and each domain can have multiple memory regions.

Key Properties:

- **Thread Membership**: All threads (user and supervisor) are part of a memory domain. For user threads, this determines what memory they can access.
- **Inheritance**: When a user thread creates a child thread, the child automatically inherits the parent’s memory domain.
- **Supervisor Threads**: These are also part of memory domains, but the domain does not restrict their access.

3. **Memory Regions**

Memory regions are defined areas of memory that are added to a domain. These regions are:

- **Accessible by threads in the domain**
- **Configured with access permissions** (read/write/execute)

4. **APIs for Memory Domains**

Zephyr provides several APIs to manage memory domains:

- k_mem_domain_init(): Initializes a memory domain.
- k_mem_domain_add_region(): Adds a memory region to a domain.
- k_mem_domain_remove_region(): Removes a region.
- k_mem_domain_add_thread(): Adds a thread to a domain.
- k_mem_domain_remove_thread(): Removes a thread.

These APIs allow dynamic configuration of memory access during runtime.

5. **Use Cases**

Memory domains are useful for:

- **Isolating subsystems**: For example, separating networking stack from application logic.
- **Security**: Preventing unauthorized access to sensitive memory.
- **Fault containment**: Limiting the impact of bugs in one thread.

6. **Limitations**

- **User threads cannot modify their domain membership directly.**
- **Supervisor threads are not restricted by domain access.**
- **MPU limitations**: The number of regions is hardware-dependent.

7. **Integration with MPU/MMU**

Zephyr abstracts memory protection using MPU/MMU features. On systems with MMU (like x86), it behaves like an MPU with unlimited regions. On ARM Cortex-M, MPU regions are limited, so careful planning is needed.

8. **Boot-Time Configuration**

At boot, Zephyr configures memory regions for:

- **Text and ro-data**: Read-only and executable.
- **User-accessible data**: Optional, based on features like GCOV.
- **Stack protection**: Using CONFIG_HW_STACK_PROTECTION and CONFIG_STACK_CANARIES.

Would you like a **code example** showing how to define and use memory domains in Zephyr (e.g., on QEMU x86)? Or perhaps a **diagram** to visualize how threads and memory domains interact?

References

[1] Memory Protection Design — Zephyr Project Documentation

====================

Great! Let's dive into the **Zephyr RTOS kernel object model in user mode**, based on the official documentation from the Zephyr Project:

🔗 **Full Reference**: Zephyr Kernel Objects in User Mode

🧠 Core Concepts of Kernel Objects in Zephyr (User Mode)

1. **What Are Kernel Objects?**

Kernel objects are internal data structures used by the Zephyr kernel to manage system resources. Examples include:

- Semaphores
- Mutexes
- Queues
- Threads
- Pipes
- Device drivers

These objects are **opaque to user threads** — meaning user threads can only interact with them through **system calls**, not by directly accessing their memory.

2. **User Mode vs Supervisor Mode**

- **Supervisor threads** (kernel mode) have full access to kernel objects.
- **User threads** (user mode) have restricted access and must go through **permission checks** and **system call interfaces** to interact with kernel objects.

3. **Memory Placement Rules**

To ensure safety and isolation:

- Kernel objects **must not reside in user-accessible memory**.
- They must be placed in **kernel-only memory regions**.
- Static kernel objects must be:
  - Declared at the top level (global scope).
  - Present in the ELF symbol table.
  - Not part of a union.
  - Not located in user-accessible memory partitions.

A post-build script (gen_kobject_list.py) scans the ELF file to collect metadata about kernel objects for runtime validation.

4. **Permissions and Access Control**

- User threads must be **granted permission** to use a kernel object.

- Permissions are managed using APIs like:
- k_object_access_grant(&amp;my_sem, user_thread_id);
- k_object_access_all_grant(&amp;my_sem); // for public access
- If a user thread tries to access an object without permission, a **memory protection fault** occurs.

5. **System Call Interface**

All interactions with kernel objects from user mode go through **system calls**. These calls:

- Validate the object pointer.
- Check permissions.
- Execute the requested operation in kernel mode.

6. **Dynamic Kernel Objects**

- Can be created at runtime.
- Must be allocated in kernel memory.
- If all references to a dynamic object are lost:
  - Cleanup functions may be called.
  - Memory may be freed.

7. **Object Lifecycle and Cleanup**

- Kernel objects may have **cleanup handlers**.
- When no thread holds a reference, the object may be destroyed or cleaned up.

8. **Best Practices**

- Always declare kernel objects at global scope if they need to be accessed from user mode.
- Use k_object_access_grant() early in thread setup.
- Avoid placing kernel objects in user-accessible memory.

Would you like a **code example** showing how to declare a kernel object and grant access to a user thread? Or maybe a **diagram** to visualize the memory and access model?

Certainly, I can provide a detailed explanation of Zephyr's kernel objects, highlighting all the core concepts, based on the provided documentation.

Zephyr's Kernel Objects: A Foundation for Secure and Controlled Execution

In the Zephyr RTOS, a **kernel object** serves as a fundamental building block for managing system resources and enabling controlled interaction between different parts of an application, especially when **user mode** is enabled. These objects are critical for enforcing memory protection and ensuring system stability in resource-constrained embedded environments.

A kernel object in Zephyr can be one of three distinct types of data:

- A **core kernel object**, such as a semaphore, a thread, or a pipe. These are the primary synchronization and communication primitives provided by the kernel.
- A **thread stack**, which is a specific memory region defined as an array of z_thread_stack_element and typically declared using the K_THREAD_STACK_DEFINE() macro.
- A **device driver instance** (const struct device) that belongs to a predefined set of subsystems. This allows the kernel to manage and validate access to hardware peripherals.

The comprehensive list of known kernel objects and driver subsystems is internally defined within include/kernel.h as k_objects.

Core Concepts of Zephyr Kernel Objects

Understanding the following core concepts is crucial to grasping how Zephyr's kernel objects function and contribute to a secure system:

- **Opaqueness to User Threads**: Kernel objects are entirely opaque to user threads. While a user thread can interact with a kernel object by passing its memory address to a kernel API call (which then becomes a system call), the user thread is strictly forbidden from directly dereferencing or accessing the contents of that memory address. Any attempt to do so from user mode will result in a memory protection fault, safeguarding the kernel's integrity.
- **Memory Placement**: To prevent accidental or malicious corruption, all kernel objects must be placed in memory regions that are *not* directly accessible by user threads. This separation is a critical security measure.
- **System Call Requirement**: Since user threads cannot directly manipulate kernel objects, all operations on these objects must be performed through **system calls**. When a user thread invokes a kernel API that operates on a kernel object, the system transitions to supervisor mode, and the system call handler performs rigorous checks. These checks validate that the provided kernel object address is legitimate and that the calling thread possesses the necessary permissions to interact with that specific object.
- **Permissions as References**: In Zephyr, permission to access a kernel object also functions as a **reference** to that object. This dual role is particularly important for objects that perform temporary internal allocations or for objects that are themselves dynamically allocated from a runtime memory pool. The kernel uses these references for internal management and resource tracking.
- **Object Cleanup and Freeing**: When a kernel object loses all its references (meaning no threads currently hold permissions on it), the kernel can initiate cleanup procedures. If the object has an associated cleanup function, it may be called to release any runtime-allocated buffers the object was using. Furthermore, if the object itself was dynamically allocated, its memory will be automatically freed, preventing memory leaks.

Object Placement Details

The placement of kernel objects in memory is critical for security and proper functioning, especially in systems with user mode enabled:

- **Supervisor Threads**: Kernel objects used exclusively by supervisor threads (which run in a privileged mode) have fewer restrictions on their memory location. They can be placed anywhere in the binary or even declared on a thread's stack. However, they must still avoid memory regions directly accessible by user threads to prevent potential corruption.
- **Static Kernel Objects for User Threads**: For a static kernel object to be safely usable by a user thread via system calls, it must meet specific criteria during its declaration and the build process:
  - It must be declared as a **top-level global variable** at build time. This ensures its presence in the ELF symbol table, even if it has static scope.
  - A post-build script, scripts/build/gen_kobject_list.py, scans the generated ELF file. This script identifies valid kernel objects and stores their memory addresses along with other metadata in a special internal table. Kernel objects can be part of arrays or embedded within other data structures, and this script accounts for that.
  - These objects must reside in memory explicitly reserved for the kernel, not in any user-accessible memory partitions.
  - Any memory allocated for a kernel object must be used *exclusively* for that object; kernel objects cannot be members of a union data type.
  - If a kernel object does not satisfy these conditions, it will not be included in the kernel's internal table used for validating user-mode pointers. The debug output of gen_kobject_list.py (when run with --verbose or with verbose build output) can assist in diagnosing why an object is not being tracked.

Dynamic Objects

Zephyr supports the allocation of kernel objects at runtime, provided that the CONFIG_DYNAMIC_OBJECTS Kconfig option is enabled.

- The k_object_alloc() API is used by a calling thread to instantiate a dynamic object from its assigned resource pool.
- Dynamic objects can be freed in two ways:
  - A supervisor thread can explicitly call k_object_free() to force the release of a dynamic object.
  - Objects are automatically freed when their reference count (i.e., the number of threads with permissions on them) drops to zero. User threads can relinquish their own permission using k_object_release(), and permissions are automatically cleared when a thread terminates. Supervisor threads can also revoke permissions for another thread using k_object_access_revoke().
- Even though access control isn't strictly enforced for supervisor threads, they should still acquire permissions on objects they use, as these permissions are integral to the reference counting mechanism.

Implementation Details of Dynamic Objects

The scripts/build/gen_kobject_list.py script plays a crucial role in managing kernel objects:

- It's a post-build step that parses DWARF debug information from the kernel's ELF file to find valid kernel object instances.
- The memory addresses of these instances (structs or arrays corresponding to kernel objects) are then placed into a special **perfect hash table**, generated by the 'gperf' tool. This table allows for constant-time lookup, which is essential for quickly validating memory addresses of potential kernel objects passed from user mode during system calls.
- **Device drivers** are a special category. All driver instances are of type const struct device. The kernel examines their API pointer to determine the specific subsystem they belong to, preventing incorrect operations (e.g., attempting to call a UART API on a sensor driver object).
- The hash table maps kernel object memory addresses to z_object instances. Each z_object contains vital metadata, including:
  - A bitfield indicating permissions, indexed by a numerical ID assigned to each thread. The size of this bitfield is controlled by CONFIG_MAX_THREAD_BYTES.
  - A type field, which specifies the object's kind (an instance of k_objects).
  - A set of flags to track the object's initialization state and whether it's public or private.
  - An extra data field (z_object_data) whose meaning varies depending on the object type.
- Dynamically allocated objects are tracked in a **runtime red/black tree**, which works in parallel with the gperf table to validate object pointers.

Access Permissions

Zephyr's permission model dictates how threads can interact with kernel objects:

- **Supervisor Thread Access Permission**: Supervisor threads have unrestricted access to any kernel object. However, permissions are still tracked for them because:
  - If a supervisor thread transitions to user mode using k_thread_user_mode_enter(), it will retain any permissions it had been granted while in supervisor mode.
  - If a supervisor thread creates a user thread with the K_INHERIT_PERMS option, the child thread will inherit the parent's permissions (excluding the parent thread object itself).
- **User Thread Access Permission**: By default, a newly created user thread only has access permissions on its own thread object. Access to other kernel objects must be explicitly or implicitly granted:
  - Using K_INHERIT_PERMS when creating a thread allows it to inherit all permissions from its parent thread (except for the parent thread object).
  - A thread that already has object permission or is running in supervisor mode can grant permission to another thread using k_object_access_grant(). The convenience pseudo-function k_thread_access_grant() can also be used.
  - Supervisor threads can declare a kernel object **public** using k_object_access_all_grant(). This makes the object usable by all current and future threads, but it should be used with caution due to its security implications.
  - For statically declared threads using K_THREAD_DEFINE(), the K_THREAD_ACCESS_GRANT() macro can grant boot-time access to a predefined set of kernel objects.
- Access can be removed using k_object_access_revoke() (which is not available to user threads). User threads can voluntarily relinquish their own permissions with k_object_release().
- API calls from supervisor mode to set permissions on untracked kernel objects will be no-ops, whereas the same call from user mode would result in a fatal error.
- Objects allocated with k_object_alloc() implicitly grant permission to the calling thread.

Initialization State

Most operations on kernel objects will fail if the object is uninitialized; therefore, the appropriate initialization function must be called first.

- Some objects are implicitly initialized at boot time:
  - Kernel objects declared with static initialization macros (e.g., K_SEM_DEFINE) are initialized during the build process.
  - Device driver objects are initialized after their init function runs early in the boot process.
- If a kernel object is initialized with a private static initializer, a supervisor thread must call k_object_init() on it. Otherwise, the kernel will consider it uninitialized if a user thread attempts to access it. This scenario is uncommon and typically applies to kernel objects embedded within larger structures that are statically initialized.

Creating New Kernel Object Types

To extend Zephyr with new kernel object types:

- **Core Kernel Objects**: Add the struct name of the new object to the kobjects list within the scripts/build/gen_kobject_list.py script.
- **Driver Subsystem Kernel Objects**: Add the name of the API struct for the new subsystem to the subsystems list in scripts/build/gen_kobject_list.py. All driver instances are const struct device and are differentiated by their specific API struct.

Configuration Options

Key Kconfig options related to kernel objects include:

- CONFIG_USERSPACE: Enables the user mode functionality and memory protection.
- CONFIG_MAX_THREAD_BYTES: Controls the size of the bitfield used for tracking permissions, indexed by thread ID.

API Reference

The core APIs for managing kernel objects, particularly those related to user mode, are primarily found in the User Mode APIs documentation.

Here's a detailed explanation of the **Zephyr RTOS MPU Stack Objects** concept, based on the official documentation:

🔗 **Full Reference**: MPU Stack Objects — Zephyr Project Documentation

🧠 What Are MPU Stack Objects?

In Zephyr RTOS, when **user mode** is enabled, thread stacks must be protected to prevent memory corruption and privilege escalation. This is achieved using the **Memory Protection Unit (MPU)**, which enforces access control on memory regions.

🧱 Key Concepts

1. **Thread Stack Creation**

- Stacks are declared using:
- **K_THREAD_STACK_DEFINE(stack_name, size);**
- For MPU-enabled architectures, stacks must be **physically contiguous** in memory.
- This is essential for:
  - **Stack protection**
  - **User mode isolation**
  - **MPU region alignment**

2. **Stack Guards**

- A **stack guard** is a protected memory region placed at the **bottom of the stack**.
- It is configured to **disallow write access**.
- If a thread overflows its stack into the guard region, a **memory fault** is triggered.
- This helps detect **stack overflows** early and safely.

3. **Memory Placement Constraints**

Due to MPU hardware limitations, stack memory must follow strict rules:

a. **Alignment Requirements**

- Some MPUs (e.g., ARMv7-M) require:
  - Stack base address aligned to a **power of two**
  - Stack size also aligned to the same power of two
- Example:
  - A 1500-byte stack must be aligned and padded to 2048 bytes (2 KB)

b. **Region Size and Overlap**

- MPU regions must not overlap improperly.
- Some MPUs use **start and end addresses**, others use **base + size**.
- This affects how stacks are placed and protected.

4. **MPU Region Priorities**

- Some MPUs use **priority-based enforcement**:
  - The highest-priority region that matches an address determines access.
- Others **combine regions** using logical OR.
- This affects how stack guards and user access are enforced.

5. **Implications for Developers**

- You must **not manually place stacks** in user-accessible memory.
- Always use Zephyr macros like K_THREAD_STACK_DEFINE() or K_THREAD_STACK_ARRAY_DEFINE().
- Let Zephyr handle alignment and placement.

✅ Best Practices

Practice	Why It Matters
Use K_THREAD_STACK_DEFINE()	Ensures proper alignment and MPU compatibility
Avoid manual memory placement	Prevents misaligned or insecure stack regions
Enable CONFIG_HW_STACK_PROTECTION	Adds runtime stack overflow detection
Use CONFIG_USERSPACE	Enables MPU-based isolation for user threads

Would you like a **diagram** showing how the MPU stack layout looks in memory, including the guard region and alignment? Or a **code example** showing how to define a user thread with MPU-protected stack?

Here's a detailed explanation of the **MPU and Userspace Memory Protection** in Zephyr RTOS, based on the official documentation:

🔗 **Full Reference**: Memory Protection Design — Zephyr Project Documentation

🧠 Core Concepts of MPU and Userspace in Zephyr

1. **What is the MPU?**

The **Memory Protection Unit (MPU)** is a hardware feature available on many microcontrollers (e.g., ARM Cortex-M) that allows the system to:

- Define memory regions with specific access permissions.
- Enforce **isolation** between user and kernel space.
- Prevent **accidental or malicious memory access**.

Zephyr uses the MPU to implement **userspace isolation**, ensuring that user threads cannot access kernel memory or other threads' stacks.

2. **Userspace Memory Model**

When **CONFIG_USERSPACE** is enabled:

- Threads can run in **user mode** or **supervisor mode**.
- User threads are restricted by the MPU to only access:
  - Their own stack
  - Shared memory regions (via memory domains)
  - Kernel objects they have permission for

3. **Boot-Time MPU Configuration**

At system startup, Zephyr configures the MPU to:

- Protect **read-only** regions (e.g., .text, .rodata)
- Allow **user-mode access** to executable code and read-only data
- Define **stack guard regions** to detect overflows
- Set up **default access policies** for unused memory

4. **Memory Domains**

Zephyr introduces **memory domains** to allow controlled sharing of memory between user threads:

- A memory domain is a set of memory partitions.
- Threads can be assigned to a domain to gain access to its partitions.
- This enables **fine-grained control** over what memory a user thread can access.

Example:

```
struct k_mem_domain my_domain;

struct k_mem_partition my_partitions[1];



K_MEM_PARTITION_DEFINE(my_partition, my_buf, sizeof(my_buf), K_MEM_PARTITION_P_RW_U_RW);



k_mem_domain_init(&my_domain, 1, my_partitions);

k_mem_domain_add_thread(&my_domain, k_current_get());
```

5. **Stack Protection**

Zephyr uses the MPU to:

- Protect thread stacks from overflow using **guard regions**
- Ensure user threads can only access their own stack
- Prevent supervisor threads from being corrupted by user threads

6. **MPU Region Limitations**

MPUs have a **limited number of regions** (e.g., 8 on ARMv7-M), so Zephyr:

- Uses **background memory maps** where possible
- Merges regions when feasible
- Prioritizes critical protections (e.g., kernel memory, stacks)

7. **Security Benefits**

- Prevents **code injection** and **data corruption**
- Enforces **least privilege** for user threads
- Enables **safe multi-threading** in embedded systems

✅ Best Practices

Practice	Why It Matters
Use CONFIG_USERSPACE	Enables MPU-based isolation
Use K_THREAD_STACK_DEFINE()	Ensures stack is MPU-compatible
Use memory domains for shared buffers	Allows safe inter-thread communication
Avoid placing kernel objects in user memory	Prevents privilege escalation

Would you like a **code example** showing how to use memory domains or how to configure MPU-protected shared memory between threads?

Here's a detailed breakdown of the **Zephyr RTOS User Mode Overview**, based on the official documentation:

🔗 **Full Reference**: User Mode Overview — Zephyr Project Documentation

🧠 What Is User Mode in Zephyr?

User mode in Zephyr allows threads to run with **reduced privileges**, enforced by hardware (typically an MPU or MMU). This is a key feature for building **secure and robust embedded systems**, where you want to isolate potentially buggy or untrusted code from the kernel and other threads.

🧱 Core Concepts

1. **Threat Model**

Zephyr treats user threads as **untrusted**:

- They are isolated from:
  - Other user threads
  - The kernel
  - Supervisor threads
- A compromised user thread **cannot corrupt** the system or access unauthorized memory or kernel objects.

2. **Design Goals**

User mode is designed to:

- Prevent access to memory not explicitly granted.
- Enforce **read/write policies** on memory regions.

- Restrict access to **kernel objects** unless permission is granted.
- Validate all **system call parameters** to avoid crashes or corruption.

3. **Memory Access Rules**

Memory Region	Access by User Thread
Own stack	✅ Read/Write
Other user stacks (same domain)	⚠️ Depends on hardware (MMU vs MPU)
Supervisor stacks	❌ No access
Kernel memory	❌ No access
Read-only data (e.g., .rodata)	✅ Read-only
Program text (e.g., .text)	✅ Read-only

On **MPU systems**, user threads can only access their **own stack**.
On **MMU systems**, threads in the same memory domain may share access.

4. **Kernel Object Access**

User threads:

- **Must be granted access** to kernel objects (e.g., semaphores, queues).
- Cannot use objects unless:
  - They are explicitly granted access via k_object_access_grant(), or
  - The object is made public via k_object_access_all_grant().

5. **System Call Validation**

Zephyr validates all system calls from user threads:

- Ensures correct object types.
- Checks parameter bounds and memory access rights.
- Prevents misuse that could lead to kernel corruption.

6. **Use Cases**

User mode is ideal for:

- **Sandboxing** third-party or untrusted code (e.g., network stacks, interpreters).
- **Isolating applications** in multi-tenant systems.
- **Preventing bugs** in one thread from affecting the entire system.

✅ Best Practices

Practice	Why It Matters
Use CONFIG_USERSPACE=y	Enables user mode support
Use K_THREAD_STACK_DEFINE()	Ensures MPU/MMU compatibility
Grant object access explicitly	Prevents unauthorized use
Use memory domains for shared buffers	Enables safe inter-thread communication
Validate all user input	Avoids privilege escalation or crashes

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Atomic Services

Here's a detailed explanation of the **Atomic Services** in Zephyr RTOS, based on the official documentation: Atomic Services — Zephyr Project Documentation [1].

🔧 What Are Atomic Services?

Atomic services in Zephyr provide mechanisms to safely manipulate shared variables across multiple execution contexts—like threads and ISRs (Interrupt Service Routines)—without race conditions.

An **atomic variable** is:

- A 32-bit value on 32-bit systems.
- A 64-bit value on 64-bit systems.
- Guaranteed to be modified in an **uninterruptible** and **thread-safe** manner.

🧠 Core Concepts

1. **Atomic Variable Definition**

Atomic variables are defined using the atomic_t type.

atomic_t flags = ATOMIC_INIT(0xFF); // Initializes with 0xFF

You can also define an array of atomic variables using:

ATOMIC_DEFINE(flag_bits, NUM_FLAG_BITS);

This creates a bit array of atomic variables.

2. **Manipulating Atomic Variables**

Zephyr provides a rich set of APIs for atomic operations:

Basic Operations

- atomic_get() – Get the current value.
- atomic_set() – Set a new value.
- atomic_clear() – Clear the value.
- atomic_inc() / atomic_dec() – Increment or decrement.
- atomic_add() / atomic_sub() – Add or subtract.

Bitwise Operations

- atomic_or() / atomic_and() / atomic_xor() / atomic_nand() – Bitwise logic.

Compare and Swap

- atomic_cas() – Compare and set if the value matches.

Bit Manipulation in Arrays

- atomic_set_bit() / atomic_clear_bit() – Set or clear a specific bit.
- atomic_test_bit() – Test a bit.
- atomic_test_and_set_bit() / atomic_test_and_clear_bit() – Atomically test and modify a bit.

3. **Memory Ordering**

All atomic operations in Zephyr include **full memory barriers**:

- Ensures consistency across threads and ISRs.
- Prevents reordering of instructions that could lead to race conditions.

Examples:

- On x86: serializing instructions.
- On ARM: DMB (Data Memory Barrier).
- In C++ terms: sequentially consistent operations.

4. **Suggested Use Cases**

- **Single atomic variable**: For simple counters or flags.
- **Array of atomic bits**: For managing large sets of flags (e.g., 200 bits).

Example:

```
#define NUM_FLAG_BITS 200

ATOMIC_DEFINE(flag_bits, NUM_FLAG_BITS);
```

```
int set_flag_bit(int bit_position) {

    return (int)atomic_set_bit(flag_bits, bit_position);

}
```

✅ Benefits

- **Thread safety** without needing mutexes.
- **ISR compatibility**.
- **Efficient** for small-scale synchronization.
- **Portable** across architectures supported by Zephyr.

Would you like a working example using QEMU x86 or another Zephyr board to demonstrate atomic operations in practice?

References

[1] Atomic Services — Zephyr Project Documentation

Here are the core concepts and details of Zephyr's Atomic Services, presented in bullet points:

- **Core Concept: Atomicity**
  - **Definition:** Operations are **indivisible and uninterruptible**. They either complete entirely or don't happen at all.
  - **Guarantees:** No intermediate state is observable; no other thread, ISR, or CPU core can interfere during the operation.
  - **Importance in Concurrent Environments:**
    - **Concurrency Control:** Prevents race conditions and data corruption when multiple threads/ISRs access shared data.
    - **Read-Modify-Write (RMW) Safety:** Ensures operations like incrementing a counter (read, modify, write) are safe from interference.
    - **Low-Level Primitives:** Fundamental building blocks for higher-level synchronization (mutexes, semaphores).
    - **Performance:** Generally faster and lighter-weight than mutexes/semaphores as they avoid context switching.
- **Zephyr's Atomic Services (atomic.h):**
  - Provides architecture-specific, highly optimized atomic operations.
  - Guarantees atomicity even across multiple CPU cores (SMP-safe).
- **Key Data Type:**
  - **atomic_val_t:**
    - Fundamental type for atomic variables.
    - Guaranteed to hold a pointer and align with the native word size (e.g., 32-bit or 64-bit).
    - Ensures correct compiler/hardware handling for atomic guarantees.
- **Key Atomic Functions (Read/Write Operations):**
  - **atomic_set(atomic_t *target, atomic_val_t value):**
    - Atomically sets target to value.
    - Returns the *previous* value of target.
  - **atomic_get(const atomic_t *target):**
    - Atomically reads the current value of target.

        - Returns the current value.
- **Key Atomic Functions (Arithmetic Read-Modify-Write Operations):**
    - **atomic_add(atomic_t *target, atomic_val_t value):** Atomically adds value to target. Returns the *previous* value.
    - **atomic_sub(atomic_t *target, atomic_val_t value):** Atomically subtracts value from target. Returns the *previous* value.
- **Key Atomic Functions (Bitwise Read-Modify-Write Operations):**
    - **atomic_or(atomic_t *target, atomic_val_t value):** Atomically performs bitwise OR. Returns the *previous* value.
    - **atomic_xor(atomic_t *target, atomic_val_t value):** Atomically performs bitwise XOR. Returns the *previous* value.
    - **atomic_and(atomic_t *target, atomic_val_t value):** Atomically performs bitwise AND. Returns the *previous* value.
    - **atomic_nand(atomic_t *target, atomic_val_t value):** Atomically performs bitwise NAND (~(*target & value)). Returns the *previous* value.
- **Key Atomic Functions (Bit Manipulation Operations):**
    - **atomic_clear_bit(atomic_t *target, int bit):** Atomically clears a specific bit (sets to 0). Returns true if bit was previously set, false otherwise.
    - **atomic_set_bit(atomic_t *target, int bit):** Atomically sets a specific bit (sets to 1). Returns true if bit was previously clear, false otherwise.
    - **atomic_test_bit(const atomic_t *target, int bit):** Atomically tests if a specific bit is set. Returns true if set, false otherwise.
    - **atomic_test_and_clear_bit(atomic_t *target, int bit):** Atomically tests a bit and clears it if set. Returns true if bit was set *before* clearing.
    - **atomic_test_and_set_bit(atomic_t *target, int bit):** Atomically tests a bit and sets it if clear. Returns true if bit was clear *before* setting.
- **Core Concept: Compare-And-Swap (CAS)**
    - **atomic_cas(atomic_t *target, atomic_val_t old_value, atomic_val_t new_value):**
        - Atomically reads target.
        - **If** target's current value equals old_value, then new_value is atomically written to target.
        - **Otherwise**, target is not modified.
        - **Returns:** true if the swap occurred (i.e., target was updated), false otherwise.
        - **Significance:** Crucial for implementing lock-free algorithms and non-blocking data structures, allowing conditional updates and retries.
    -
- **Why Use Atomic Operations in Zephyr?**
    - **Efficiency:** Often implemented with single, specialized CPU instructions (e.g., LDREX/STREX, LOCK CMPXCHG), making them faster than mutexes.
    - **ISR Safety:** Can be used safely in Interrupt Service Routines (ISRs) where blocking mechanisms like mutexes are not allowed.
    - **Building Blocks:** Provide the foundation for more complex synchronization primitives and advanced concurrent algorithms.
    - **SMP Safety:** Designed to guarantee atomicity and data integrity even on multi-core systems (Symmetric Multi-Processing).

Memory Management

Memory Heaps :: Zephyr RTOS Heap Memory Management : Zephyr Heap Memory Management [1].

🔧 Core Concepts of Zephyr Heap Memory Management

Zephyr provides a **heap memory allocator** that allows threads to dynamically allocate and free memory at runtime, similar to malloc() and free() in standard C. This is useful for applications where memory needs are not known at compile time.

1. **Heap Types**

Zephyr supports two main heap types:

- **k_heap**: Kernel-synchronized heap allocator.
- **sys_heap**: Low-level, non-synchronized heap allocator for advanced use cases.

🧱 k_heap – Kernel Heap

✅ Creating a Heap

You can define a heap statically using:

K_HEAP_DEFINE(my_heap, 1024);

Or dynamically initialize it with:

struct k_heap my_heap;

uint8_t heap_area[1024];

k_heap_init(&my_heap, heap_area, sizeof(heap_area));

📥 Allocating Memory

void *ptr = k_heap_alloc(&my_heap, size, timeout);

- size: Number of bytes to allocate.
- timeout: How long to wait if memory is not immediately available.
  - K_NO_WAIT: Return immediately.
  - K_FOREVER: Wait indefinitely.

📤 Freeing Memory

k_heap_free(&my_heap, ptr);

- ptr must be a pointer returned by k_heap_alloc().
- Passing NULL is safe and has no effect.

⚙️ sys_heap – Low-Level Heap

This is the underlying implementation used by k_heap, but **without synchronization**. It is suitable for:

- Userspace applications.
- Custom memory management scenarios.

⚠️ Important:

- All access to a sys_heap must be **manually synchronized**.
- Simultaneous access from multiple threads is **not allowed**.

🧠 Internal Implementation Details

- Memory is divided into **8-byte chunks**.
- Each chunk has a **header**with:
  - Size of the chunk.
  - Size of the previous chunk.
  - In-use flag.
  - Pointers to previous and next free chunks.

🪣 Free List Buckets

- Free blocks are grouped into **buckets** by size (powers of two).
- This helps reduce fragmentation and speeds up allocation.

🔄 Coalescing

- When memory is freed, adjacent free blocks are **merged** to reduce fragmentation.

🧪 Use Cases

- Dynamic buffer allocation.
- Temporary data structures.
- Memory-constrained applications needing flexible memory usage.

Would you like a **code example** demonstrating heap usage in a Zephyr application on QEMU x86? Or should I help you compare k_heap with other memory allocators like k_mem_slab or k_malloc?

References

[1] Memory Heaps — Zephyr Project Documentation

Here are the details about Zephyr's memory management heap utilities, presented in bullet points:

- **Core Concepts:**
  - **Dynamic Memory Allocation:** Programs request and release memory during runtime, adapting to varying data needs. Essential for threads requiring flexible memory.
  - **Heaps:** Dedicated regions of memory from which dynamic allocations are made.
  - **Fragmentation:** Occurs when free memory becomes broken into small, non-contiguous blocks, even if total free space is sufficient. Zephyr's allocators employ strategies to mitigate this.
- **Zephyr's Heap Utilities (Detailed):**
  - **1. Synchronized Heap Allocator (k_heap)**

        - **Purpose:** Primary high-level, general-purpose dynamic memory allocator for the Zephyr kernel.
        - **Thread-Safe:** Allows multiple threads to concurrently allocate and free memory without corruption.
        - **Definition:**
            - Statically defined using K_HEAP_DEFINE macro (e.g., K_HEAP_DEFINE(my_heap, 1024);).
            - Can manage arbitrary application-controlled memory regions via k_heap_init().
        - **Allocation (k_heap_alloc()):**
            - Similar to malloc() in C.
            - Returns pointer to allocated memory on success, NULL on failure.
            - **Blocking Support:** Threads can block (sleep) until memory becomes available or a timeout occurs, preventing busy-waiting.
        - **Deallocation (k_heap_free()):**
            - Similar to free() in C.
            - Releases memory back to the heap, preventing leaks.
    - **2. Low Level Heap Allocator (sys_heap)**
        - **Purpose:** Provides core memory allocation/deallocation logic *without* built-in kernel synchronization.
        - **Usage Contexts:** Suitable for userspace or contexts where the caller guarantees serialization.
        - **Serialization Requirement: Crucial:** All sys_heap functions on a single heap **must be serialized by the caller**; concurrent access will lead to issues.
        - **Internal Mechanism:**
            - Divides memory into 8-byte "chunks."
            - Each block (allocated or free) has a "chunk header" storing length, usage status, and free list pointers.
            - **Fragmentation Prevention:**
                - Free blocks organized into size-based "buckets" (by powers of two).
                - Automatic coalescing (merging) of adjacent free blocks when memory is freed.
            - All metadata is stored at the beginning of the heap memory.
        - **Performance:**
            - High performance, predictable latency (1-200 cycles typically).
            - Guaranteed constant time completion.
            - CONFIG_SYS_HEAP_ALLOC_LOOPS: Compile-time upper bound on list searches for predictable latency, potentially at a slight cost to fragmentation resistance.
    - **3. Multi-Heap Wrapper Utility (sys_multi_heap)**
        - **Purpose:** Manages allocation from multiple, potentially discontiguous memory regions or regions with different properties (e.g., cache, DMA). Acts as a wrapper around one or more sys_heap objects.
        - **Initialization:** sys_multi_heap_init().
        - **Adding Heaps:** Individual sys_heap objects are added using sys_multi_heap_add_heap().
        - **Allocation (sys_multi_heap_alloc(), sys_multi_heap_aligned_alloc()):**
            - Accepts an opaque "configuration" parameter.
            - An application-provided callback function uses this parameter to decide *which* managed sys_heap to use for the allocation, enabling flexible memory placement.
        - **Reallocation (sys_multi_heap_realloc(), sys_multi_heap_aligned_realloc()):** Can resize buffers and even reallocate them on a different eligible heap.
        - **Deallocation:** sys_multi_heap_free().
    - **4. System Heap**
        - **Purpose:** A special, predefined, and globally accessible malloc()-like allocator for general-purpose kernel-level dynamic allocations.
        - **Single Instance:** Only one system heap exists.
        - **Size Configuration:** Configured via CONFIG_HEAP_MEM_POOL_SIZE Kconfig option (defaults to zero, meaning it's disabled unless configured).
        - **Access:** Cannot be directly referenced by memory address; accessed via k_malloc() and k_free().
        - **Allocation (k_malloc()):**
            - Returns NULL if no suitable chunk.
            - Guaranteed pointer-size alignment of allocated address.
        - **Deallocation (k_free()):** Releases memory back to the system heap.
        - **Subsystem Requirements:** Some kernel subsystems may define minimum size requirements for the system heap.