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Retrofitting Zephyr Memory Protection

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Acknowledgements

These slides are based on Andrew Boie (Intel)’s
“**Retrofitting Zephyr Memory Protection**”

Thank you, Andrew!

CONTENTS

Background

What is Zephyr

- Zephyr: a modular RTOS and a complete solution stack
  - RTOS for use on connected resource-constrained and embedded devices
  - Focused on safety, security, connections with Bluetooth support and a full native networking stack
  - Apache 2.0 license, hosted at Linux Foundation
  - Support diverse use cases and architectures: ARC, ARM, RISC-V, X86 …
  - Web site: https://www.zephyrproject.org/

- More Zephyr related events:
  - "Introduction to the Zephyr Project" - Ryan Qian, NXP & Kate Stewart, The Linux Foundation, Tuesday, June 26 • 11:20 - 12:00
  - "License Information Management " – Kate Stewart, The Linux Foundation, Tuesday, June 25 • 15:50 - 16:30
  - IoT Meetup, Tuesday, June 26 • 18:00 - 21:00, 北京海淀区科学院南路2号, 融科资讯中心C座南楼1层 南极洲会议室

Why Required

- Security concern of IoT devices
  - More and more "things" are connected, traditionally offline->online
    - Secure communication
    - Trusted execution (secure boot)
    - Data protection
    - ….
- Zephyr uses systematic approaches for security
  - Static: high quality design, code review, tests, certification
  - Dynamic: secure communication, cryptography, memory protection
- Memory protection
  - One important approach for more secure, reliable and safe system
  - 1st step to implement security

Memory Protection Hardware

Memory Protection Unit(MPU)

- Popular in low-end device, ARM Cortex M4, ARC EM
- Fixed number of configurable regions, each with their own access policy
- No virtualization, physical memory addresses
- Typically have constraints on region specification, e.g. region sizes must be power of two, aligned to their size

Memory Management Unit(MMU)

- Popular in Application processors, x86, ARM Cortex A series, ARC HS series
- Address space divided into equal sized pages (typically 4K).
- Configuration for caching and access, policy for each page set in page tables
- MPU-like behavior with identity page table, but Optional support for virtual memory

Memory Protection in Zephyr

- Zephyr had no means of preventing unwanted memory access before
- Joint effort with most contributions from Linaro (ARM), Synopsys (ARC), and Intel (x86), initial efforts targeting MPU-based systems
- Milestones
  - 1.9 release (7/2017): MMU/MPU enabled, stack overflow protection on ARM/x86
  - 1.10 release (11/2017): user mode support on x86 MMU
  - 1.11 release (3/2018): user mode support on ARC/ARM MPU
  - 1.12 release (6/2018): more tests, refinement
- Future work
  - Additional CPU architecture support
  - Flesh out APIs and iterative refinement
  - Support of TEE (Trusted Execution Environment), e.g., secure and non-secure world (1.13 or later)

Use Cases

- Protect against unintentional programming errors
  - Stack overflows
  - Writing to bad memory
  - Data corruption
- Sandbox complex data parsers and interpreters
  - Network stacks/protocols
  - File systems
  - Reduce likelihood of third-party data compromising the system
- Support the notion of multiple logical isolated applications

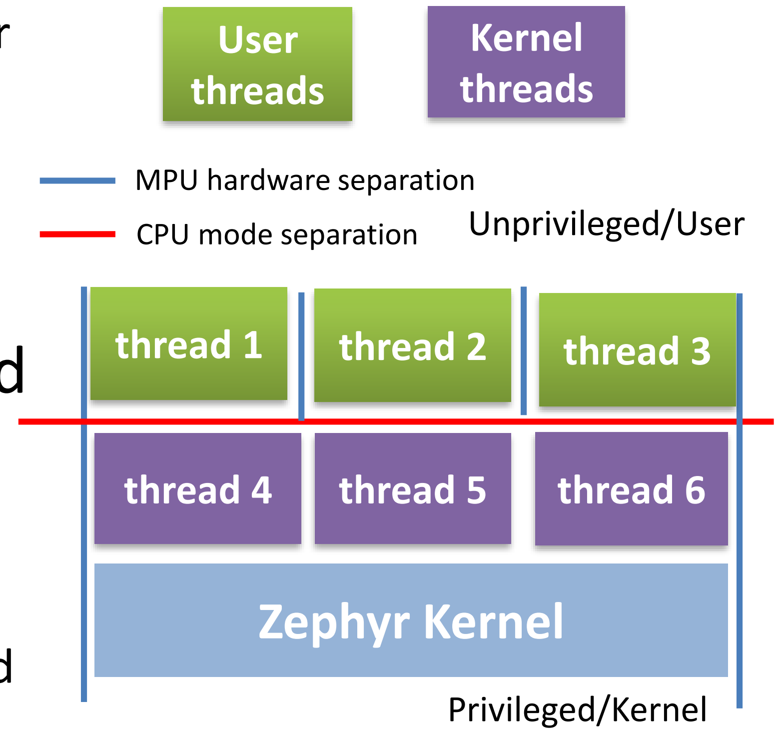
Comparison with Other RTOSes

- FreeRTOS-MPU
  - not default configuration of FreeRTOS
  - Unprivileged "User" threads with configurable memory access, system calls for privileged operations
  - Not well maintained, often doesn't compile
- ThreadX Modules
  - MPU or MMU Virtualized address spaces for separately loaded modules with thread-level memory protection features
  - Support for lots of different CPUs
  - Not free. Royalty-free license with significant upfront cost, modules feature costs extra
- NuttX Protected Build
  - Supports ARM MPU and MMU (with identity page table)
  - Unprivileged threads similar to FreeRTOS-MPU
  - Separately loaded applications
  - Many features proposed but still WIP
- Zephyr
  - Thread-level protection
  - Support for lost of different CPUS
  - Same kernel & driver APIs for kernel and user mode threads
  - Free, Apache 2.0 License
  - More features in the future

Design and Implementation in Zephyr

Threat Model

- User thread
  - Untrusted
  - Isolated from the kernel and each other
- Kernel thread and kernel
  - Trusted, privilege to access all
- A flawed or malicious user thread cannot:
  - Leak or modify private data of another thread unless specifically granted permission
  - Interfere with or control another thread except through designed thread communication APIs (pipes, semaphores, etc.)



User Mode

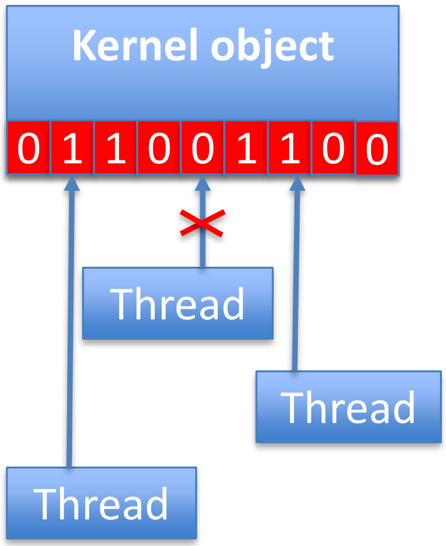
- Control access to kernel objects and device drivers
  - Per-object and per-thread basis
- Maintain compatibility with existing Zephyr APIs
- Implement system calls for privilege elevation
- Arch-specific code to enter user mode
- Validate system call parameters including kernel object pointers
- Do not require changes to individual drivers
- Manage user mode access to memory

High-Level Policy

- User threads are by default granted only
  - Read/write access to their own stack memory and application memory
  - Read-only/execute access to program text and ROM
  - Memory domain APIs to configure access to additional regions with child thread inheritance
- User threads cannot use device drivers or kernel objects without being granted permission
  - Permission granted by other threads with sufficient permission or inherited
- System call API parameters are rigorously checked
- User mode stack overflows are safely caught

Permission Model

- Each kernel object has a bitfield indicating what user threads have access to it
- Kernel threads can grant object access to any user thread
- User threads may grant object access to another user thread if the calling thread has permissions on both the object and the target user thread
- Newly created user threads may optionally inherit object permissions of the parent thread.



Kernel Object

- Three main types of kernel-private data structures
  - Kernel API data structures - *k_thread, k_sem, k_mutex, k_pipe*, etc.
  - All device driver instances
  - All thread stacks, instead of individual structs, these are arrays of a special typedef to character data

- To preserve Zephyr API compatibility, all are referenced by memory address
  - Act as a handle for user threads, object memory not accessible
  - Need a system for validating object pointers passed to system calls

Kernel Object Permissions

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- Kernel threads can access all objects
  - Permissions still tracked, because
    - Thread drops to user mode
    - Creates child user threads with object permission inheritance enabled
  - May designate some objects as "public" and usable by all threads

- User threads
  - If created with permission inheritance, gain access to all parent thread's permissions except parent thread object
  - *k_object_access_grant()* calls must have permission on both the target thread and the object being granted permission to

Kernel Object: New Type

- Creating new kernel object types is easy!
  - Add the name of the associated data structure to the build
    - Struct name itself for new kernel APIs
    - API struct name for new device driver subsystem types
  - Small modifications to some lists in two C files
    - Could eventually be automated

- Recognizing instances of kernel objects and providing a validation function for them is all handled automatically at build time

Kernel Object: Constraints

- Must be declared as a top-level global
  - Needs to appear in the kernel's ELF symbol table
  - OK to declare with static scope
  - May be embedded as members of larger data structures
- Memory for an object must be exclusive to that object
  - Can't be part of a union data type
- Must be in the kernel data section
- Objects that do not meet these constraints will not be accessible from user mode
- Future work: support runtime allocation use-cases from slabs/kernel heap

Kernel Object: Definition

- perms: permission bitfield indicating thread permissions for that object
- type: object type information enum, *K_OBJ_THREAD*, *K_OBJ_UART_DRIVER*, ...
- flags: initialization state, public/private, others as needed
- data: extra data in some cases
  - Stack object size
  - Build-time assigned thread ID

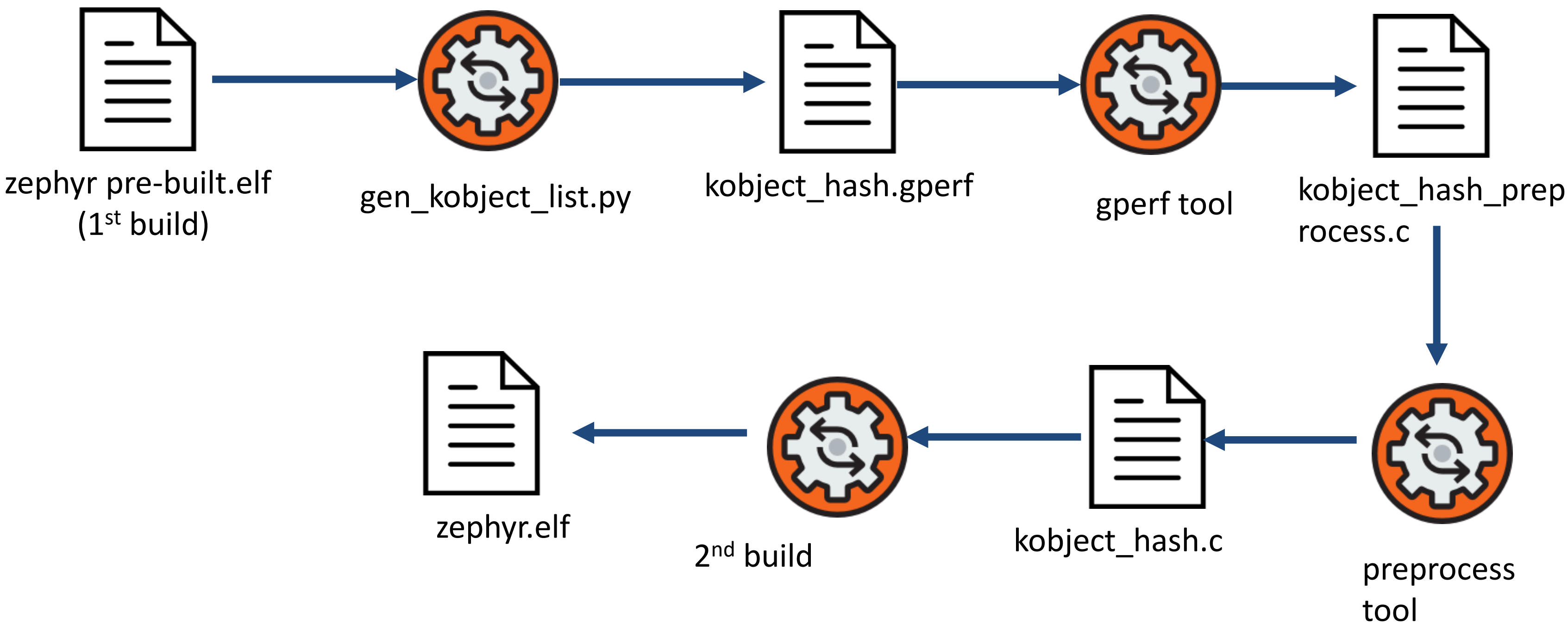
```
struct _k_object {
	char *name;
	u8_t
perms[CONFIG_MAX_THREAD_BYTES];
	u8_t type;
	u8_t flags;
	u32_t data;
}

extern struct _k_object *
_k_object_find(void *obj);
```

How to Get Kernel Object Info?

- Problem: need to find all the kernel objects
  - Map object memory addresses to instantiations of struct _k_object containing metadata
  - Validate kernel object pointers passed in from user thread

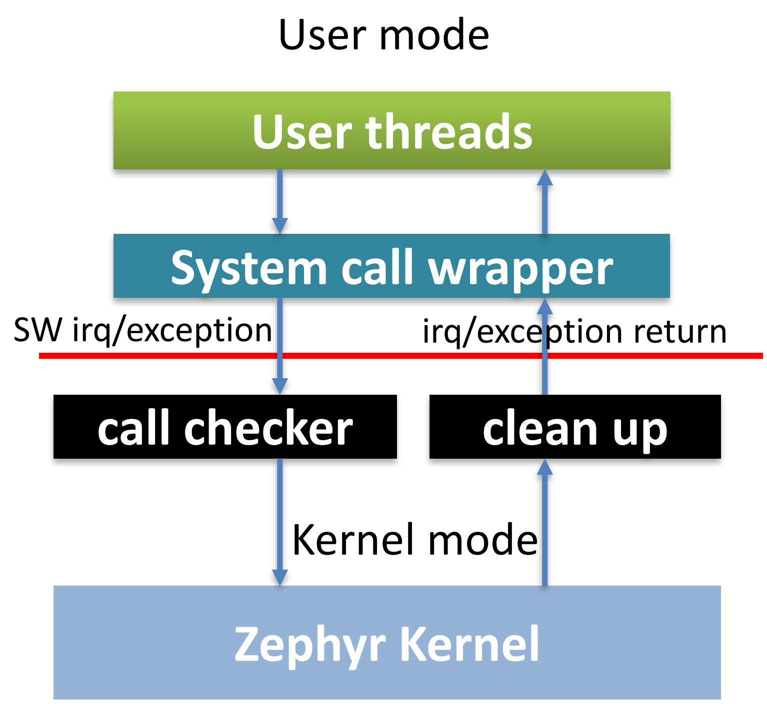
- Solution:
  - gen_kobject_list.py
    - Use pyelftools to unpack ELF binary and fetches all the DWARF debug information, and does object identification
  - gperf
    - a GNU tool for creating perfect hash tables
    - Generate the hash table of kernel objects for efficiency

Kernel Object: Flow



System Call

- Typical OS mechanism for allowing user threads to perform operations they can't do
- On all arches, API ID and parameters are marshaled into registers and a software interrupt/exception is triggered
  - Up to six registers used; additional args passed in via struct and stack
- Common landing site for system calls on kernel side
  - Validate API ID, execute the handler function
  - Clean general purpose registers on exit to prevent private data leakage
- Use build-time logic to make adding new system calls as painless as possible



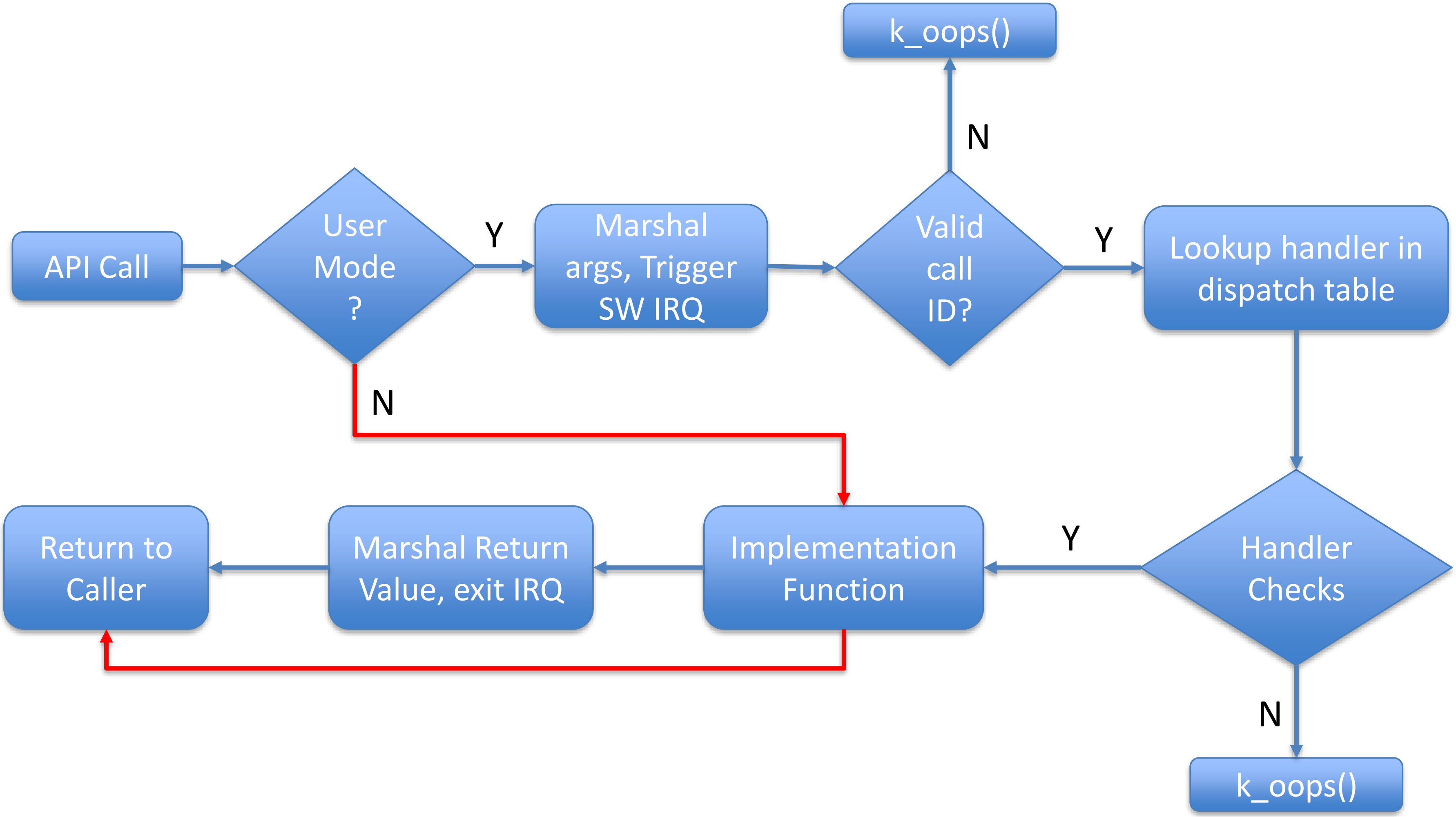
System Call: Components

- Very easy for developers to define

- Created by developer for each system call:
  - System call header prototype *__syscall void k_sleep(s32_t duration)*
  - Handler function for argument validation *Z_SYSCALL_HANDLER(k_sleep, duration)*
    - Verify caller permissions on provided memory buffers or data passed via pointer
    - Copy any parameter data passed in via pointer to local memory
    - Verify object pointers, permission, initialization state
    - Verify parameter values which are otherwise left to assertions or simply un-checked
  - Implementation function *void _impl_k_sleep(s32_t duration)*
    - Kernel object API code under *kernel/*
    - Driver subsystem API functions defined at the subsystem level

- Auto-generated for each system call:
  - System call ID enumerated type
  - Handler function prototypes
  - *_k_syscall_table* entry mapping ID to handler function
  - __weak handler function for system calls excluded from kernel config
  - System call invocation function

System Call: Flow



System Call: Build-Time Magic

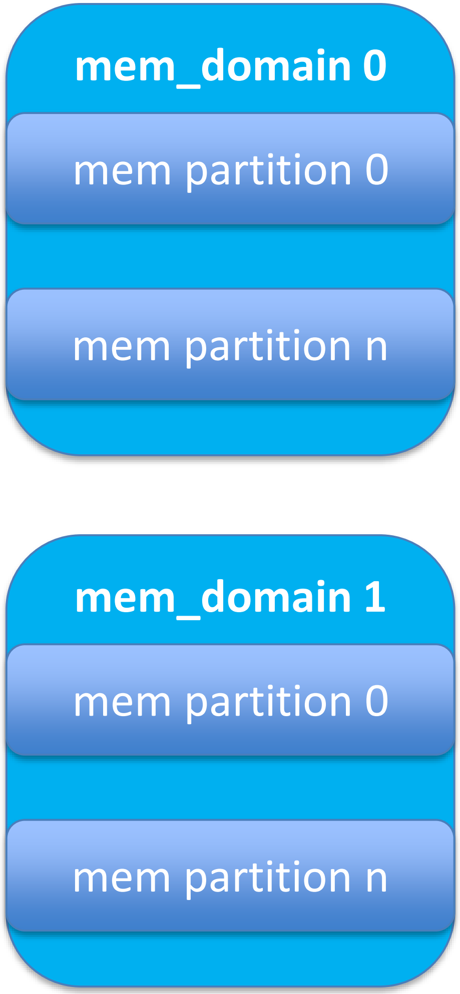
- Limited parsing of kernel header files, looking for function prototypes prefixed with "*__syscall*"
- Parsing limited to determining return value and argument types to generate additional functions
  - Some minor limitations in parsing with array/function pointer argument types which can be easily worked around
- Generated headers contains implementation of API as an inline function - invokes system call trap or direct call to implementation as appropriate
- Some generated C code for default handler and dispatch table entry

Memory Domain

- User threads by default can't look at any RAM except their own stacks
- Need a flexible way to designate additional memory areas that a thread has access to
- Limited number of total MPU regions needs to be taken into consideration
- Grant access to top-level data or BSS section globals defined and used by the thread, or application data that needs to be shared between threads
- Memory Domain APIs exist to handle re-programming the MPU for the incoming thread's memory access policy on context switch

Memory Domain: Implementation

- Memory domain APIs are kernel-access only, no system calls
- Implemented as an object *struct k_mem_domain*
  - Contains some number of memory partitions (*struct k_mem_partition*)
    - Up to the maximum number of regions supported by MPU hardware, no limit for MMU
    - Each partition is a starting address, size, and access policy
    - Hardware dictates alignment and size constraints
  - APIs to add/remove partitions to an initialized memory domain object
- Any thread may be added/removed to a particular memory domain to implement an access policy for that thread
- MPU region registers or MMU page tables updated upon context switch to activate policy for incoming thread
- Special Case: Application Memory
  - Shared to all threads, CONFIG_APPLICATION_MEMORY in Kconfig
  - All top level globals in non-kernel object files (libs, application code) placed in user read/writable section by linker and access policy configured in MMU/MPU at boot
- Facilities for grouping data by the linker (WIP)



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ARC Specific Implementation

Introduction of ARC

EM Family

- Optimized for **ultra low power** IoT
- 3-stage pipeline w/ high efficiency DSP
- Power as low as 3uW/ MHz
- Area as small as 0.01mm^2 in 28HPM
- Well supported in Zephyr

ARC EM Starter Kit

HS Family

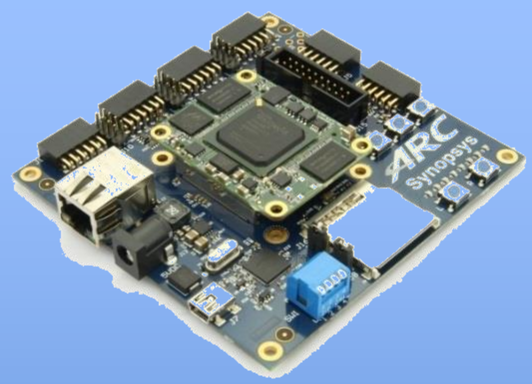
- **Highest performance** ARC cores to date
- High speed 10- stage pipeline
- SMP Linux support
- Single, dual, quad core configurations
- Support in Zephyr: in progress

ARC HS Development Kit

ARC Support in Zephyr

- ARC in Zephyr
  - *<zephyr root>/arch/arc*
  - Board:
    - ARC EM Starter Kit
    - Arduino 101 sensor subsystem
    - Quark_se based board
- Processor:
  - User/kernel mode
  - Stack overflow check
  - DSP, fast IRQ
  - SecureShield
- MPU:
  - em_starterkit_em7d_v22 (emsk 2.2 firmware)
    - MPUv2, power of 2, >2048 bytes
  - em_starterkit_em7d (emsk 2.3 firmware)
    - MPUv3, 32 bytes aligned, no overlapping

ARC EM Starter Kit



- FPGA-based board
- 128 MB DDR3 RAM + PMOD interfaces
- Fmax 20-25 MHz
- Supports all ARC EM Processors:
  - em7d, em9d, em11d
- Usage: Early protyping

Layered Approach

L4: Virtual Memory

- Zephyr "processes" in their own VM
- Demanding Pages
- Implementation in progress

L3: User thread

- User threads running in un-privileged mode
- System calls
- Stack & memory isolation
- Thread-level kernel object/driver permissions and memory policy

L2: Stack Overflow detection

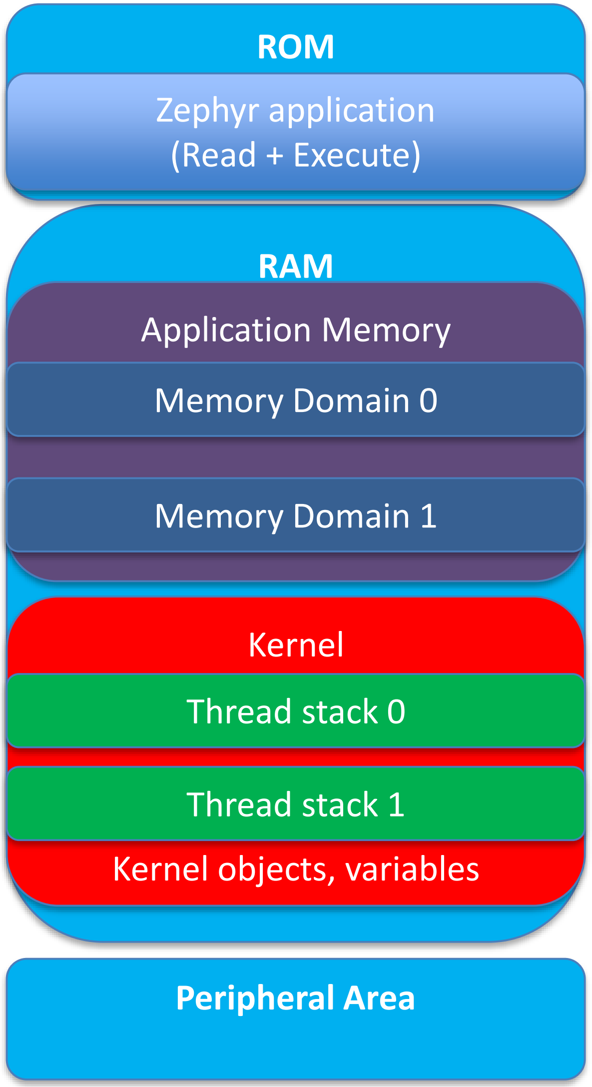
- In kernel mode
- Detection of Stack overflow errors

L1: Boot-time

- Config MMU/MPU
- No-execute for non-text
- NULL pointer dereferences
- exceptions for nonsense address

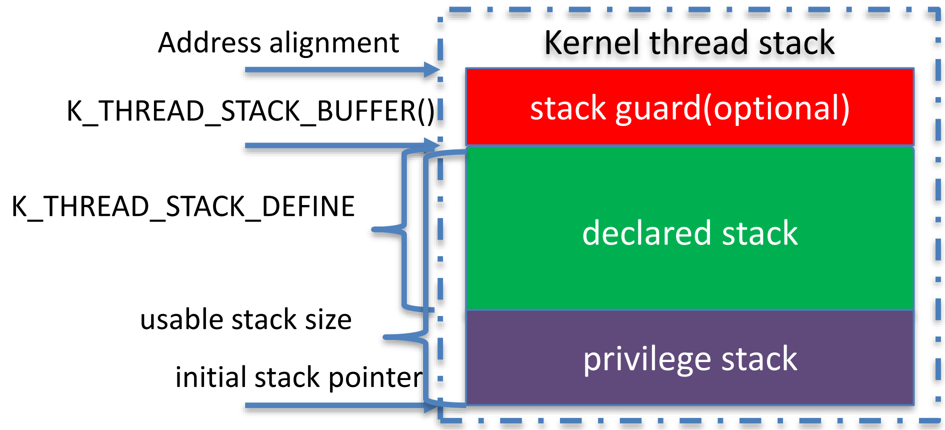
Memory Map

- Correct memory map is the foundation of memory protection
- Static MPU entries
  - Boot time memory configuration
  - ROM: 1 MPU entry, RO+EXE
  - RAM(kernel): 1 MPU entry, kernel RW
  - RAM(application memory): 1 mpu entry , User RW
  - Peripheral area: 1 mpu entry, kernel RW
- Dynamic MPU entries
  - Thread stack
  - Memory domain

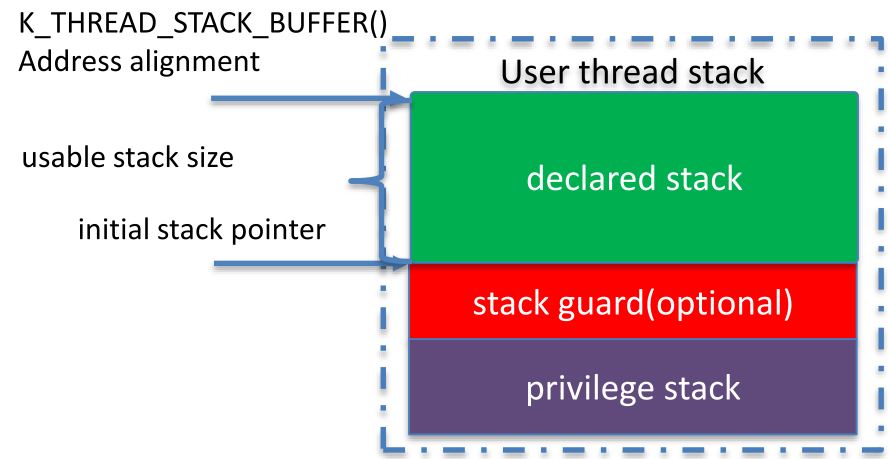


Thread Stack

- Kernel thread
  - Merge the privilege stack into thread stack for more stack space



- User thread
  - 1 MPU entry for user stack



- Stack overflow protection
  - STACK_CHECKING(optional)
    - both for user stack and privilege stack
  - MPU based: stack guard page

Future work

Runtime Kernel Object Allocation

- Not always possible to define all kernel objects used at build time
  - Build-time constraints prevent allocation of kernel objects in separately loaded application code at all
- Two approaches, both under implementation
  - Build-time defined slab pools of kernel objects
    - Pools are build-defined arrays of various objects and validated as normal
  - Kernel-side heap allocation of kernel objects
    - Supplemental runtime hash table for tracking validity of new objects
    - User mode no direct access to this heap!

Kernel API Improvements

- Not all kernel APIs exposed as system calls
  - Many combine user and private kernel data in ways which could be attacked
  - *k_mem_pool, k_poll, k_queue*
- Need some better heap features
  - *k_mem_pool* APIs were designed to be ISR-safe and not usable from user mode
  - newlib heap is just a singleton for entire address space since no VM
- Need a *k_mem_pool* equivalent that runs entirely in user mode, using memory domains to control access
- User-mode work queues
  - *k_work_q* threads currently run in kernel mode using *k_queue* for data buffering

Memory Organization Features

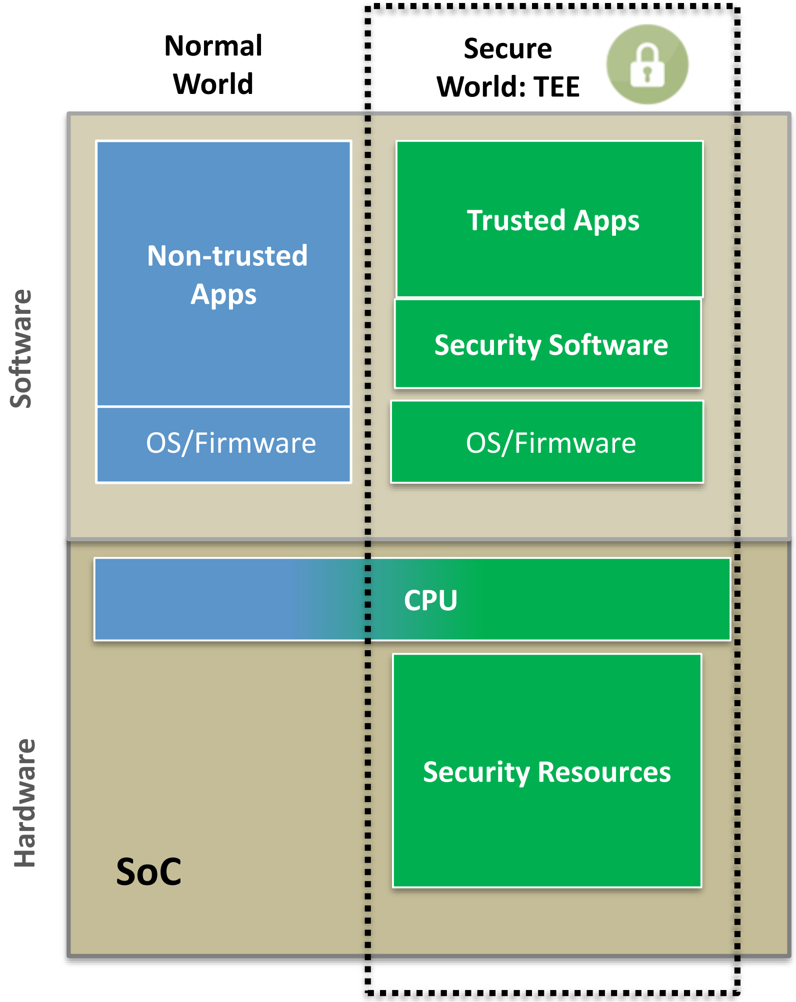
- "Application Memory" feature was useful for getting test cases up but does not work well for real-world uses

- Need a solution which handles both setting up 1..N memory areas for applications
  - Configure memory domains
  - Tie into linker scripts to ensure the data gets where it needs to be
  - Handle alignment constraints

- No design for this yet, under discussion

TEE & Secure Mode Support

- Zephyr
  - High-level design on discussion
  - Arch specific work starts
- ARM
  - Hardware: Trustzone-M, Cortex M23/33
  - Software: PR #6766, #6748, #4985 …
- ARC
  - Hardware: SecureShield, em7d of emsk 2.3
  - Software: WIP



Call To Action

- Want to learn more? Have some ideas? Get started here:
  - https://www.zephyrproject.org/
- Check out codebase on GitHub:
  - https://github.com/zephyrproject-rtos/zephyr
- Join our mailing list or hang out in our IRC channel (WeChat, etc)
- Join weekly on-line meetings, TSC meeting, secure, network, ….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