UNSW SYDNEY Australia's Global University

School of Computer Science & Engineering

**COMP9242 Advanced Operating Systems**

2020 T2 Week 01b

# Introduction: Using seL4

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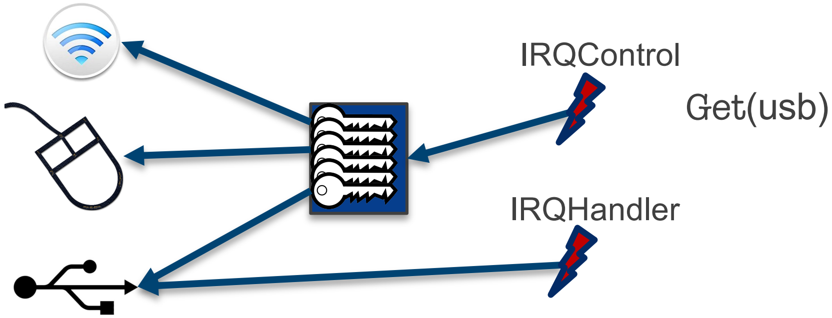
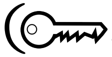


# seL4 Mechanisms

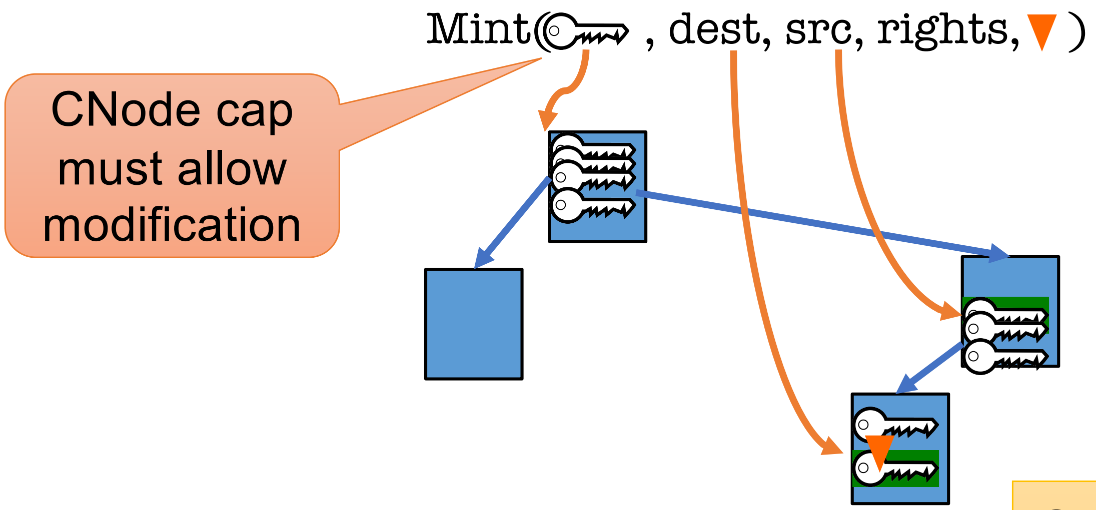
Capabilities

# Derived Capabilities

- Badging is an example of *capability derivation*
- The *Mint* operation creates a new, less powerful cap
  - Can add a badge: `Mint` (, ▼) → 
  - Can strip access rights, eg RW→R/O
- *Granting* transfers caps over an Endpoint
  - Delivers copy of sender's cap(s) to receiver
  - Sender needs Endpoint cap with Grant permission
  - Receiver needs Endpoint cap with Write permission
    - else Write permission is stripped from new cap
- *Retyping*: fundamental memory management operation
  - Details later…

Remember:
Caps are
kernel objects!

# Capability Derivation




Copy, Mint, Mutate, Revoke are invoked on CNodes

Copy takes a CNode cap as destination

- Allows copying between CSpaces
- Alternative to IPC cap transfer

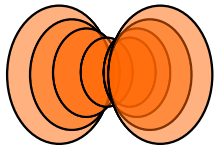
# seL4 System Calls

- seL4 has 11 syscalls:
  - Yield(): invokes scheduler
    - doesn't require a capability!
  - Send(), Recv() and variants/combinations thereof
    - Call(), ReplyRecv()
    - Send(), NBSend()
    - Recv(), NBRecv(), NBSendRecv()
    - Wait(), NBWait(), NBSendWait()
  - Call() is atomic Send() + reply-object setup + Wait()
    - cannot be simulated with one-way operations!
  - ReplyRecv() is NBSend() + Recv()

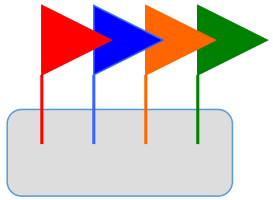
That's why I earlier said "approximately 3" 😀

# seL4 System Calls

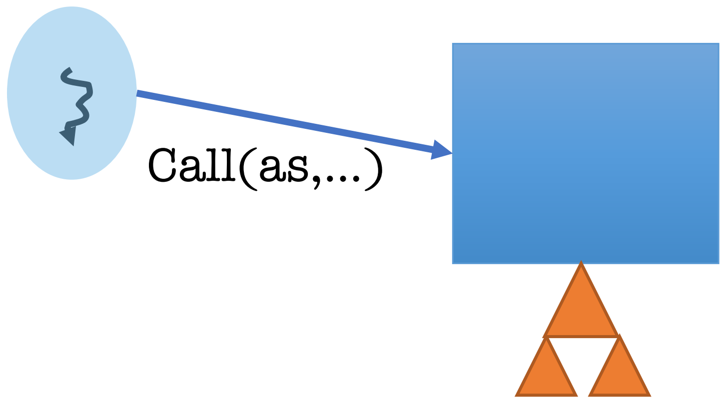
- Endpoints support all 10 IPC variants



- Notifications support:
  - NBSend() – aliased as Signal()
  - Wait()
  - NBWait() – aliased as Poll()



- Other objects only support Call()
  - Appear as (kernel-implemented) servers
  - Each has a kernel-defined protocol
    - operations encoded in message tag
    - parameters passed in message words
  - Mostly hidden behind "syscall" wrappers



# seL4 Memory-Management Principles

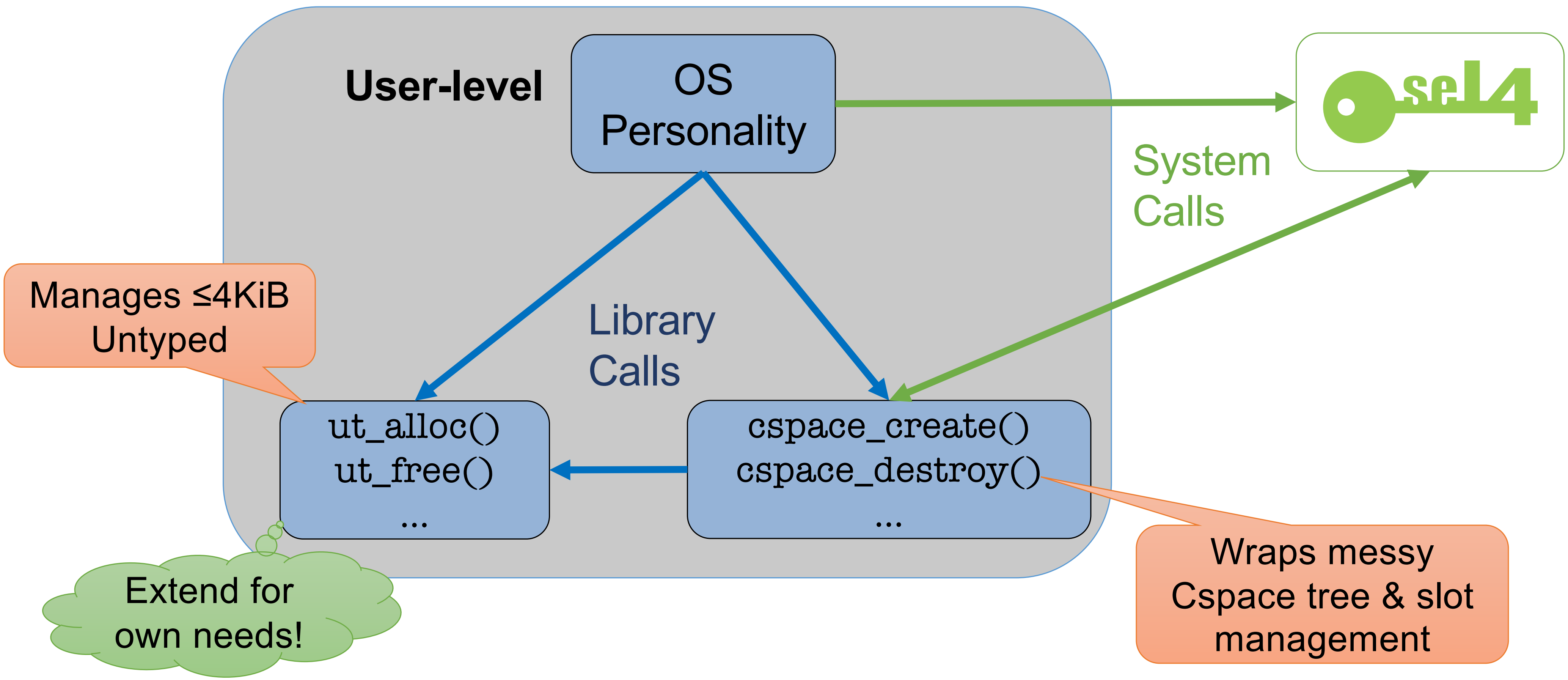
- Memory (and caps referring to it) is *typed*:
  - *Untyped* memory:
    - unused, free to `Retype` into something else
  - Frames:
    - (can be) mapped to address spaces, no kernel semantics
  - Rest: TCBs, address spaces, CNodes, EPs, …
    - used for specific kernel data structures
- After startup, kernel *never* allocates memory!
  - All remaining memory made Untyped, handed to initial address space
- Space for kernel objects must be explicitly provided to kernel
  - Ensures strong resource isolation
- Extremely powerful tool for shooting oneself in the foot!
  - We hide much of this behind the *cspace* and *ut* allocation libraries

# CSpace Operations

```
int cspace_create_two_level(cspace_t *bootstrap, cspace_t *target, cspace_alloc_t cspace_alloc);
int cspace_create_one_level(cspace_t *bootstrap, cspace_t *target);
void cspace_destroy(cspace_t *c);
seL4_CPtr cspace_alloc_slot(cspace_t *c);
void cspace_free_slot(cspace_t *c, seL4_CPtr slot);
```

```
seL4_Error cspace_copy(cspace_t *dest, seL4_CPtr dest_cptr, cspace_t *src,
                       seL4_CPtr src_cptr, seL4_CapRights_t rights)
cspace_delete(cspace_t *cspace, seL4_CPtr cptr)
seL4_Error cspace_mint(cspace_t *dest, seL4_CPtr dest_cptr, cspace_t *src,
                       seL4_CPtr src_cptr, seL4_CapRights_t rights, seL4_Word badge)
cspace_move(cspace_t *dest, seL4_CPtr dest_cptr, cspace_t *src, seL4_CPtr src_cptr)
seL4_Error cspace_mutate(cspace_t *dest, seL4_CPtr dest_cptr, cspace_t *src,
                         seL4_CPtr src_cap, seL4_Word badge)
seL4_Error cspace_revoke(cspace_t *cspace, seL4_CPtr cptr)
seL4_Error cspace_save_reply_cap(cspace_t *cspace, seL4_CPtr cptr)
seL4_Error cspace_irq_control_get(cspace_t *dest, seL4_CPtr cptr, seL4_IRQControl irq_cap, int irq, int level)
seL4_Error cspace_untyped_retype(cspace_t *cspace, seL4_CPtr ut,  seL4_CPtr target,
                                 seL4_Word type, size_t size_bits);
```

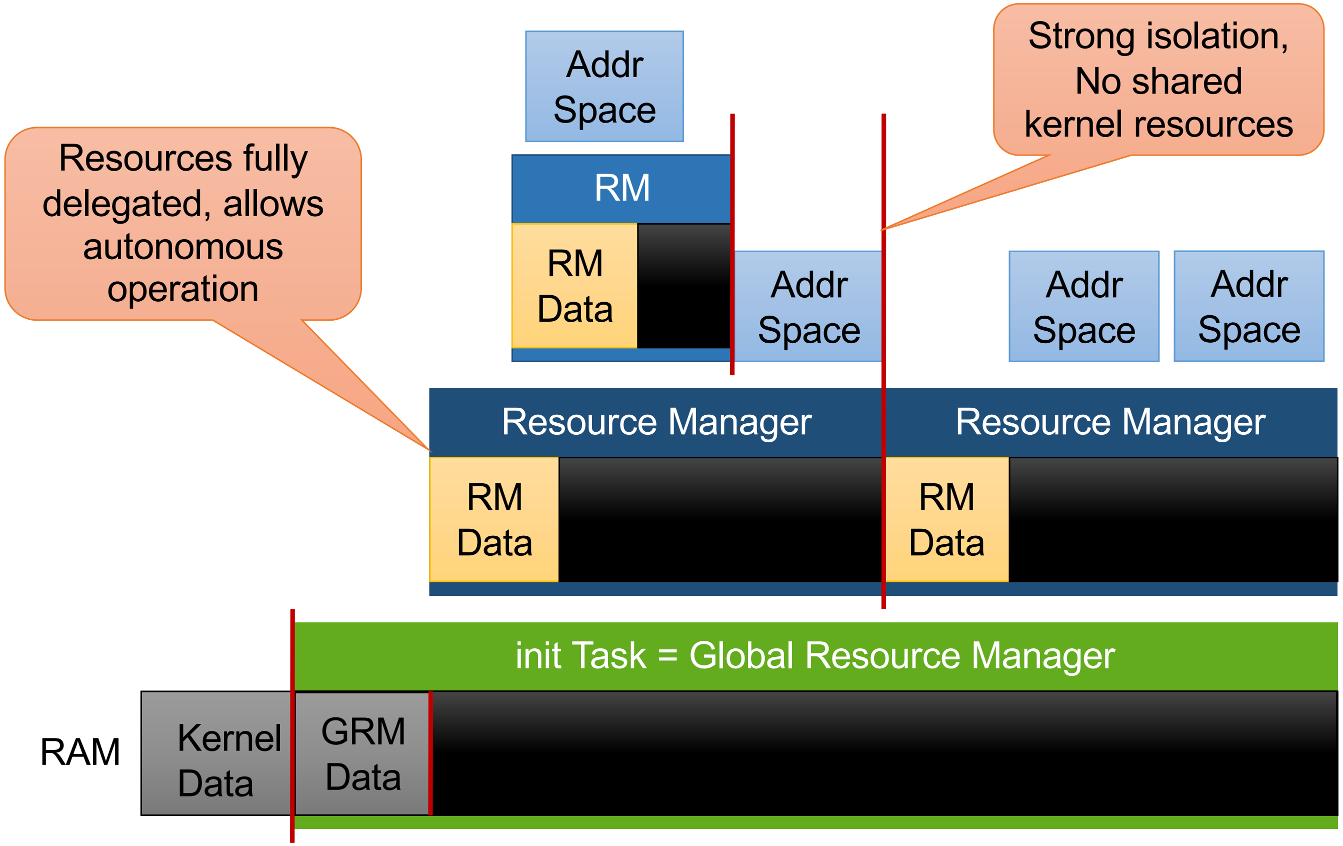
# Project: cspace and ut libraries



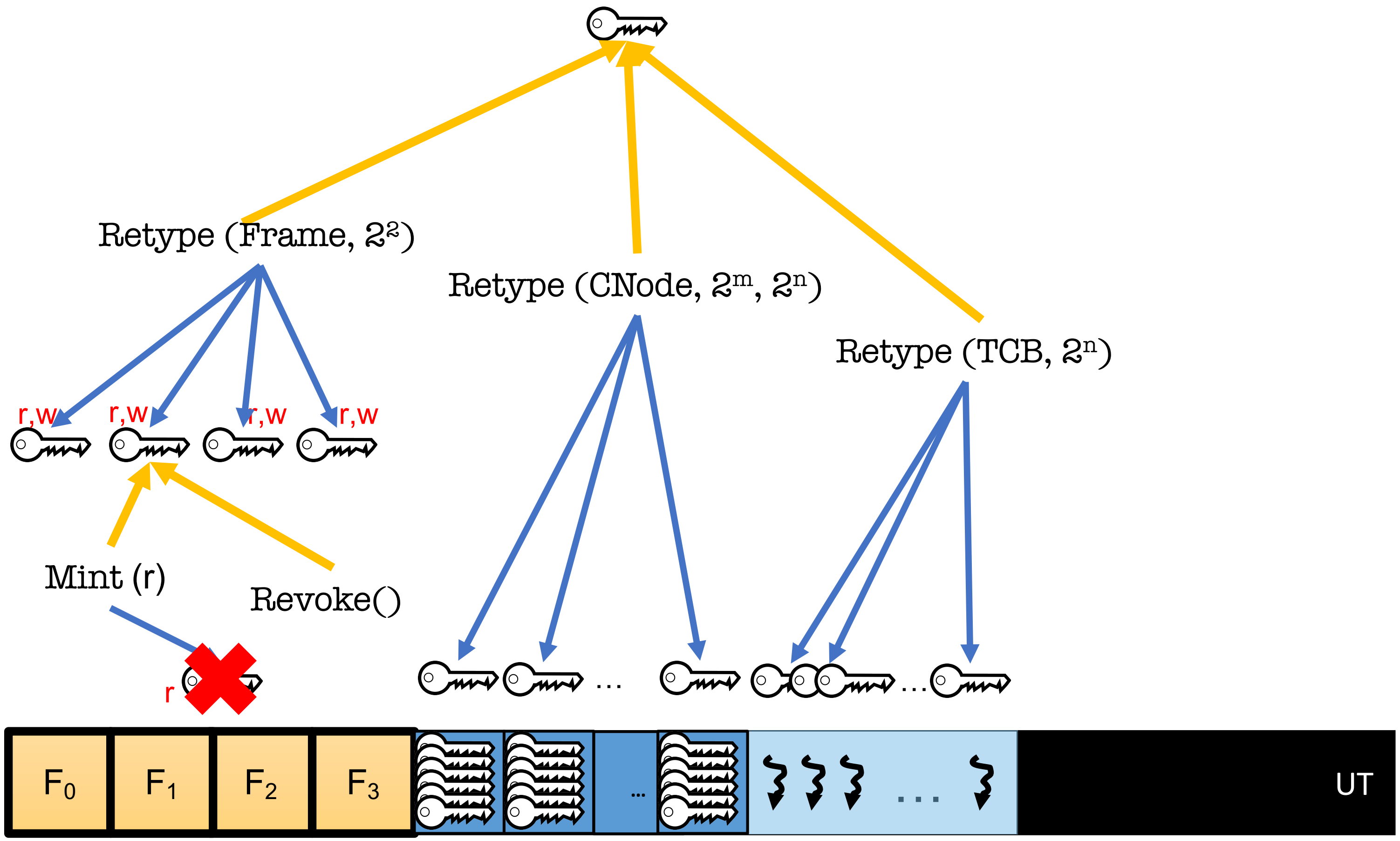
# seL4 Mechanisms

Address Spaces and Memory Management

# seL4 Memory Management Approach

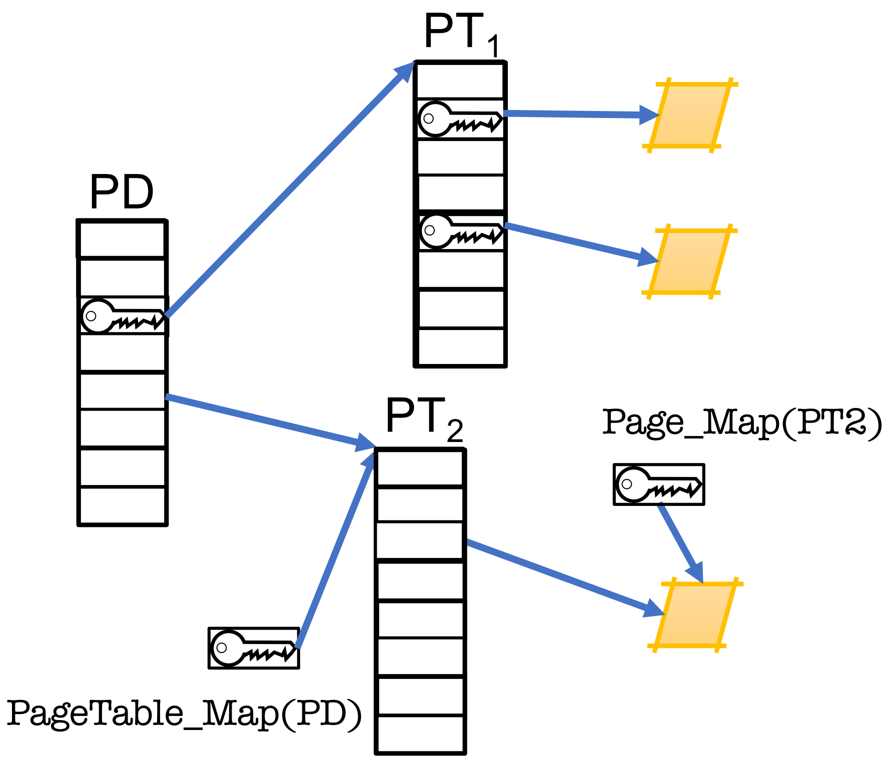


# Memory Management Mechanics: Retype



# seL4 Address Spaces (VSpaces)

- Very thin (arch-dependent) wrapper of hardware page tables
  - Arm & x86 similar (32-bit 2-level, 64-bit 4–5 level)
- Arm 64-bit ISA (AARCH64):
  - page global directory (PGD)
  - page upper directory (PUD)
  - page directory (PD)
  - page table (PT)
- PGD object represents VSpace:
  - Creating a PGD (by Retype) creates the VSpace
  - Deleting PGD deletes VSpace



# Address Space Operations

Poor API choice!

```
seL4_Word paddr = 0;
ut_t *ut = ut_alloc_4k_untyped(&paddr);
seL4_CPtr frame = cspace_alloc_slot(&cspace);
err = cspace_untyped_retype(&cspace, ut->cap, frame,
                seL4_ARM_SmallPageObject, seL4_Pa
err = map_frame(&cspace, frame, pgd_cap, 0xA0000000,
                seL4_AllRights, seL4_Default_VMAttributes);
```

Cap to top-level page table

Each mapping has:

- virtual_address, phys_address, address_space and frame_cap
- address_space struct identifies the level 1 page_directory cap
- you need to keep track of (frame_cap, PD_cap, v_adr, p_adr)!

```
seL4_ARCH_Page_Unmap(frame_cap);
cspace_delete(&cspace, frame);
cspace_free_slot(&cspace, frame);
ut_free(ut, seL4_PageBits);
```

# Multiple Frame Mappings: Shared Memory

```
seL4_CPtr new_frame_cap = cspace_alloc_slot(&cspace);
seL4_Error err = cspace_copy(&cspace, new_frame_cap,
                             &cspace, frame, seL4_AllRights);
err = map_frame(&cspace, new_frame_cap, pgd_cap, 0xA0000000,
                seL4_AllRights, seL4_Default_VMAttributes);
```

Allocate frame

Duplicate cap

Map frame

Each mapping requires its own frame cap even for the same frame!

```
seL4_ARCH_Page_Unmap(frame);
cspace_delete(&cspace, frame);
cspace_free_slot(&cspace, frame);
seL4_ARCH_Page_Unmap(new_frame_cap);
cspace_delete(&cspace, new_frame_cap);
cspace_free_slot(&cspace, new_frame_cap);
ut_free(ut, seL4_PageBits);
```

# Memory Management Caveats

- The UT table handles allocation for you
- But: very simple buddy-allocator:
  - Freeing an object of size *n* ⇒ can allocate new objects ≤ size *n*
  - Freeing 2 objects of size *n* ⇏ can allocate an object of size *2n.*

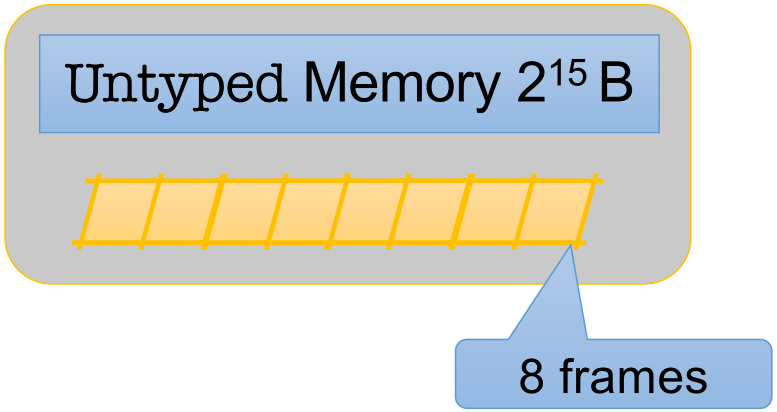
| Object | Size (B) | Align (B) |
|---|---|---|
| Frame | $2^{12}$ | $2^{12}$ |
| PT/PD/PUD/PGD | $2^{12}$ | $2^{12}$ |
| Endpoint | $2^{4}$ | $2^{4}$ |
| Notification | $2^{5}$ | $2^{5}$ |
| Scheduling Context | $\geq 2^{8}$ | $2^{8}$ |
| Cslot | $2^{4}$ | $2^{4}$ |
| Cnode | $\geq 2^{12}$ | $2^{12}$ |
| TCB | $2^{11}$ | $2^{11}$ |

Values for AARCH64

# Memory-Management Caveats

- Objects are allocated by Retype() of Untyped memory
- The kernel will not allow you to overlap objects
- ut_alloc and ut_free() manage user-level view of allocation.
  - Major pain if kernel and user view diverge
  - TIP: Keep objects address and CPtr together!

But debugging nightmare if you try!!




- Be careful with allocations!
- Don't try to allocate all of physical memory as frames, you need more memory for TCBs, endpoints etc.
- Your frametable will eventually integrate with ut_alloc to manage the 4KiB untyped size.

# seL4 Mechanisms

Threads

# Threads

- Theads are represented by TCB objects
- They have a number of attributes (recorded in TCB):
  - VSpace: a virtual address space, can be shared by multiple threads
  - CSpace: capability storage
  - *Fault endpoint* and *timeout endpoint*
  - IPC buffer (backing storage for virtual registers)
  - stack pointer (SP), instruction pointer (IP), general-purpose registers
  - *Scheduling priority* and *maximum controlled priority (MCP)*
  - *Scheduling context*: right to use CPU time
- These must be explicitly managed – we provide examples

PGD reference

CNode reference: root of CSpace

Invoked by kernel upon exception

# Threads

**Creating a thread:**

- Obtain a TCB object
- Set attributes: Configure()
  - associate with VSpace, CSpace, fault EP, define IPC buffer
- Set scheduling parameters
  - priority, scheduling context, timeout EP (maybe MCP)
- Set SP, IP (and optionally other registers): WriteRegisters()

Thread is now initialised
- if resume_target was set in call thread is runnable
- else activate with Resume()

# Creating a Thread in Own AS and Cspace

```
static char stack[100];
int thread_fct() {
        while(1);
        return 0;
}

ut_t *ut = ut_alloc(seL4_TCBBits, &cspace);
seL4_CPtr tcb = cspace_alloc_slot(&cspace);
err = cspace_untyped_retype(&cspace, ut->cap, tcb, seL4_TCBObject, seL4_TCBBits);

err = seL4_TCB_Configure(tcb, cspace.root_cnode, seL4_NilData, seL4_CapInitThreadVSpace,
                         seL4NilData, PROCESS_IPC_BUFFER, ipc_buffer_cap);
if (err != seL4_NoError) return err;

err = seL4_TCB_SetSchedParams(tcb, seL4_CapInitThreadTCB, seL4_MinPrio,
                              TTY_PRIORITY, sched_context, fault_ep);
```

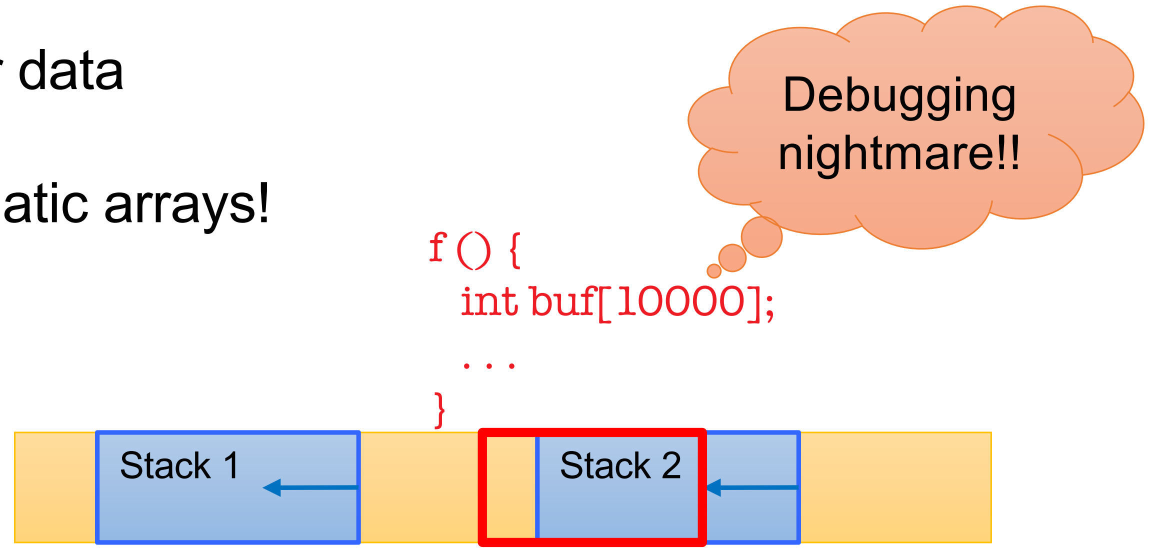
Alloc & map frame for IPC buffer

Alloc slot

Tip: If you use threads, write a library for create/destroy!

# Threads and Stacks

- Stacks are completely user-managed, kernel doesn't care!
  - Kernel only preserves SP, IP on context switch
- Stack location, allocation, size must be managed by userland
- Beware of stack overflow!
  - Easy to grow stack into other data
    - Pain to debug!
  - Take special care with automatic arrays!



# Creating a Thread in *New* AS and CSpace

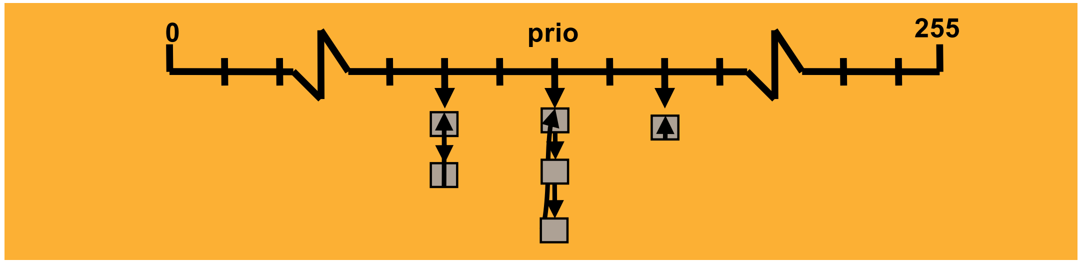
```
/* Allocate, retype and map new frame for IPC buffer as before
 * Allocate and map stack???
 * Allocate and retype a TCB  as before
 * Allocate and retype a  PageGlobalDirectoryObject of size seL4_PageDirBits
 * Mint a new badged cap to the syscall endpoint
 */
cspace_t * new_cpace = ut_alloc(seL4_TCBBits);

char *elf_base = cpio_get_file(_cpio_archive, app_name, &elf_size);
seL4_Word sp = init_process_stack(&cspace, new_pgd_cap, elf_base);
err = elf_load(&cspace, seL4_CapInitThreadVSpace, tty_test_process.vspace, elf_base);
err = seL4_TCB_Configure(tcb, new_cspace.root_cnode, seL4_NilData, new_pgd_cap
                         seL4NilData, PROCESS_IPC_BUFFER, ipc_buffer_cap);

seL4_UserContext context = {
        .pc = elf_getEntryPoint(elf_base),
        .sp = sp,
    };
err = seL4_TCB_WriteRegisters(tty_test_process.tcb, 1, 0, 2, &context);
```

# seL4 Scheduling

- 256 hard priorities (0–255), strictly observed
  - The scheduler will always pick the highest-prio runnable thread
  - Round-robin within priority level
  - Kernel will never change priority (but can do with syscall)
- Thread with no scheduling context or no budget is not runnable
  - SC contains *budget*: when exhausted, thread removed from run queue
  - SC contains *period*: specifies when budget is replenished
  - Budget = period: Operates as a time slice




> Aim is real-time performance, not fairness!
> - Can implement fair policy at user level

# seL4 Mechanisms

Interrupts and Exceptions

# Exception Handling

**Exception types:**

- invalid syscall
  - eg for instruction emulation, virtualisation
- capability fault
  - cap lookup failed or found invalid cap
- page fault
  - address not mapped
  - maybe invalid address
  - maybe grow stack, heap, load library…
- architecture-defined
  - divide by zero, unaligned access, …
- timeout
  - scheduling context out of budget

has its own fault endpoint

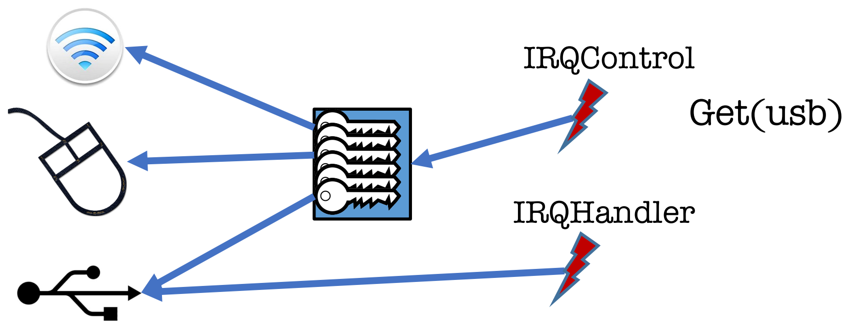
On exception:

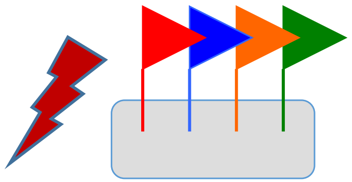
- message sent to fault endpoint
- pretends to be from faulter
- replying will restart thread

# Interrupt Management

2 special objects for managing and acknowledging interrupts:

- Single IRQControl object
  - single IRQControl cap provided by kernel to initial VSpace
  - only purpose is to create IRQHandler caps
- Per-IRQ-source IRQHandler object
  - interrupt association and dissociation
  - interrupt acknowledgment
  - edge-triggered flag

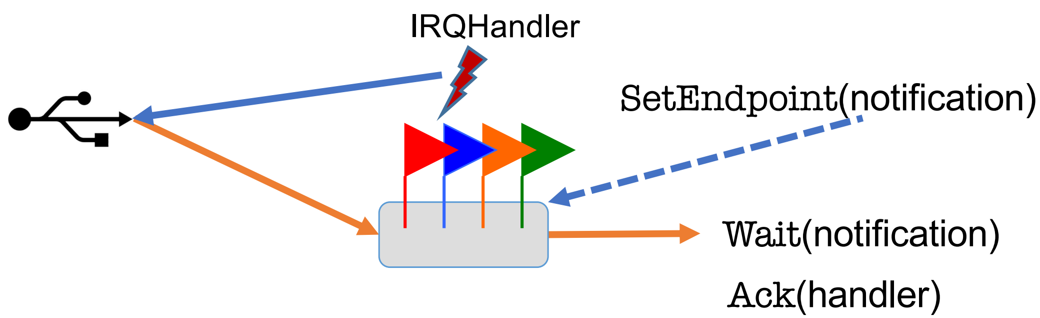




# Interrupt Handling

IRQHandler cap allows driver to bind Notification to interrupt

- Notification is used to receive interrupt
- IRQHandler is used to acknowledge interrupt




Unmasks IRQ

```
seL4_CPtr irq = cspace_alloc_slot(&cspace);
seL4_Error err = cspace_irq_control_get(&cspace, irq, seL4_CapIRQControl,
                                        irq_number, true_if_edge_triggered);
seL4_IRQHandler_SetNotification(irq, ntfn);
seL4_IRQHandler_Ack(irq);
```

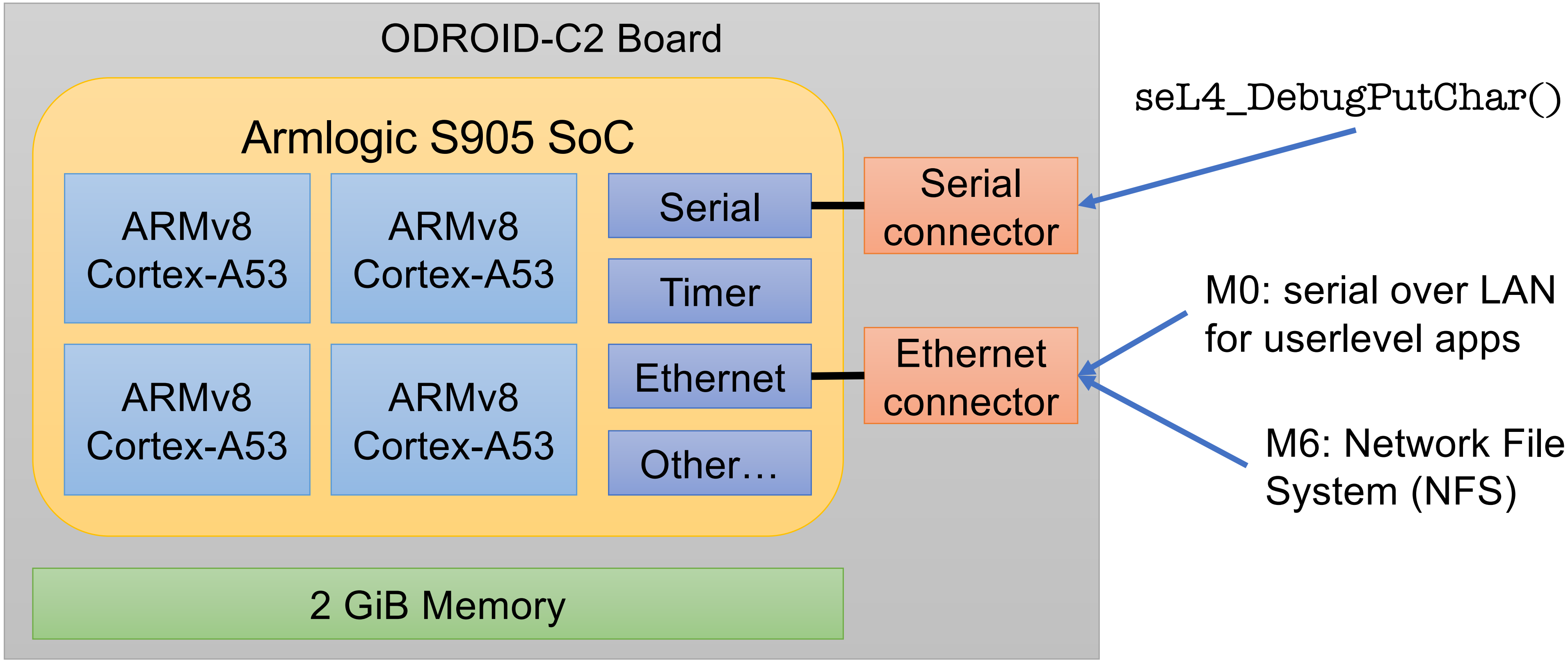
# Device Drivers

- In seL4 (and all other L4 kernels) drivers are usermode processes
- Drivers do three things:
  - Handle interrupts (already explained)
  - Communicate with rest of OS (IPC + shared memory)
  - Access device registers
- Device register access (ARM uses memory-mapped IO)
  - Have to find frame cap from bootinfo structure
  - Map the appropriate page in the driver's VSpace

Magic device register access

```
device_vaddr = sos_map_device(&cspace, 0xA0000000, BIT(seL4_PageBits));
...
*((void *) device_vaddr= ...;
```

# Project Platform: ODROID-C2



# seL4 in the Real World (Courtesy Boeing, DARPA)