School of Computer Science & Engineering

COMP9242 Advanced Operating Systems

2024 T3 Week 01 Part 2

Introduction: Using seL4

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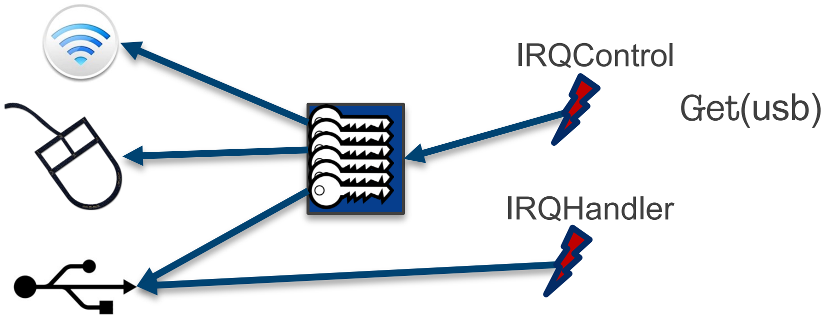

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Today’s Lecture

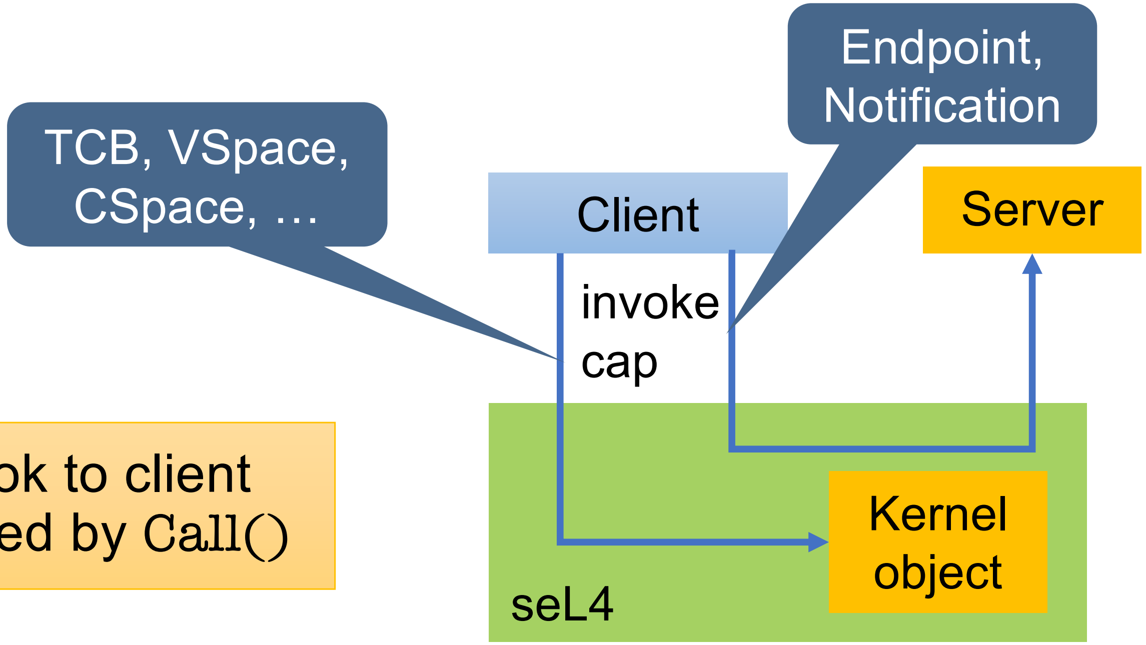
- seL4 Mechanisms
  - Capabilities
  - Address spaces & memory management
  - Threads
  - Interrupts and Exceptions
- seL4 System Design Hints

Aim: You should then be ready to start the project

seL4 Mechanisms

Capabilities

Conceptually: Invoke Service Through Cap



Kernel services look to client like servers, invoked by `Call()`

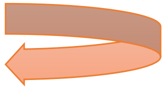
seL4 System Calls [1/3]

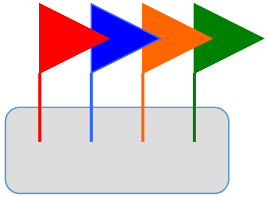
That's why I earlier said "approximately 3" 😀

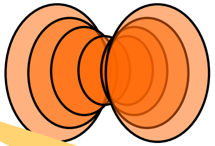
- seL4 has 11 syscalls:
  - **Yield**(): invokes scheduler
    - doesn't require a capability!
  - **Call**(), **ReplyRecv**() and (variants/combinations thereof) invoke cap
    - Send(), NBSend()
    - Recv(), NBRecv(), NBSendRecv()
    - Wait(), NBWait(), NBSendWait()
  - Call() is atomic Send() +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

seL4 System Calls [2/3]

- Endpoints support all 10 Send/Receive variants
- ROs support:
  - NBSend ()
  - NBSendRecv()
- Notifications support:
  - NBSend() – aliased as Signal()
  - Wait()
  - NBWait() – aliased as Poll()



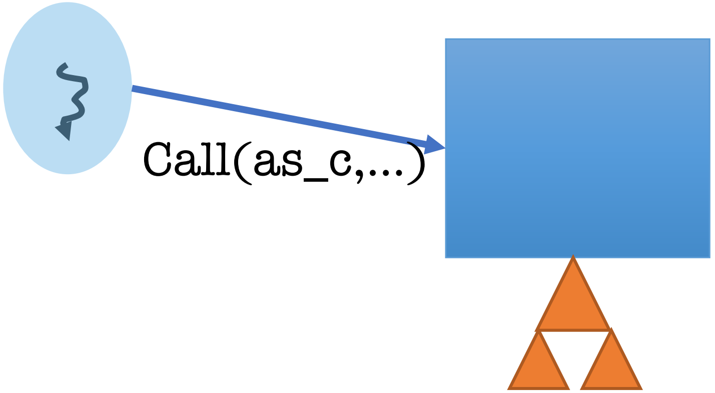




But remember, you should normally use Call() and ReplyRecv()

seL4 System Calls [3/3]

- Endpoints support all 10 IPC variants
- ROs support NBSend (), NBSendRecv()
- Notifications support NBSend(), Wait(), NBWait
- 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



Most of this is hidden behind "syscall" wrappers

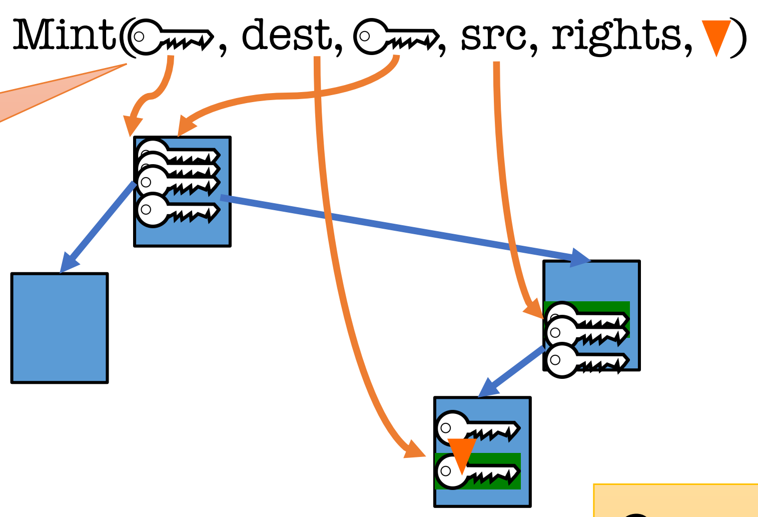
Derived Capabilities

- *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

CNode cap must allow modification



Mint(🔑, dest, 🔑, src, rights, ▼)

Copy, Mint, Mutate, Revoke are invoked on CNodes

Copy takes a CNode cap as destination

- Allows copying between CSpaces
- Alternative to cap transfer by PPC

seL4 Memory-Management Principles

- Memory (and caps referring to it) is *typed*:
  - *Untyped* memory:
    - unused, free to `Retype` into something useful
  - 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 gun for shooting yourself in the foot!
  - We hide much of this behind the *cspace* and *ut* allocation libraries

CSpace Operations

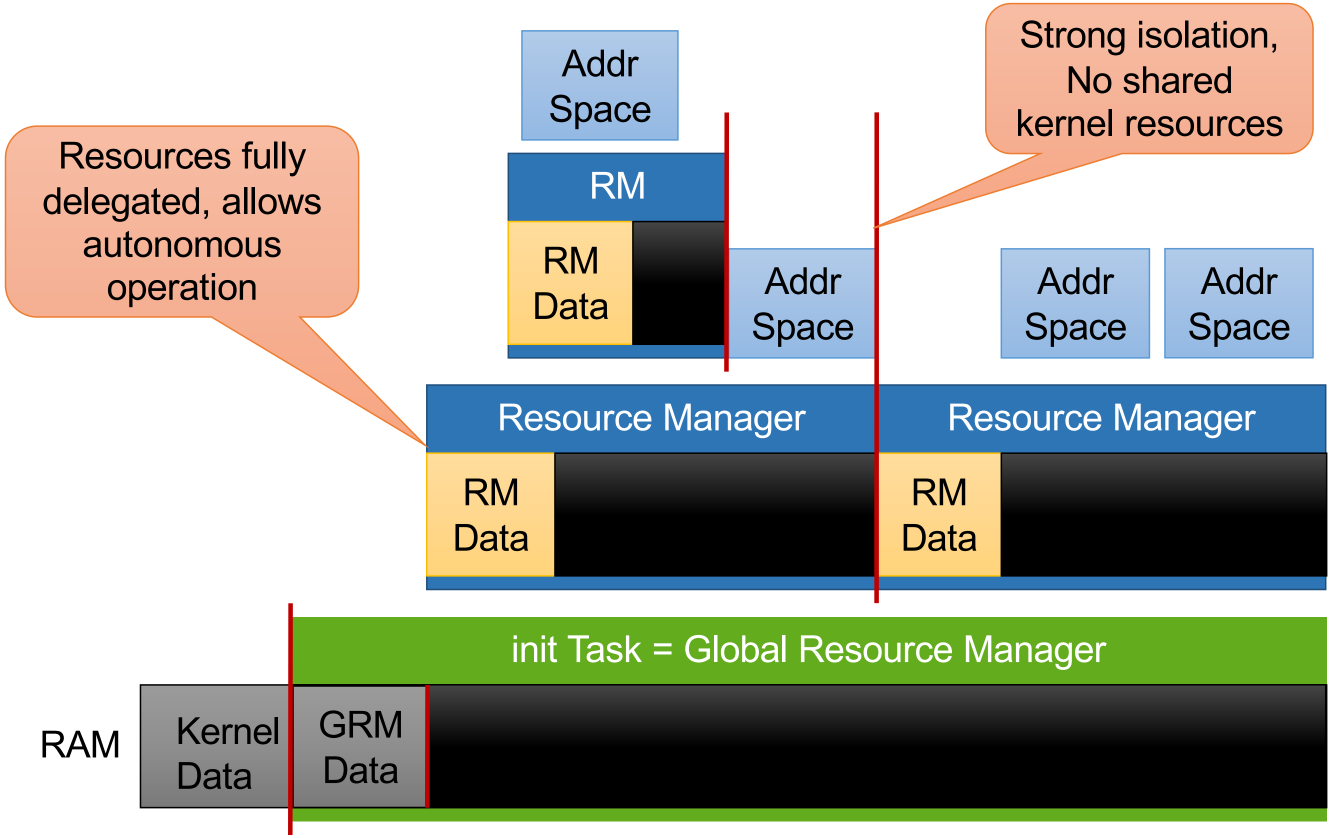
```
int cspace_create_two_level(cspace_t *bootstrap, cspace_t *target, cspace_alloc_t cspace_alloc);
int cspace_create_one_level(cspace_t *bootstrap, cspace_t *target);
void cspace_destroy(cspace_t *c);
seL4_CPtr cspace_alloc_slot(cspace_t *c);
void cspace_free_slot(cspace_t *c, seL4_CPtr slot);
```

```
seL4_Error cspace_copy(cspace_t *dest, seL4_CPtr dest_cptr, cspace_t *src,
                        seL4_CPtr src_cptr, seL4_CapRights_t rights)
seL4_Error 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)
seL4_Error 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);
```

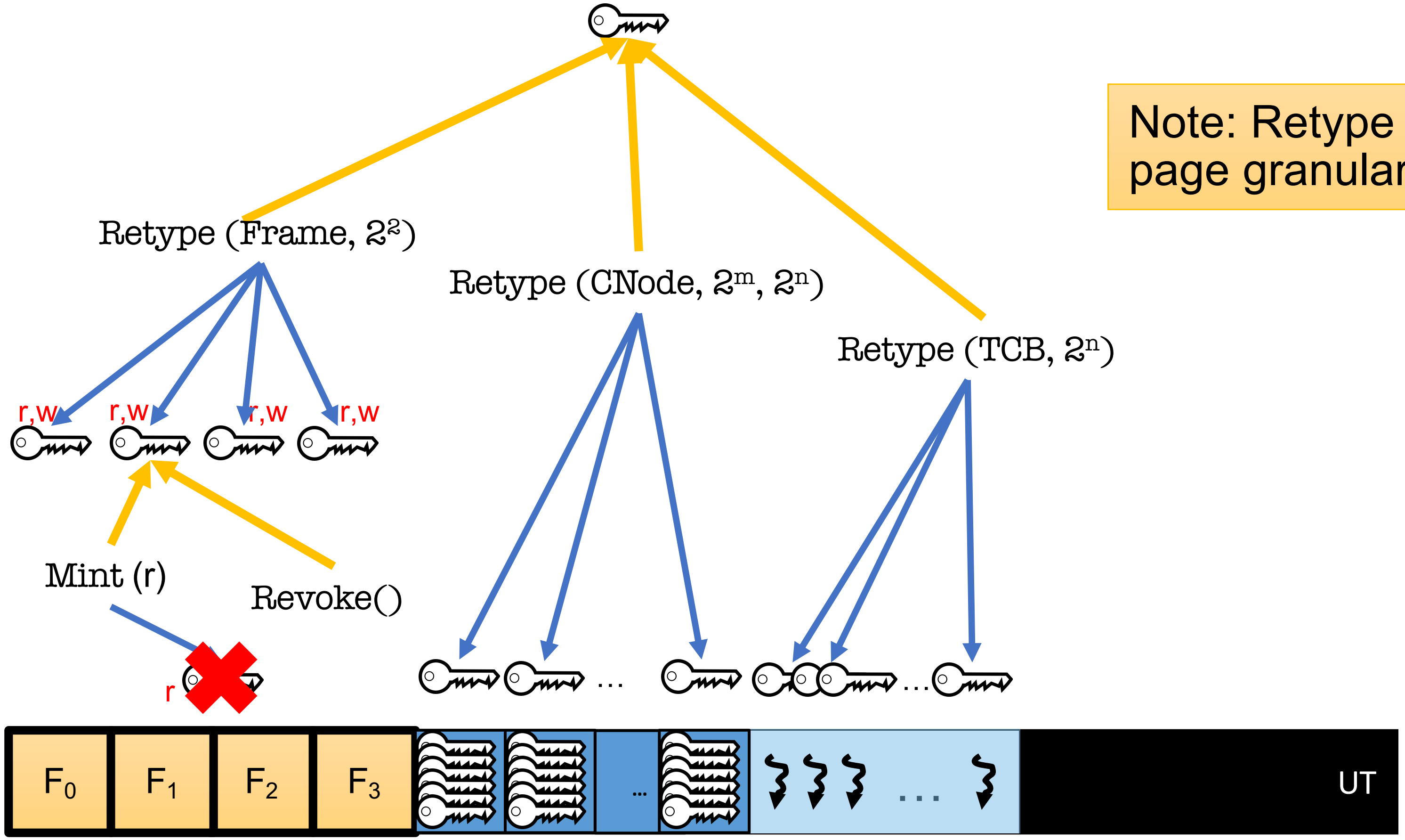
seL4 Mechanisms

Address Spaces and Memory Management

seL4 Memory Management Approach


Addr Space
Strong isolation, No shared kernel resources
RM
Resources fully delegated, allows autonomous operation
RM Data
Addr Space
Addr Space
Addr Space
Resource Manager
Resource Manager
RM Data
RM Data
init Task = Global Resource Manager
RAM
Kernel Data
GRM Data

Memory Management Mechanics: Retype



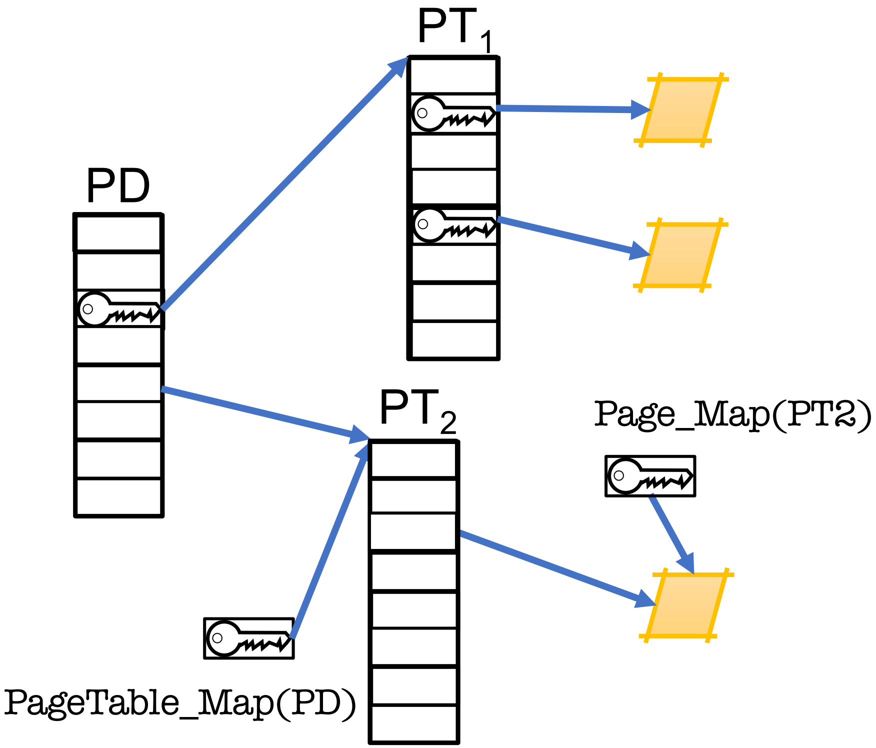
Note: Retype has page granularity!

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

```
seL4_Word paddr = 0;
ut_t *ut = ut_alloc_4k_untyped(&p_addr);
seL4_CPtr frame = cspace_alloc_slot(&cspace);
err = cspace_untyped_retype(&cspace, ut->cap, frame
                   seL4_ARM_SmallPageObject, seL4_PageBits);
err = map_frame(&cspace, frame, pgd, v_addr,
                   seL4_AllRights, seL4_Default_VMAttributes);
```

Poor API choice!

Cap to top-level page table

Each frame 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, PD, v_addr, p_addr)!

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

Poor API choice!

Multiple Frame Mappings: Shared Memory

```
seL4_CPtr new_frame = cspace_alloc_slot(&cspace);
seL4_Error err = cspace_copy(&cspace, new_frame,
                             &cspace, frame, seL4_AllRights);
err = map_frame(&cspace, new_frame, pgd, new_v_addr,
                    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);
cspace_delete(&cspace, new_frame);
cspace_free_slot(&cspace, new_frame);
ut_free(ut, seL4_PageBits);
```

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, can be shared
- *Fault endpoint* and *timeout endpoint*
- IPC buffer (backing storage for virtual message registers)
- stack pointer (SP), instruction pointer (IP), general-purpose registers
- *Scheduling priority* and *maximum controlled priority (MCP)*
- *Scheduling context*: right to use CPU time

PGD reference:
root of VSpace

CNode reference:
root of CSpace

Invoked by kernel
upon exception

These must be explicitly managed

- we provide examples
- you probably don’t need to deal with scheduling parameters

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);
if (err != seL4_NoError) return err;

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

Alloc & map frame for IPC buffer

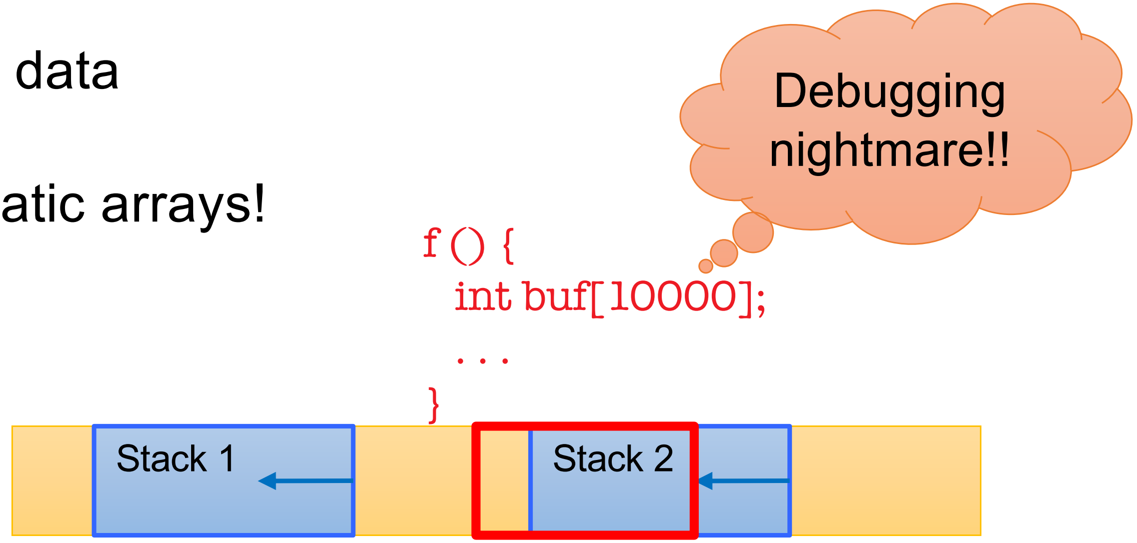
Alloc slot

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!

Recommend leaving page beyond top of stack unmapped!



Debugging nightmare!!

```
f() {
  int buf[10000];
  ...
}
```

Creating a Thread in *New* AS and CSpace

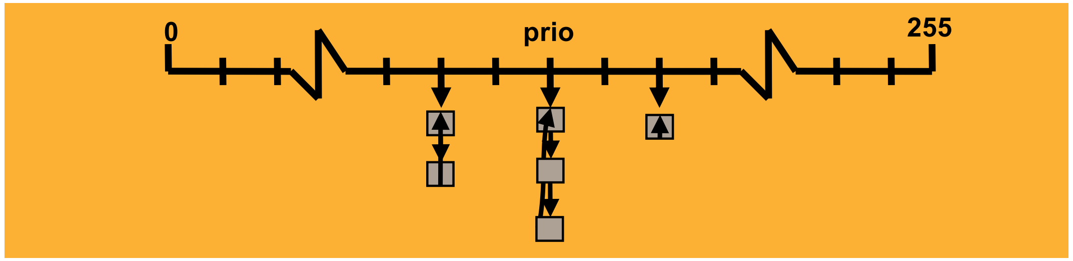
```
/* Allocate, retype and map new frame for IPC buffer as before
 * Allocate and map stack – note: this leaks, see m3, m6
 * Allocate and retype a TCB  as before
 * Allocate and retype a  PageGlobalDirectoryObject of size seL4_PageDirBits
 * Mint a new badged cap to the syscall endpoint */
cspace_t *new_cspace = ut_alloc(seL4_TCBBits);
elf_t elf_file;

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

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

seL4 Scheduling (MCS kernel)

- 256 hard priorities (0 is lowest, 255 highest), strictly observed
  - The scheduler will always pick the highest-prio runnable thread
  - Round-robin within priority level
  - Kernel will never change priority (but user can do with syscall)
- Thread without scheduling context or 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 best-effort time slice (round robin)



Aim is real-time performance, not fairness!

- Can implement fair policy at user level

seL4 Mechanisms

Interrupts and Exceptions

Exception Handling

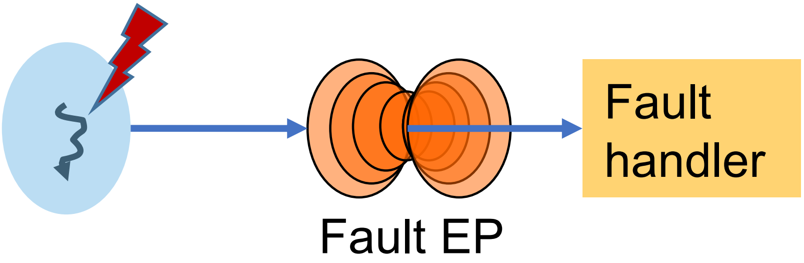
Exception types:

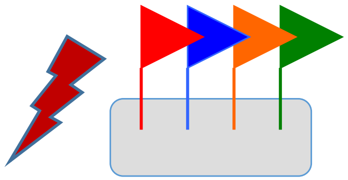
- invalid syscall
  - eg for instruction emulation, virtualisation
- capability fault
  - cap lookup failed or found invalid cap
- page fault
  - address not mapped
  - maybe invalid address
  - maybe grow stack, heap, load library…
- architecture-defined
  - divide by zero, unaligned access, …
- timeout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

Has its own fault endpoint

On exception:

- kernel invokes fault EP
- on behalf of faulter
- replying will restart thread

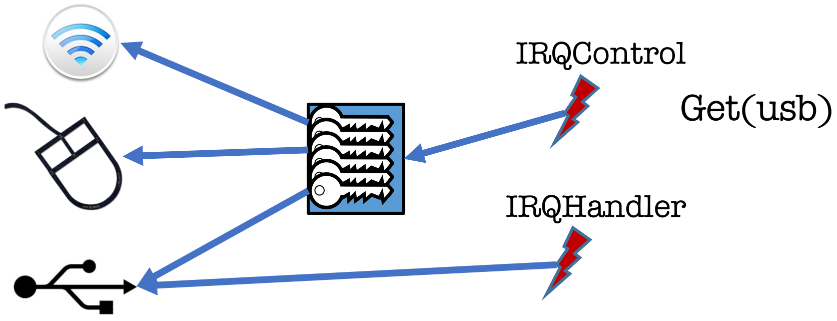




Interrupt Management

2 special objects for managing and acknowledging interrupts:

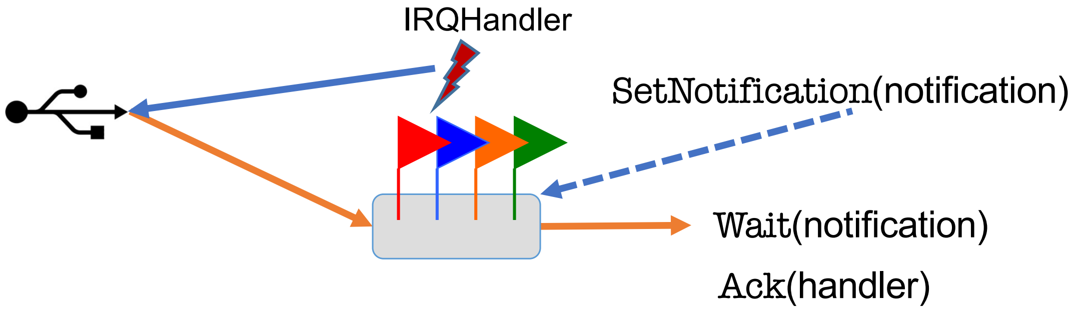
- Single IRQControl object
  - single IRQControl cap provided by kernel to initial VSpace
  - only purpose is to create IRQHandler caps
- Per-IRQ-source IRQHandler object
  - interrupt association and dissociation
  - interrupt acknowledgment
  - edge-triggered flag



Interrupt Handling

IRQHandler cap allows driver to bind Notification to interrupt

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



IRQHandler

SetNotification(notification)

Wait(notification)

Ack(handler)

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, notification);
seL4_IRQHandler_Ack(irq);
```

Device Drivers

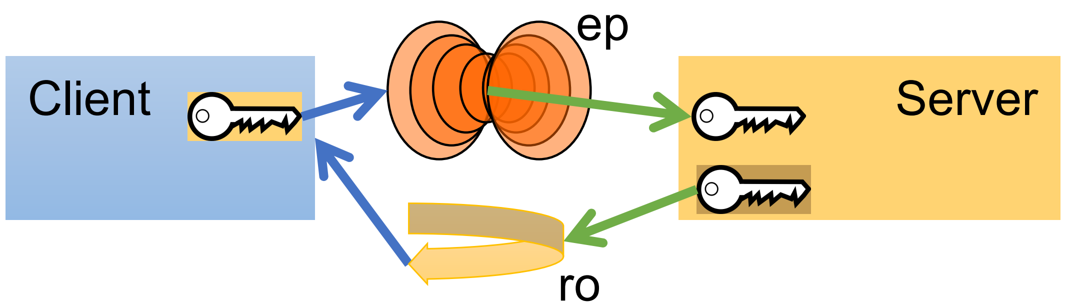
- In seL4 (and all other L4 kernels) drivers are usermode processes
- Drivers do three things:
  - Handle interrupts (already explained)
  - Communicate with rest of OS (PPC + shared memory)
  - Access device registers
- Device register access (Arm uses memory-mapped IO)
  - Have to find frame cap from 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_v_addr= ...;
```

seL4 System Design Hints

PS on Reply Objects



Client

Kernel

Server

ReplyRecv(ro,ep,&args)

Call(ep, args) →

deliver args to server

block client on RO

→ *process*

Kernel sets up reply channel in RO

- overwrites previous RO state
- ⇒ need multiple ROs to support concurrent client requests!

← ReplyRecv(ro,ep,&args)

deliver result to client

process ←

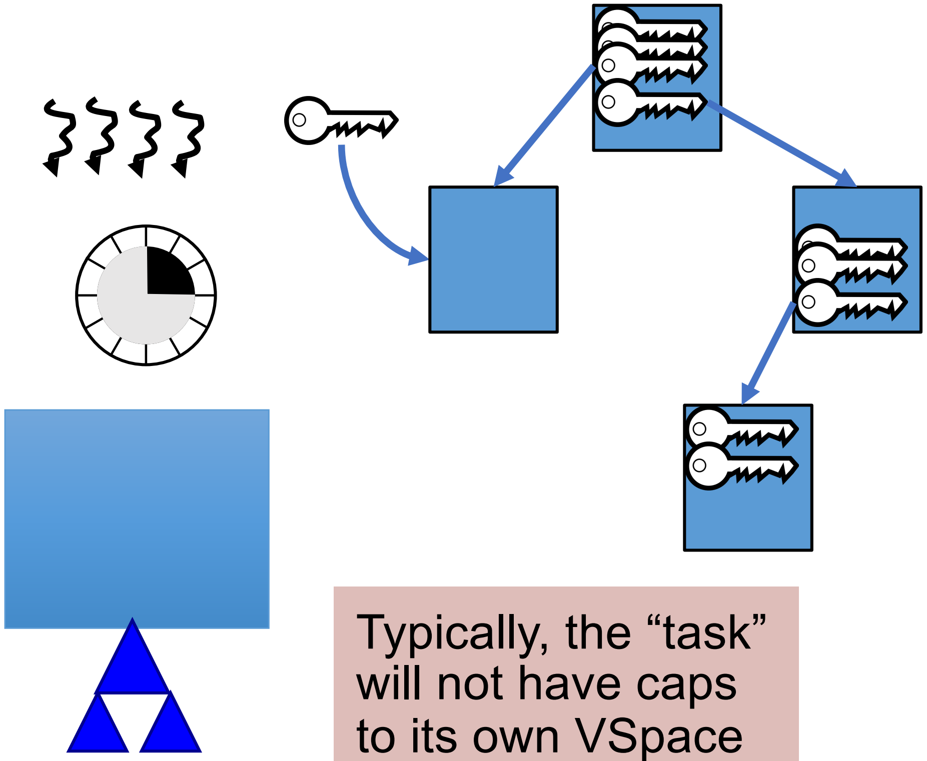
Kernel has no notion of a process/task!

Informally, a "task" consists of:

- a virtual address space (VSpace)
- a capability space (CSpace)
- one or more threads
- zero or more scheduling contexts
- likely Endpoint(s) & Notification(s)

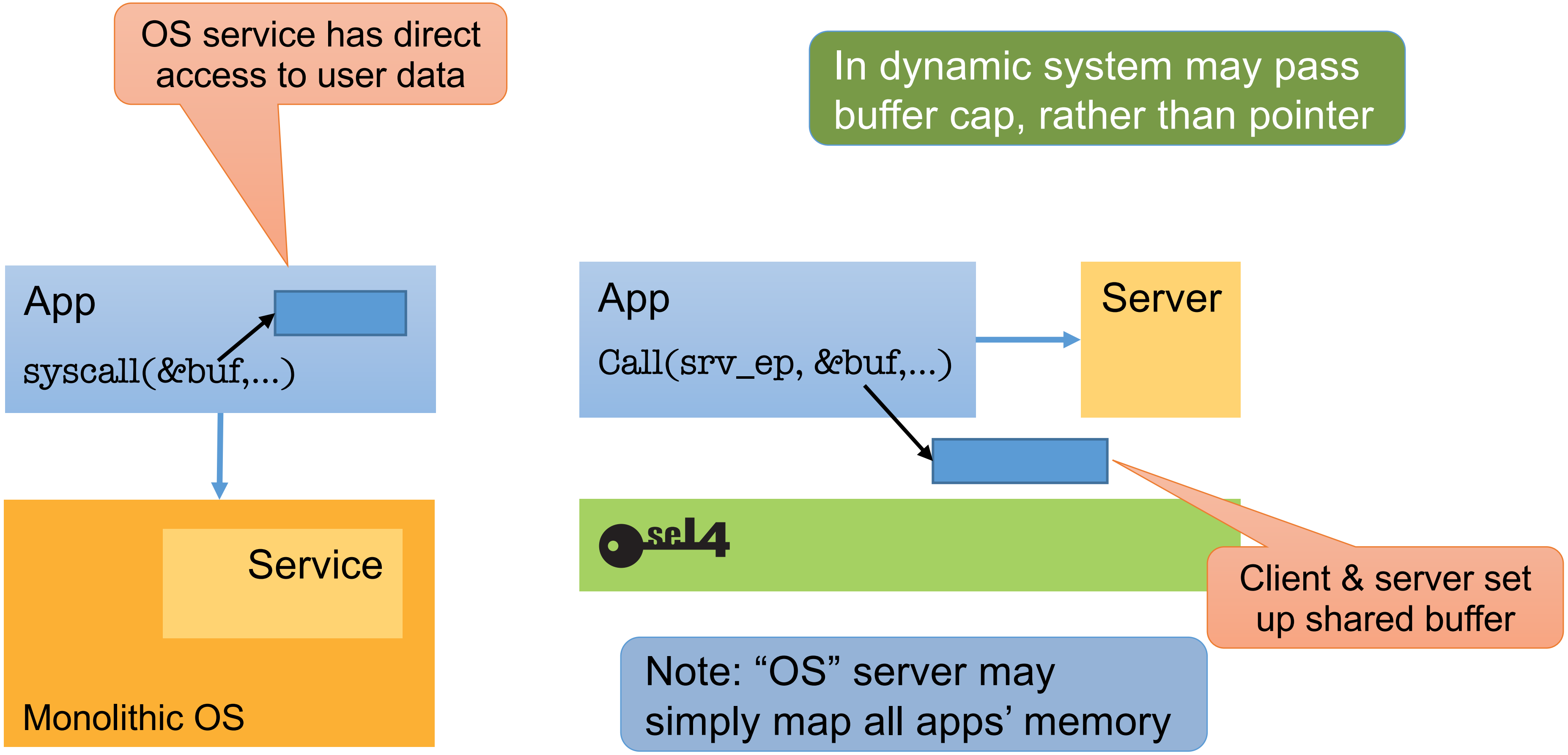
A server may not need an SC, runs on client's

Related tasks may share a CSpace

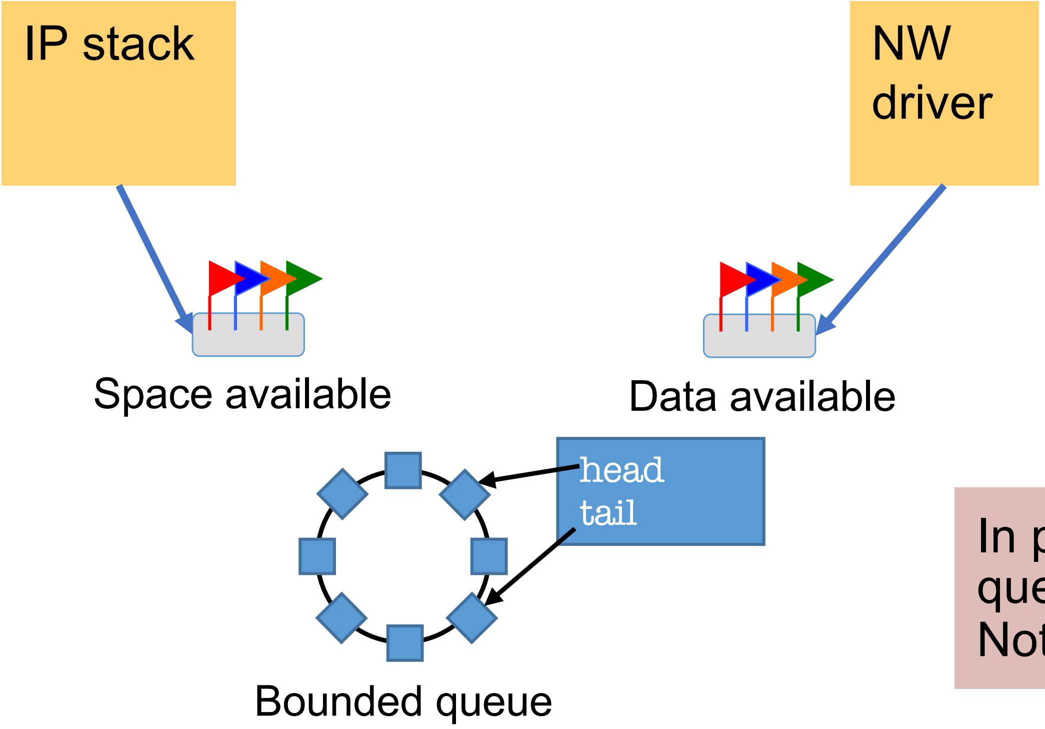


Typically, the "task" will not have caps to its own VSpace and CSpace!

Shared memory is usually required…

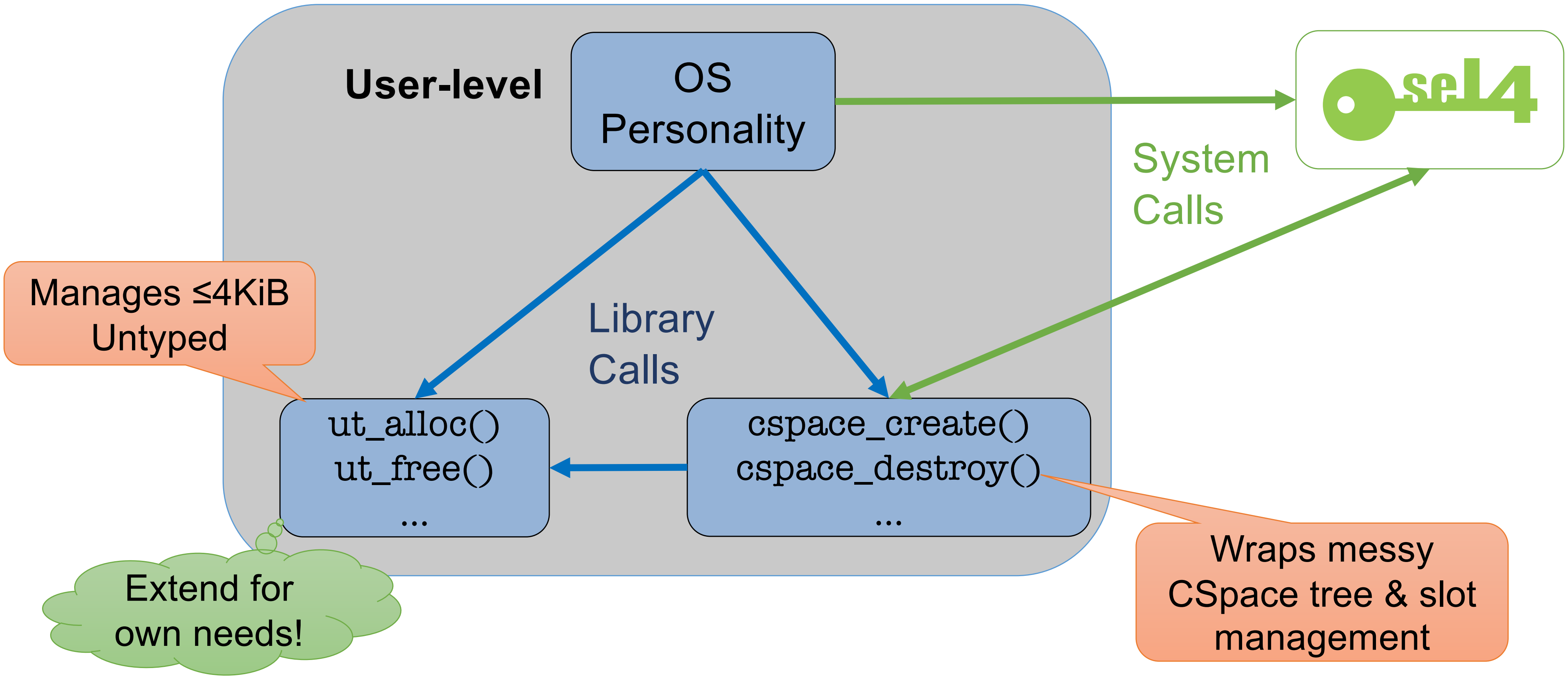

OS service has direct access to user data
App
syscall(&buf,...)
Service
Monolithic OS
In dynamic system may pass buffer cap, rather than pointer
App
Call(srv_ep, &buf,...)
Server
seL4
Client & server set up shared buffer
Note: “OS” server may simply map all apps’ memory

… especially for high-performance I/O



In practice separate queues & Notifications for Tx/Rx

Project: cspace and ut libraries



Manages ≤4KiB Untyped

Wraps messy CSpace tree & slot management

Extend for own needs!

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.*

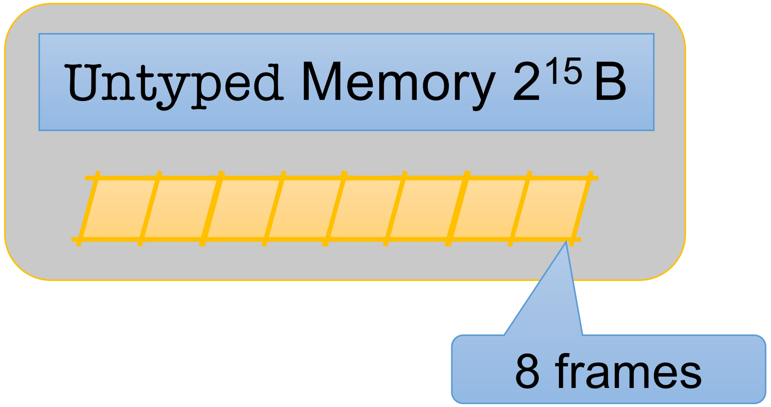
Object	Size (B)	Align (B)
Frame	2^{12}	2^{12}
PT/PD/PUD/PGD	2^{12}	2^{12}
Endpoint	2^{4}	2^{4}
Notification	2^{5}	2^{5}
Scheduling Context	$\geq 2^{8}$	2^{8}
Cnode slot	2^{4}	2^{4}
CNode	$\geq 2^{12}$	2^{12}
TCB	2^{11}	2^{11}

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!!

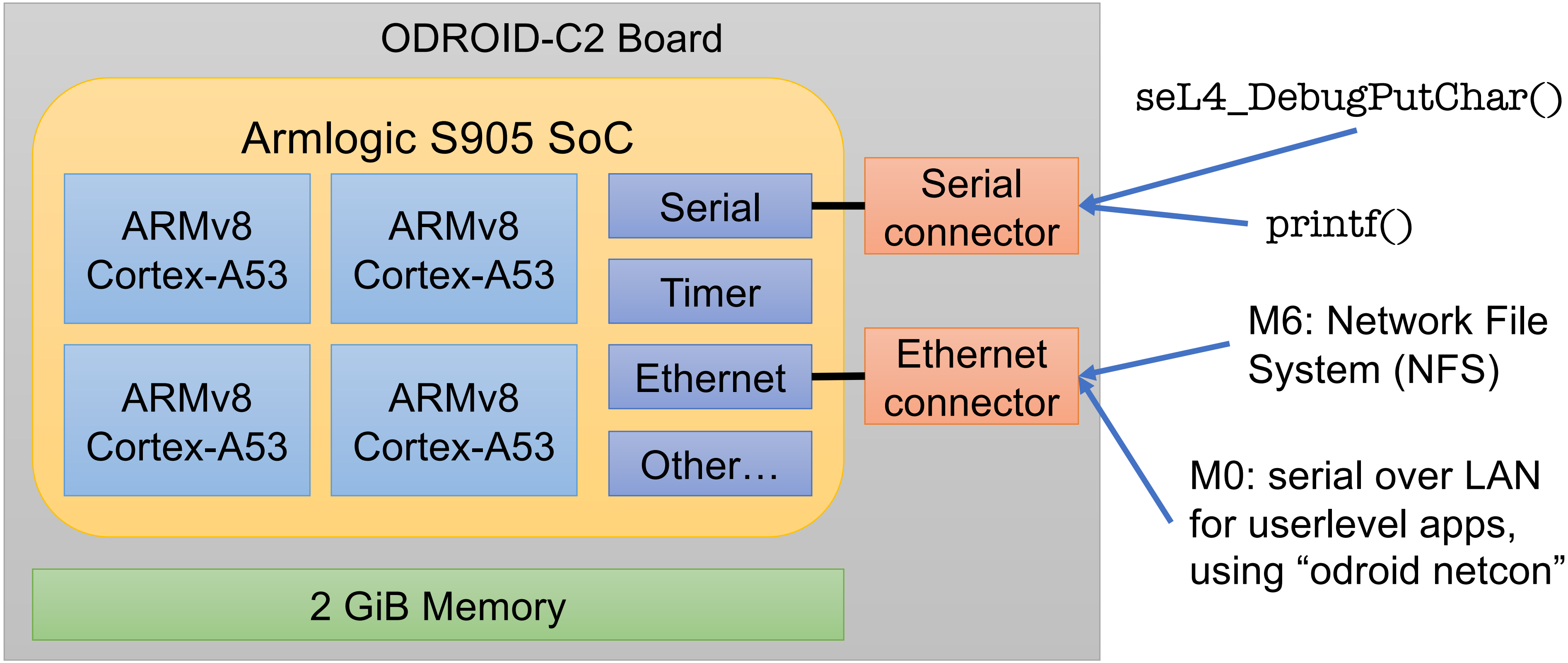


Untyped Memory 2^{15} B

8 frames

- 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.

Project Platform: ODROID-C2



seL4 in the Real World (Courtesy Boeing, DARPA)