COMP9242 Advanced OS

S2/2016 W01: **Introduction to seL4**

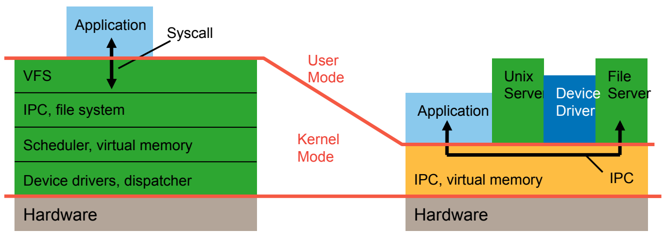
@GernotHeiser

Never Stand Still | Engineering | Computer Science and Engineering

Copyright Notice

Monolithic Kernels vs Microkernels

- Idea of microkernel:
  - Flexible, minimal platform
  - Mechanisms, not policies
  - Goes back to Nucleus [Brinch Hansen, CACM'70]

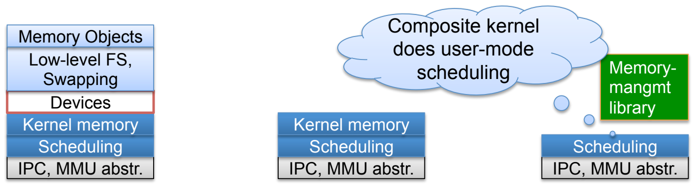


Microkernel Evolution

First generation
- Eg Mach ['87]

Second generation
- Eg L4 ['95]

Third generation
- seL4 ['09]



First generation:
- 180 syscalls
- 100 kLOC
- 100 μs IPC

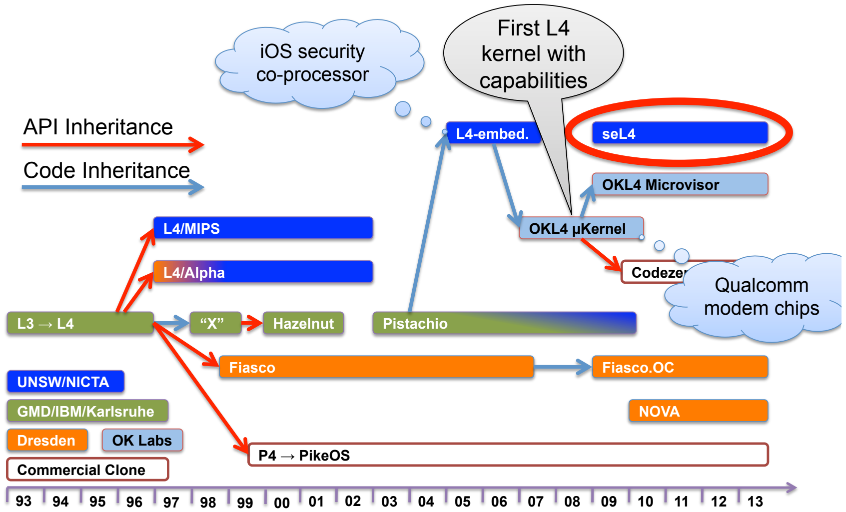
Second generation:
- ~7 syscalls
- ~10 kLOC
- ~ 1 μs IPC

Third generation:
- ~3 syscalls
- 9 kLOC
- 0.1 μs IPC
- *capabilities*
- *design for isolation*

2nd-Generation Microkernels

- 1st-generation kernels (Mach, Chorus) were a failure
  - Complex, inflexible, slow
- L4 was first 2G microkernel [Liedtke, SOSP'93, SOSP'95]
  - Radical simplification & manual micro-optimisation
  - *"A concept is tolerated inside the microkernel only if moving it outside the kernel, i.e. permitting competing implementations, would prevent the implementation of the system's required functionality."*
  - High IPC performance
- Family of L4 kernels:
  - Original Liedtke (GMD) assembler kernel ('95)
  - Family of kernels developed by Dresden, UNSW/NICTA, Karlsruhe
  - Commercial clones (PikeOS, P4, CodeZero, …)
  - Influenced commercial QNX ('82), Green Hills Integrity ('90s)
  - Generated NICTA startup Open Kernel Labs (OK Labs)
    - large-scale commercial deployment (multiple billions shipped)

L4: A Family of High-Performance Microkernels

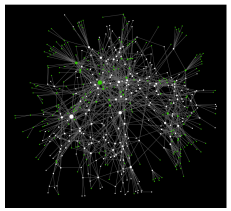


Issues of 2G Microkernels

- L4 solved performance issue [Härtig et al, SOSP'97]
- Left a number of security issues unsolved
- Problem: ad-hoc approach to protection and resource management
  - Global thread name space ⇒ covert channels [Shapiro'03]
  - Threads as IPC targets ⇒ insufficient encapsulation
  - Single kernel memory pool ⇒ DoS attacks
  - Insufficient delegation of authority ⇒ limited flexibility, performance
  - Unprinciple management of time
- Addressed by seL4
  - Designed to support safety- and security-critical systems
  - Principled time management not yet mainline (RT branch)

seL4 Principles

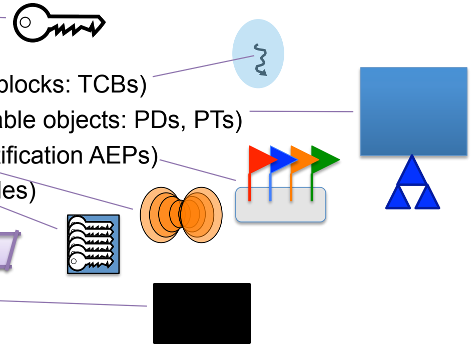
- Single protection mechanism: capabilities
  - Proper time management to be finished this year
- All resource-management policy at user level
  - Painful to use
  - Need to provide standard memory-management library
    - Results in L4-like programming model
- Suitable for formal verification (proof of implementation correctness)
  - Attempted since '70s
  - Finally achieved by L4.verified project at NICTA [Klein et al, SOSP'09]



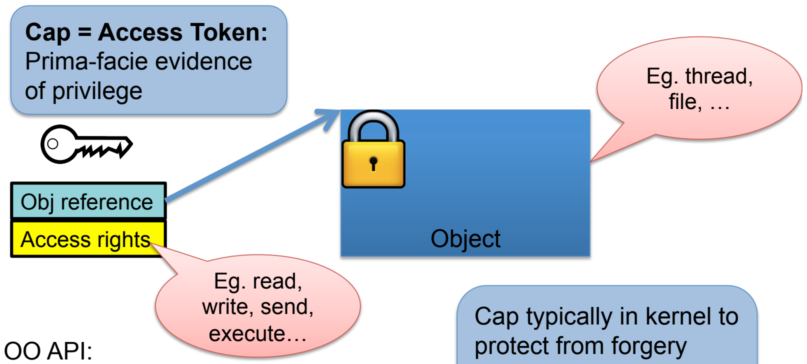
seL4 Concepts

Note: differences between AOS and mainline kernels!

- Capabilities (Caps)
  - mediate access
- Kernel objects:
  - Threads (thread-control blocks: TCBs)
  - Address spaces (page table objects: PDs, PTs)
  - Endpoints (IPC EPs, Notification AEPs)
  - Capability spaces (CNodes)
  - Frames
  - Interrupt objects
  - Untyped memory
- System calls
  - Send, Wait (and variants)
  - Yield



What are (Object) Capabilities?



- OO API:

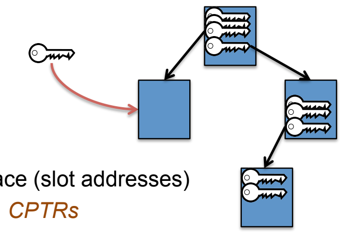
  `err = method( cap, args );`
- Used in some earlier microkernels:
  - KeyKOS ['85], Mach ['87], EROS ['99]

Cap typically in kernel to protect from forgery

➢ user references cap through handle

seL4 Capabilities

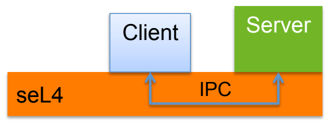
- Stored in cap space (*CSpace*)
  - Kernel object made up of *CNodes*
  - each an array of cap "slots"
- Inaccessible to userland
  - But referred to by pointers into CSpace (slot addresses)
  - These CSpace addresses are called *CPTRs*
- Caps convey specific privilege (access rights)
  - `Read`, `Write`, `Grant` (cap transfer)
- Main operations on caps:
  - *`Invoke`*: perform operation on object referred to by cap
    - Possible operations depend on object type
  - *`Copy`*/*`Mint`*/*`Grant`*: create copy of cap with *same*/*lesser* privilege
  - *`Move`*/*`Mutate`*: transfer to different address with same/lesser privilege
  - *`Delete`*: invalidate slot (cleans up object if this is the only cap to it)
  - *`Revoke`*: delete any derived (eg. copied or minted) caps



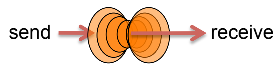
Mainline has `Execute` too

Inter-Process Communication (IPC)

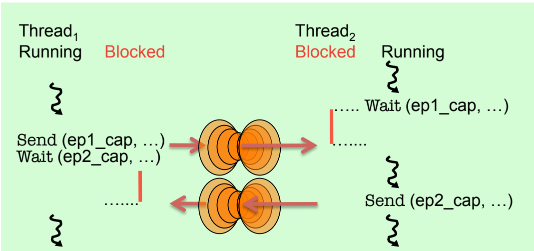
- Fundamental microkernel operation
  - Kernel provides no services, only mechanisms
  - OS services provided by (protected) user-level server processes
  - invoked by IPC



- seL4 IPC uses a handshake through *endpoints*:
  - Transfer points without storage capacity
  - Message must be transferred instantly
    - Single-copy user ➞ user by kernel

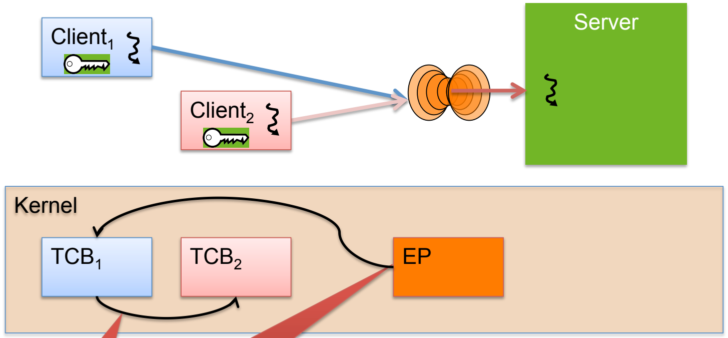


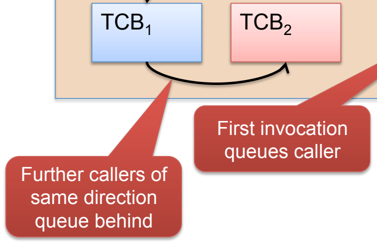
IPC: (Synchronous) Endpoints



- Threads must rendez-vous for message transfer
  - One side blocks until the other is ready
  - Implicit synchronisation
- Message copied from sender's to receiver's *message registers*
  - Message is combination of caps and data words
    - Presently max 121 words (484B, incl message "tag")
    - Should never use anywhere near that much!

IPC Endpoints are Message Queues

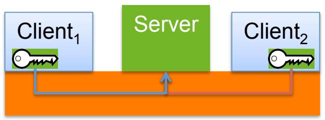




- EP has no sense of direction
- May queue senders or receivers
  - never both at the same time!
- *Communication needs 2 EPs!*

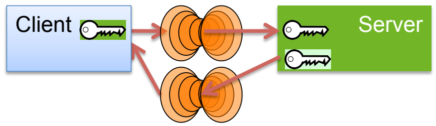
Client-Server Communication

- Asymmetric relationship:
  - Server widely accessible, clients not
  - How can server reply back to client (distinguish between them)?



- Client can pass (session) reply cap in first request
  - server needs to maintain session state
  - forces stateful server design
- seL4 solution: Kernel provides single-use *reply cap*
  - only for Call operation (Send+Wait)
  - allows server to reply to client
  - cannot be copied/minted/re-used but can be moved
  - one-shot (automatically destroyed after first use)

Call RPC Semantics

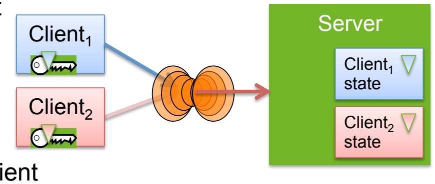


Client	**Kernel**	**Server**
		Wait(ep,&rep)
Call(ep,…)		
	mint rep	
	deliver to server	
		process
		Send(rep,…)
	deliver to client	
	destroy rep	
process		*process*

Identifying Clients

Stateful server serving multiple clients

- Must respond to correct client
  - Ensured by reply cap
- Must associate request with correct state

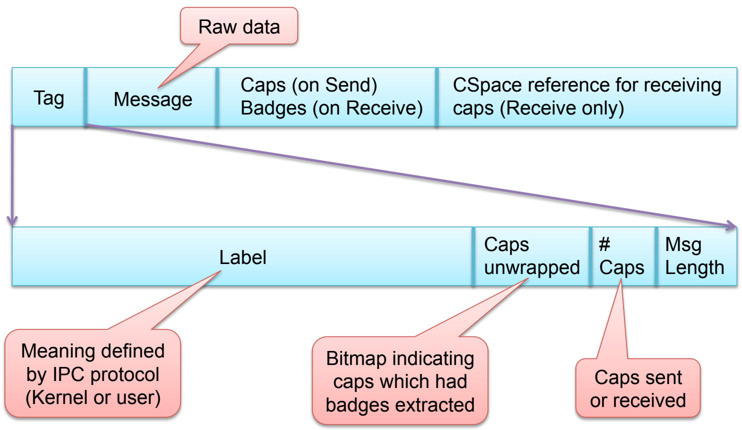


- Could use separate EP per client
  - endpoints are lightweight (16 B)
  - but requires mechanism to wait on a set of EPs (like select)
- Instead, seL4 allows to individually mark ("badge") caps to same EP
  - server provides individually badged caps to clients
  - server tags client state with badge (through `Mint()`)
  - kernel delivers badge to receiver on invocation of badged caps

IPC Mechanics: Virtual Registers

- Like physical registers, virtual registers are thread state
  - context-switched by kernel
  - implemented as physical registers or thread-local memory
- Message registers
  - contain message transferred in IPC
  - architecture-dependent subset mapped to physical registers
    - 5 on ARM, 3 on x86
  - library interface hides details
    - 1st transferred word is special, contains *message tag*
  - API MR[0] refers to next word (not the tag!)
- Reply cap
  - *overwritten by next receive!*
  - can move to CSpace with `cspace_save_reply_cap()`

IPC Message Format



Note: Don't need to deal with this explicitly for project

Client-Server IPC Example

Client

```
seL4_MessageInfo_t tag = seL4_MessageInfo_new(0, 0, 0, 1);
seL4_SetTag(tag);
seL4_SetMR(0,1);
seL4_Call(server_c, tag);
```

Load into tag register

Set message register #0

Server

```
seL4_Word addr = ut_alloc(seL4_EndpointBits);
err = cspace_ut_retype_addr(tcb_addr, seL4_EndpointObject,
                            seL4_EndpointBits, cur_cspace, &ep_cap)
seL4_CPtr cap = cspace_mint_cap(dest, cur_cspace, ep_cap, seL4_all_rights,
                                seL4_CapData_Badge_new(0xff));
...
seL4_Word badge;
seL4_MessageInfo_t msg = seL4_Wait(ep, &badge);
...
seL4_MessageInfo_t reply = seL4_MessageInfo_new(0, 0, 0, 0);
seL4_Reply(reply);
```

Allocate EP and retype

Insert EP into CSpace

Cap is badged 0xff

Implicit use of reply cap

Server Saving Reply Cap

Server

```
seL4_Word addr = ut_alloc(seL4_EndpointBits);
err = cspace_ut_retype_addr(tcb_addr, seL4_EndpointObject,
          seL4_EndpointBits, cur_cspace, &ep_cap)
seL4_CPtr cap = cspace_mint_cap(dest, cur_cspace, ep_cap, seL4_all_rights,
                    seL4_CapData_Badge_new(0xff));
...
seL4_Word badge;
seL4_MessageInfo_t msg = seL4_Wait(ep, &badge);
seL4_CPtr slot = cspace_save_reply_cap(cur_cspace);
...
seL4_MessageInfo_t reply = seL4_MessageInfo_new(0, 0, 0, 0);
seL4_Send(slot, reply);
cspace_free_slot(slot);
```

Save reply cap in CSpace

Explicit use of reply cap

Reply cap no longer valid

IPC Operations Summary

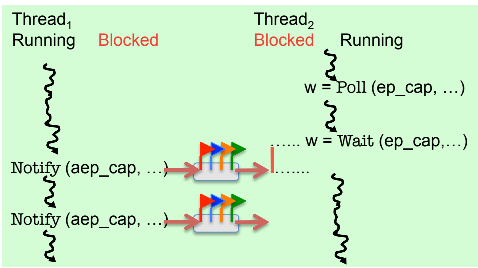
- Send (ep_cap, …), Wait (ep_cap, …)
  - blocking message passing
  - needs Write, Read permission, respectively
- NBSend (ep_cap, …)
  - Polling send: *silently* discard message if receiver isn't ready
- Call (ep_cap, …)
  - equivalent to Send (ep_cap,…) + reply-cap + Wait (ep_cap,…)
  - *Atomic*: guarantees caller is ready to receive reply
- Reply (…)
  - equivalent to Send (rep_cap, …)
- ReplyWait (ep_cap, …)
  - equivalent to Reply (…) + Wait (ep_cap, …)
  - at present solely for efficiency of server operation

Need error handling protocol !

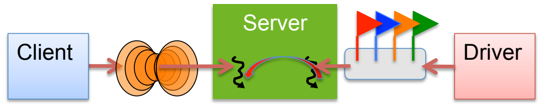
No failure notification where this reveals info on other entities!

Notifications: Asynchronous Endpoints

- Logically, AEP is an array of binary semaphores
  - Multiple signalling, select-like wait
  - Not a message-passing IPC operation!
- Implemented by *data word* in AEP
  - Send OR-s sender's *cap badge* to data word
  - Receiver can poll or wait
    - waiting returns and clears data word
    - polling just returns data word



Receiving from EP *and* AEP



Server with synchronous and asynchronous interface

- Example: file system
  - synchronous (RPC-style) client protocol
  - asynchronous notifications from driver
- Could have separate threads waiting on endpoints
  - forces multi-threaded server, concurrency control
- Alternative: allow single thread to wait on both EP types
  - AEP is *bound* to thread with BindAEP() syscall
  - thread waits on synchronous endpoint
  - Notification delivered as if caller had been waiting on AEP

AOS vs Mainline Kernel Differences

- "Synchronous" vs "asynchronous" endpoint terminology is confusing
- seL4 really has only synchronous IPC, plus signal-like notifications
- Fixed in recent mainline kernels

AOS Kernel	**Mainline**
Sync EP, sync message	EP, message
AEP, async notification	Notification obj, notification
Send/Receive/Call/Reply&Wait	Send/Receive/Call/Reply&Wait
NBSend (EP)	NBSend, Poll, NBReply&Wait
AEP: NBSend, Wait	Signal, Poll, Wait

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 WR→R/O
- *Granting* transfers caps over an Endpoint
  - Delivers copy of sender's cap(s) to receiver
    - reply caps are a special case of this
  - Sender needs Endpoint cap with Grant permission
  - Receiver needs Endpoint cap with Write permission
    - else Write permission is stripped from new cap
- *Retyping*
  - Fundamental operation of seL4 memory management
  - Details later…

Remember, caps are kernel objects!

seL4 System Calls

Will change soon

- Notionally, seL4 has 6 syscalls:
  - Yield(): invokes scheduler
    - only syscall which doesn't require a cap!
  - Send(), Receive() and 3 variants/combinations thereof
    - Notify() is actually not a separate syscall but same as Send()
  - This is why I earlier said "approximately 3 syscalls" ☺
- All other kernel operations are invoked by "messaging"
  - Invoking Call() on an object cap
    - Logically sending a message to the kernel
  - Each object has a set of kernel protocols
    - operations encoded in message tag
    - parameters passed in message words
  - Mostly hidden behind "syscall" wrappers

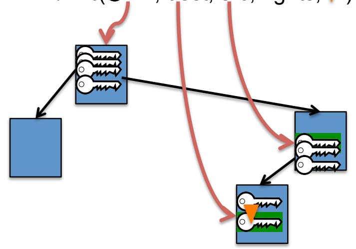
seL4 Memory-Management Principles

- 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

Capability Derivation

- Copy, Mint, Mutate, Revoke are invoked on CNodes

Mint(, dest, src, rights,)



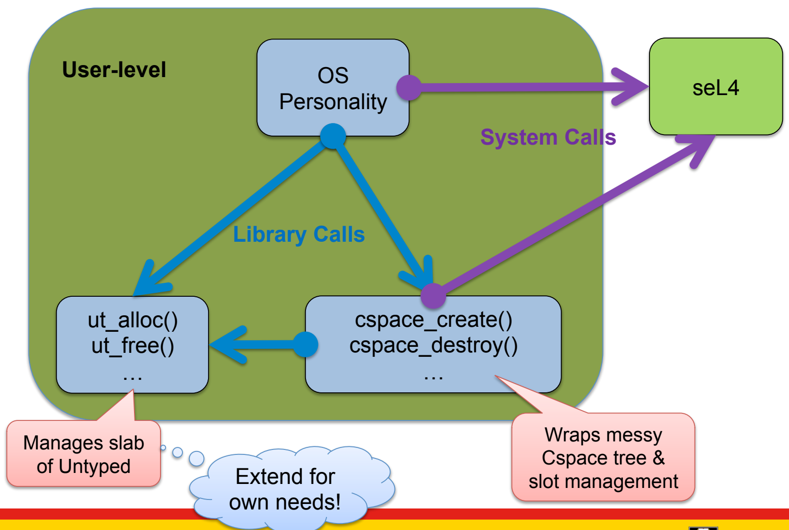
  - CNode cap must provide appropriate rights
- Copy takes a cap for destination
  - Allows copying of caps between Cspaces
  - Alternative to granting via IPC (if you have privilege to access Cspace!)

Cspace Operations

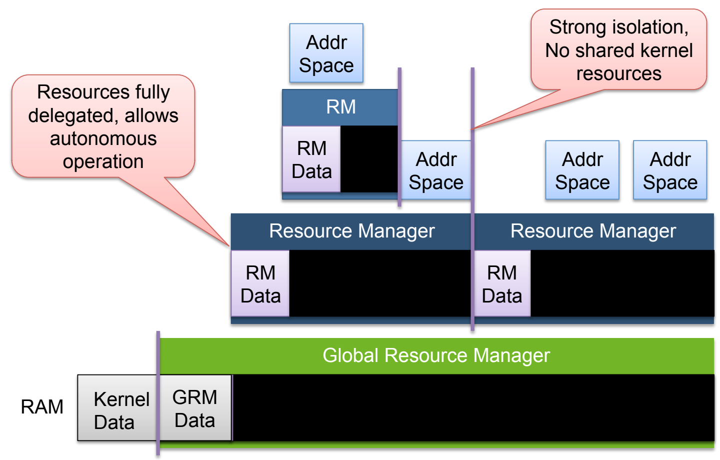
```
extern cspace_t * cspace_create(int levels); /* either 1 or 2 level */
extern cspace_err_t cspace_destroy(cspace_t *c);
```

```
extern seL4_CPtr cspace_copy_cap(cspace_t *dest, cspace_t *src,
                        seL4_CPtr src_cap, seL4_CapRights rights);

extern seL4_CPtr cspace_mint_cap(cspace_t *dest, cspace_t *src,
                        seL4_CPtr src_cap,  seL4_CapRights rights,
                        seL4_CapData badge);

extern seL4_CPtr cspace_move_cap(cspace_t *dest, cspace_t *src,
                        seL4_CPtr src_cap);

extern cspace_err_t cspace_delete_cap(cspace_t *c, seL4_CPtr cap);

extern cspace_err_t cspace_revoke_cap(cspace_t *c, seL4_CPtr cap);
```

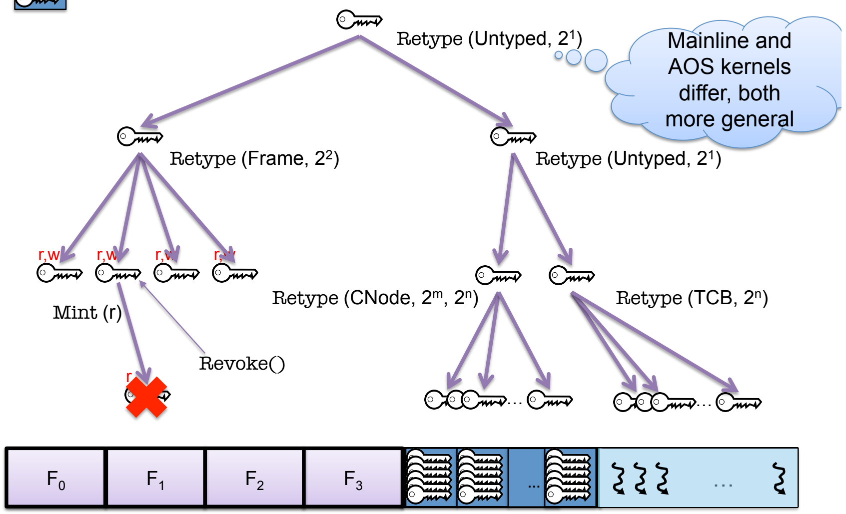

cspace and ut libraries



seL4 Memory Management Approach

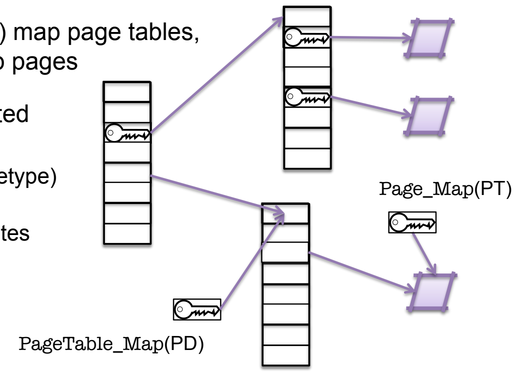


Memory Management Mechanics: Retype



seL4 Address Spaces (VSpaces)

- Very thin wrapper around hardware page tables
  - Architecture-dependent
  - ARM and (32-bit) x86 are very similar
- Page directories (PDs) map page tables, page tables (PTs) map pages
- A VSpace is represented by a PD object:
  - Creating a PD (by Retype) creates the VSpace
  - Deleting the PD deletes the VSpace



Address Space Operations

```
seL4_Word frame_addr = ut_alloc(seL4_PageBits);
err = cspace_ut_retype_addr(frame_addr, seL4_ARM_Page,
          seL4_ARM_PageBits, cur_cspace, &frame_cap);

map_page(frame_cap, pd_cap, 0xA0000000, seL4_AllRights,
          seL4_ARM_Default_VMAttributes);
bzero((void *)0xA0000000, PAGESIZE);
```

cap to level 1 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_ARM_Page_Unmap(frame_cap);
cspace_delete_cap(frame_cap);
ut_free(frame_addr, seL4_PageBits);
```

Poor API choice!

Multiple Frame Mappings: Shared Memory

```
seL4_CPtr new_frame_cap = cspace_copy_cap(cur_cspace, cur_cspace,
                                           existing_frame_cap,
                                           seL4_AllRights);

map_page(new_frame_cap, pd_cap, 0xA0000000, seL4_AllRights,
          seL4_ARM_Default_VMAttributes);
bzero((void *)0xA0000000, PAGESIZE);
```

```
seL4_ARM_Page_Unmap(existing_frame_cap);
cspace_delete_cap(existing_frame_cap)
seL4_ARM_Page_Unmap(new_frame_cap);
cspace_delete_cap(new_frame_cap)
ut_free(frame_addr, seL4_PageBits);
```

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

Memory Management Caveats

- The object manager handles allocation for you
- Very simple buddy-allocator, you need to understand how it works:
  - Freeing an object of size *n*: you can allocate new objects <= size *n*
  - Freeing 2 objects of size *n* ***does not mean*** that you can allocate an object of size *2n*.

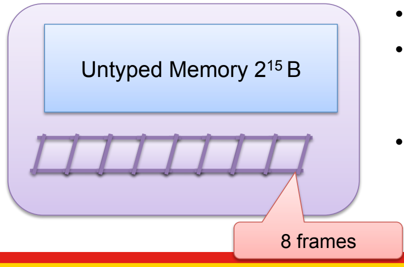
Object	Size (B), ARM	Alignment (B), ARM
Frame	2^{12}	2^{12}
Page directory	2^{14}	2^{14}
Endpoint	2^{4}	2^{4}
Cslot	2^{4}	2^{4}
Cnode	2^{14}	2^{14}
TCB	2^{9}	2^{9}
Page table	2^{10}	2^{10}

Implementation choice!

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's view of Untyped allocation.
  - Major pain if kernel and user's 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.

Threads

- Theads are represented by TCB objects
- They have a number of attributes (recorded in TCB):
  - VSpace: a virtual address space
    - page directory reference
    - multiple threads can belong to the same VSpace
  - CSpace: capability storage
    - CNode reference (CSpace root) plus a few other bits
  - *Fault endpoint*
    - Kernel sends message to this EP if the thread throws an exception
  - IPC buffer (backing storage for virtual registers)
  - stack pointer (SP), instruction pointer (IP), user-level registers
  - *Scheduling priority*
  - *Time slice length* (presently a system-wide constant)
- These must be explicitly managed
  - … we provide an example you can modify

Yes, this is broken! Fixed in later kernels

Threads

Creating a thread

- Obtain a TCB object
- Set attributes: Configure()
  - associate with VSpace, CSpace, fault EP, prio, define IPC buffer
- Set SP, IP (and optionally other registers): WriteRegisters()
  - this results in a completely initialised thread
  - will be able to run if resume_target is set in call, else still inactive
- Activated (made schedulable): Resume()

Creating a Thread in Own AS and Cspace

```
static char stack[100];
int thread_fct() {
        while(1);
        return 0;
}
/* Allocate and map new frame for IPC buffer as before */
seL4_Word tcb_addr = ut_alloc(seL4_TCBBits);

err = cspace_ut_retype_addr(tcb_addr, seL4_TCBObject, seL4_TCBBits,
                            cur_cspace, &tcb_cap)
err = seL4_TCB_Configure(tcb_cap, FAULT_EP_CAP, PRIORITY,
                         curspace->root_cnode, seL4NilData,
                         seL4_CapInitThreadPD, seL4_NilData,
                         PROCESS_IPC_BUFFER, ipc_buffer_cap);
seL4_UserContext context = { .pc = &thread, .sp = &stack};
seL4_TCB_WriteRegisters(tcb_cap, 1, 0, 2, &context);
```

If you use threads, write a library to create and destroy them.

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!


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

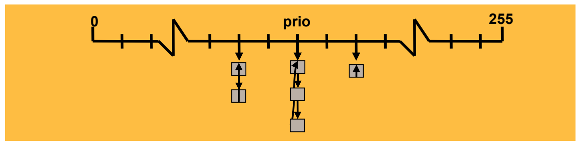

Creating a Thread in *New* AS and CSpace

```
/* Allocate, retype and map new frame for IPC buffer as before
 * Allocate and map stack???
 * Allocate and retype a TCB  as before
 * Allocate and retype a  seL4_ARM_PageDirectoryObject 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, "test")->p_base;
err = elf_load(new_pagedirectory_cap, elf_base);
unsigned int entry = elf_getEntryPoint(elf_base);

err = seL4_TCB_Configure(tcb_cap, FAULT_EP_CAP, PRIORITY,
                         new_cspace->root_cnode, seL4NilData,
                         new_pagedirectory_cap, seL4_NilData,
                         PROCESS_IPC_BUFFER, ipc_buffer_cap);
seL4_UserContext context = {.pc = entry, .sp = &stack};
seL4_TCB_WriteRegisters(tcb_cap, 1, 0, 2, &context);
```


seL4 Scheduling

Better model in "RT" branch – merge soon

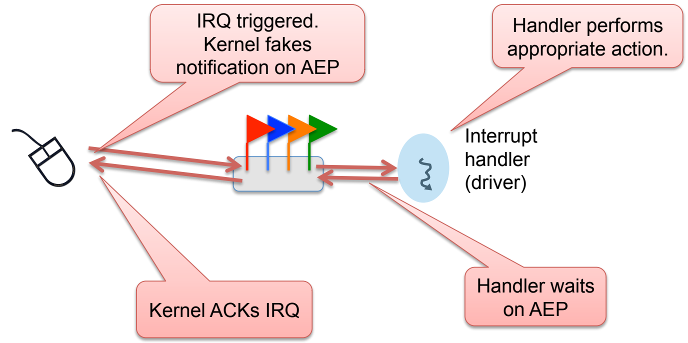
- Present seL4 scheduling model is fairly naïve
- 256 hard priorities (0–255)
  - Priorities are strictly observed
  - The scheduler will always pick the highest-prio runnable thread
  - Round-robin scheduling within prio level
- Aim is real-time performance, **not** fairness
  - Kernel itself will never change the prio of a thread
  - Achieving fairness (if desired) is the job of user-level servers



Exception Handling

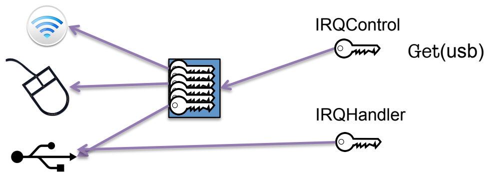
- A thread can trigger different kinds of exceptions:
  - invalid syscall
    - may require instruction emulation or result from virtualization
  - capability fault
    - cap lookup failed or operation is invalid on cap
  - page fault
    - attempt to access unmapped memory
    - may have to grow stack, grow heap, load dynamic library, …
  - architecture-defined exception
    - divide by zero, unaligned access, …
- Results in kernel sending message to fault endpoint
  - exception protocol defines state info that is sent in message
- Replying to this message restarts the thread
  - endless loop if you don't remove the cause for the fault first!

Interrupt Handling



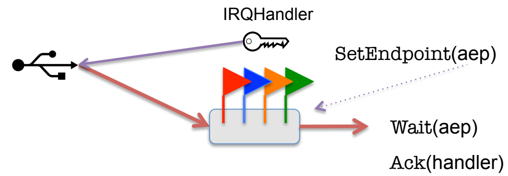
Interrupt Management

- seL4 models IRQs as messages sent to an AEP
  - Interrupt handler has Receive cap on that AEP
- 2 special objects used 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



Interrupt Handling

- IRQHandler cap allows driver to bind AEP to interrupt
- Afterwards:
  - AEP is used to receive interrupt
  - IRQHandler is used to acknowledge interrupt




```
seL4_IRQHandler interrupt = cspace_irq_control_get_cap(cur_cspace,
                                    seL4_CapIRQControl, irq_number);
seL4_IRQHandler_SetEndpoint(interrupt, async_ep_cap);
seL4_IRQHander_ack(interrupt);
```

ACK first to unmask IRQ

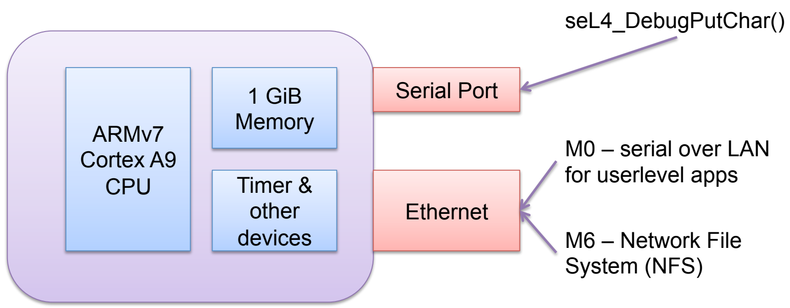
Device Drivers

- 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
  - Devices are memory-mapped on ARM
  - Have to find frame cap from bootinfo structure
  - Map the appropriate page in the driver's VSpace

```
device_vaddr = map_device(0xA0000000, (1 << seL4_PageBits));
...
*((void *) device_vaddr= ...;
```

Magic device register access

Project Platform: i.MX6 Sabre Lite



seL4 in the Real World (Courtesy Boeing, DARPA)