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NICTA

COMP9242 Advanced Operating Systems

S2/2011 Week 1: Introduction to seL4

Australian Government
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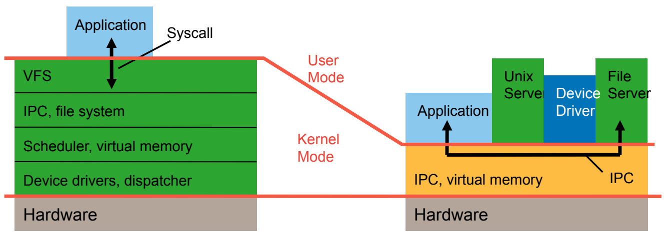
Monolithic Kernels vs Microkernels

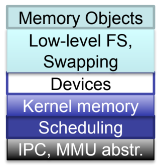
- Idea of microkernel:
  - Flexible, minimal platform
  - Mechanisms, not policies
  - Goes back to Nucleus [Brinch Hansen, CACM’70]



Microkernel Evolution

First generation

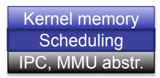
- Eg Mach (’87)



- 180 syscalls
- 100 kLOC
- 100 μs IPC

Second generation

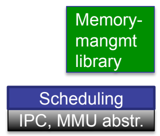
- Eg L4 (‘95)



- ~7 syscalls
- ~10 kLOC
- ~ 1 μs IPC

Third generation

- seL4 (‘09)



- ~3 syscalls
- 9 kLOC
- < 1 μs IPC

2nd-Generation Microkernels

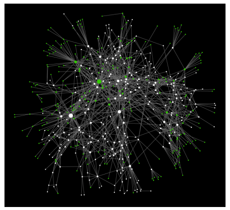
- 1st-generation kernels (Mach, Chorus) were a failure
  - Complex, inflexible, slow
- L4 was first 2G microkernel [Liedtke, SOSP'93, SOSP'95]
  - Radical simplification & manual micro-optimisation
  - "*A concept is tolerated inside the microkernel only if moving it outside the kernel, i.e. permitting competing implementations, would prevent the implementation of the system's required functionality.*"
  - High IPC performance
- Family of L4 kernels:
  - Original GMD assembler kernel ('95)
  - Fiasco (Dresden '98), Hazelnut (Karlsruhe '99), Pistachio (Karlsruhe/ UNSW '02), L4-embedded (NICTA '04)
    - L4-embedded commercialised as OKL4 by Open Kernel Labs
    - Deployed in ~ 1.5 billion phones
  - Commercial clones (PikeOS, P4, CodeZero, …)
  - Approach adopted e.g. in QNX ('82) and Green Hills Integrity ('90s)

Issues of 2G L4 Kernels

- 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
  - Threads as IPC targets ⇒ insufficient encapsulation
  - Single kernel memory pool ⇒ DoS attacks
  - Insufficient delegation of authority ⇒ limited flexibility, performance
- Addressed by seL4
  - Designed to support safety- and security-critical systems

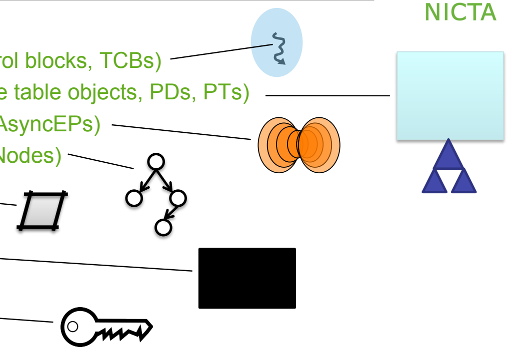
seL4 Principles

- Single protection mechanism: capabilities
  - Except for time ☹
- 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

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



Capabilities (Caps)

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- Token representing privileges [Dennis & Van Horn, '66]
  - Cap = "*prima facie* evidence of right to perform operation(s)"
- Object-specific ⇒ fine-grained access control
  - Cap identifies object ⇒ is an (opaque) object name
  - Leads to object-oriented API:

    err = method(cap, args);

  - Privilege check at invocation time
- Caps were used in microkernels before
  - KeyKOS ('85), Mach ('87)
  - EROS ('99): first well-performing cap system
  - OKL4 V2.1 ('08): first cap-based L4 kernel

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seL4 Capabilities

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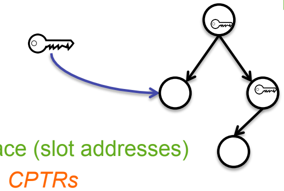
- Stored in cap space (*CSpace*)
  - Kernel object made up of *CNodes*
  - each a set of cap "slots"
- Inaccessible to userland
  - But referred to by pointers into CSpace (slot addresses)
  - These CSpace addresses are called *CPTRs*



- Caps convey specific privilege (access rights)
  - Read, Write, Grant (cap transfer) [Yes, there should be Execute!]
- 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
    - Only affects object if last cap is deleted
  - *Revoke*: delete any derived (eg. copied or minted) caps

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Inter-Process Communication (IPC)

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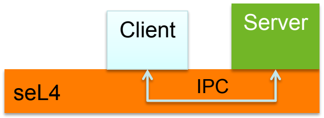
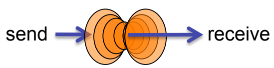
- Fundamental microkernel operation
  - Kernel provides no services, only mechanisms
  - OS services provided by (protected) user-level server processes
  - invoked by IPC



- seL4 IPC uses a handshake through *endpoints*:
  - Transfer points without storage capacity
  - Message must be transferred instantly
    - One partner may have to block
    - Single copy user → user by kernel



- Two endpoint types:
  - Synchronous (*Endpoint*) and asynchronous (*AsyncEP*)

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Synchronous Endpoint

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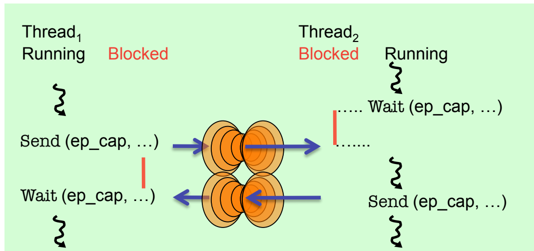

- Threads must rendez-vous for message transfer
  - One side blocks until the other is ready
- Message copied from sender's to receiver's message registers
  - Message is combination of caps and data words
    - presently max 121 words (484B, incl message "tag")

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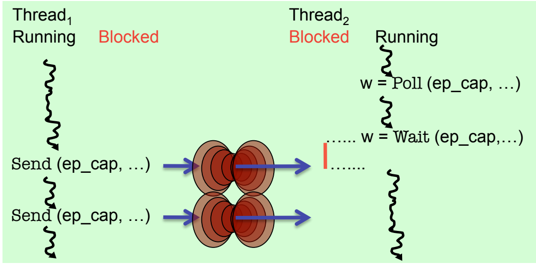
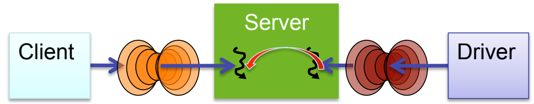
Asynchronous Endpoint



- Avoids blocking
  - send transmits 1-word message, OR-ed to receiver data word
  - no caps can be sent
- Receiver can poll or wait
  - waiting returns and clears data word
  - polling just returns data word
- Similar to interrupt (with small payload)

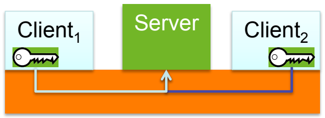
Receiving from Sync *and* Async Endpoints



Server with synchronous and asynchronous interface

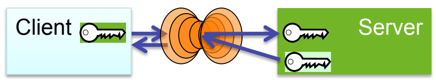
- Example: file system
  - synchronous (RPC-style) client protocol
  - asynchronous notifications from driver
- Could have separate threads waiting on endpoints
  - forces multi-threaded server, concurrency control
- Alternative: allow single thread to wait on both EP types
  - Mechanism:
    - AsyncEP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

Client-Server Communication



- Asymmetric relationship:
  - Server widely accessible, clients not
  - How can server reply back to client?
- Client can pass (session) reply cap in first request
  - server needs to maintain session state
  - client must trust server not to use cap beyond session
- 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

Call RPC Semantics



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

Identifying Clients

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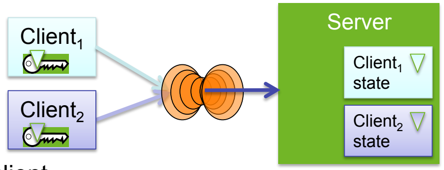
Stateful server serving multiple clients

- 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
  - kernel delivers badge to receiver on invocation of badged caps

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IPC Mechanics: Virtual Registers

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- Like physical registers, virtual registers are thread state
  - context-switched by kernel
  - implemented as physical registers or fixed memory location
- 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 message register is special, contains *message tag*
- Data word for asynchronous IPC
  - accumulates async messages (reset by `Wait`)
  - as with interrupts, information is lost if not collected timely
- Reply cap
  - overwritten by next receive
  - can move to CSpace with `SaveCaller()`

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IPC Message Format

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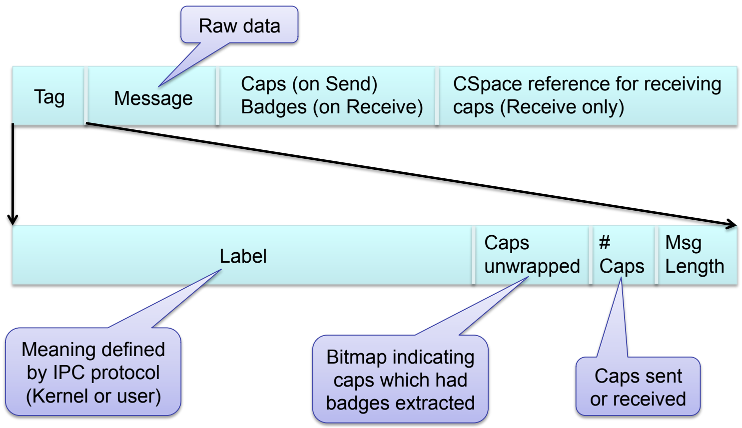

Note: Details hidden behind library wrappers

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Client-Server IPC Example

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Client

Load into tag register

Set message register #0

```
seL4_MessageInfo tag = { { .length=1, .extraCaps=0 } };
seL4_SetTag(tag);
seL4_SetMR(0,1);
seL4_Call(server_c, tag);
```

Allocate EP (retype some memory if needed)

Insert EP into CSpace

Server

```
om_endpoint_t ep = om_new_endpoint();
seL4_CPtr ep_cap = om_map_endpoint(adr_space, ep, seL4_all_rights,
                                   seL4_CapData_MakeBadge(0));
...
seL4_Word badge;
seL4_MessageInfo msg = seL4_Wait(ep, &badge);
...
seL4_MessageInfo reply = { .raw=0 };
seL4_Reply(reply);
```

Cap is badged 0

Implicit use of reply cap

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Server Saving Reply Cap

Server

```
om_endpoint_t ep = om_new_endpoint();
seL4_CPtr ep_cap = om_map_endpoint(adr_space, ep, seL4_all_rights,
                                   seL4_CapData_MakeBadge(0));
...
seL4_Word badge;
seL4_MessageInfo msg = seL4_Wait(ep, &badge);
seL4_CPtr slot = om_new_cslot (adr_space);
om_save_reply_cap(slot);
...
seL4_MessageInfo reply = { .raw=0 };
seL4_Send(slot, reply);
om_free_cslot(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, …), Wait (aep_cap, …)
  - blocking message passing
  - needs Write, Read permission, respectively
- NBSend (ep_cap, …)
  - discard message if receiver isn't ready
- Call (ep_cap, …)
  - equivalent to Send (ep_cap,…) + reply-cap + Wait (ep_cap,…)
- Reply (…)
  - equivalent to Send (rep_cap, …)
- ReplyWait (ep_cap, …)
  - equivalent to Reply (…) + Wait (ep_cap, …)
  - purely for efficiency of server operation
- Notify (aep_cap, …), Poll (aep_cap, …)
  - non-blocking send / check for message on AsyncEP

No failure notification where this reveals info on other entities!

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…

seL4 System Calls

- Notionally, seL4 has 8 syscalls:
  - Yield(): invokes scheduler
    - only syscall which doesn't require a cap!
  - Send(), Receive() and 5 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 Send()/Receive() on an object cap
  - 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

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- 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 most of this behind the *object manager* (OM) server API

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seL4 Memory Management Approach

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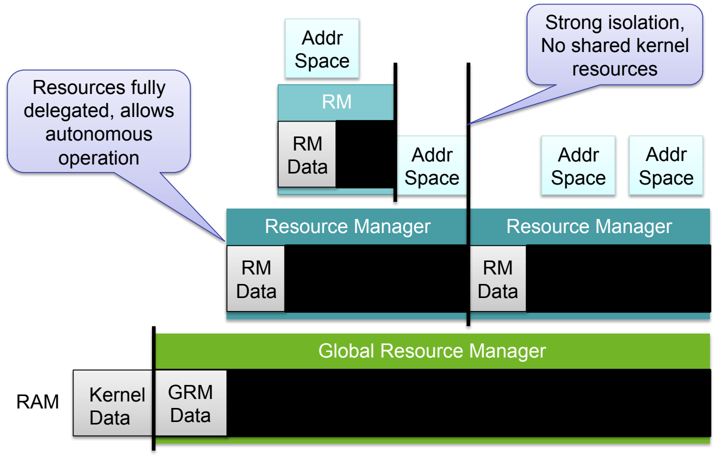

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Memory Management Mechanics: Retype

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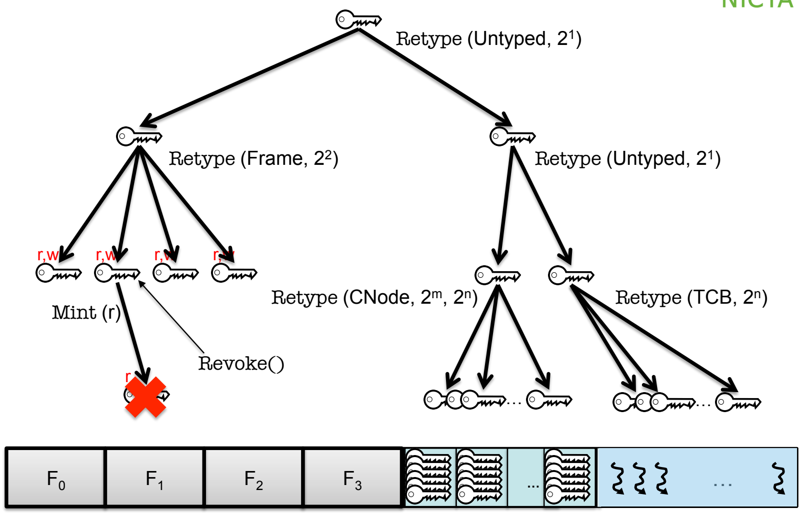

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seL4 Address Spaces (VSpaces)

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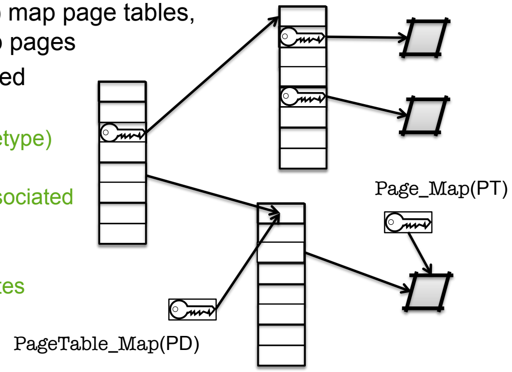
- Very thin wrapper around hardware page tables
  - Architecture-dependent
  - ARM and x86 are very similar
- Page directories (PDs) map page tables, page tables (PTs) map pages
- A VSpace is represented by a PD object:
  - Creating a PD (by Retype) creates the VSpace
  - To use it must be associated with "ASID pool"
    - hidden by OM
  - Deleting the PD deletes the VSpace



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Address Space Operations

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```
om_frame_t new_frame = om_new_frame();
om_map_frame(adr_space, new_frame,
                    0xA0000000,seL4_AllRights);
bzero((void *)0xA0000000, PAGESIZE);
```

```
om_unmap_frame(adr_space, new_frame, 0xA0000000);
om_free_frame(new_frame);
```


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Memory Management Caveats

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- The object manager handles allocation for you
- However, it is very simplistic, you need to understand how it works
- Simple rule:
  - 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 (Bytes)
Frame	2^{12}
Page directory	2^{14}
Endpoint	2^{4}
Cslot	2^{4}
TCB	2^{9}
Page table	2^{10}

- All kernel objects must be size aligned!

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Memory Management Caveats

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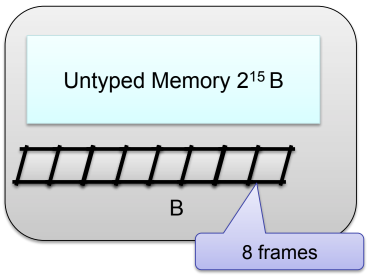
- Objects are allocated by Retype() of Untyped memory
- Free 4 frames for making a page directory may not work
  - only if they are part of the same Untyped object
  - and they are the full Untyped object



- Be careful with allocations!
- Don't try to allocate all of physical memory as frames, as you need more memory for TCBs, endpoints etc.
- Allocate big objects first
  - eg om_address_space_t
- Be aware that page table objects are also being created behind the scenes.

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Threads

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- 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)
    - Yes, this is broken! (Will be fixed soon…)
- These must be explicitly managed
  - … but our object manager hides a lot of the tedious stuff

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Threads

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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()

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Creating a Thread in Own VSpace

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

om_frame_t ipc_buf = om_new_frame();

om_map_frame(adr_space, ipc_buf, 0xA0000000,seL4_AllRights);
seL4_capData badge = seL4_CapData_MakeBadge(++trh_cnt);
om_tcb_t tcb = om_new_tcb(adr_space,  exct_hdlr, badge, 0,
                    ipc_buf, 0XA0000000);
om_start_thread(tcb, &stack, &thread_fct, 0);
```


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Threads and Stacks

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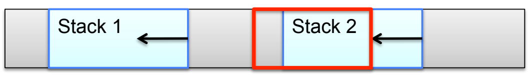
- Stacks are completely user-managed, kernel doesn't care!
  - Kernel only preserves SP, IP on context switch
- Stack location, allocation, size must be managed by userland
- Beware of stack overflow!
  - Easy to grow stack into other data
    - Pain to debug!
  - Take special care with automatic arrays!




```
f() {
  int buf[10000];
  . . .
}
```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Creating a Thread in a New VSpace

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```
om_endpoint_t exept_ep = om_new_endpoint();
seL4_CPtr endpoint_cap = om_map_endpoint(adr_space, except_ep,
                                   seL4_AllRights,
                                   seL4_CapData_MakeBadge(0));
char *dite = (char *)dite_lookup(appdite, “test”)->p_base;
unsigned int entry = elf_getEntryPoint(dite);

om_frame_t ipc_buf = om_new_frame();

om_map_frame(adr_space, ipc_buf, 0xA0000000,seL4_AllRights);
seL4_capData badge = seL4_CapData_MakeBadge(++trh_cnt);
om_tcb_t tcb = om_new_tcb(adr_space,  exct_hdlr, badge, 0,
                    ipc_buf, 0XA0000000);
om_start_thread(tcb, &stack, &thread_fct, 0);
```


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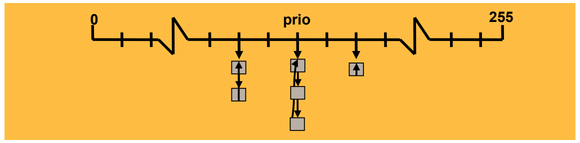
seL4 Scheduling

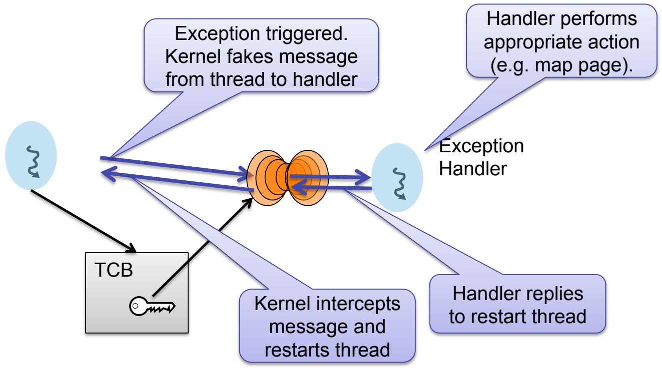
- seL4 uses 256 hard priorities (0–255)
  - Priorities are strictly observed
  - The scheduler will always pick the highest-prio runnable thread
  - Round-robin scheduling within prio level
- Aim is real-time performance, **not** fairness
  - Kernel itself will never change the prio of a thread
  - Achieving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



Exception Handling

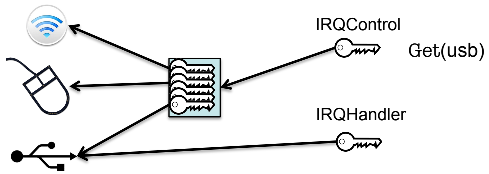
- A thread can trigger different kinds of exceptions:
  - invalid syscall
    - may require instruction emulation or result from virtualization
  - capability fault
    - cap lookup failed or operation is invalid on cap
  - page fault
    - attempt to access unmapped memory
    - may have to grow stack, 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

Exception Handling



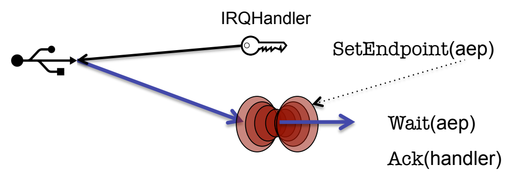
Interrupt Management

- seL4 models IRQs as messages sent to an AsyncEP
  - Interrupt handler has Receive cap on that EP
- 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 AsycEP to interrupt
- Afterwards:
  - AsyncEP is used to receive interrupt
  - IRQHandler is used to acknowledge interrupt




```
seL4_IRQHandler interrupt = om_new_interrupt(usb, tcb)
seL4_IRQHander_ack(interrupt);
```

Ack first, in case IRQ arrived during registring

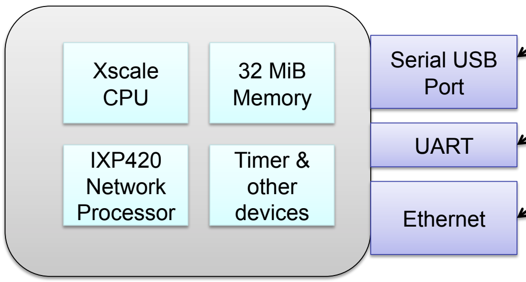
Device Drivers

- 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
  - Only have to map the appropriate page in the driver's VSpace

```
om_device_frame_t frame = om_get_device_frame(DEVICE_ADDRESS, 0);
om_map_device_frame(adr_space, frame, 0XA0000000);
...
*((void *) 0XA0000000 = 5;
```

Magic device register access

Project Platform: NSLU2 (Slug)



M0 – make user applications print to here

seL4_DebugPutChar()

M6 – Network File System (NFS)

Stuff & Gallery

- to cover
  - scheduling