


Open Kernel Labs™
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UNSW

L4 Programming

COMP9242
2009/S2 Week 2

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OKL4 API Overview (OKL4 2.1)

→ 9 privileged system calls

- control resources
- can only be executed by root task


→ 7 unprivileged system calls

- provide API to applications
- can be invoked by anyone

→ 3 communication protocols

- for kernel-user communication
- some form of exception IPC

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OKL4 API Overview

→ Privileged system calls

- *ThreadControl*
- SpaceControl
- MapControl
- CapControl
- MutexControl
- InterruptControl
- SecurityControl
- CacheControl
- PlatformControl


→ Unprivileged system calls

- ExchangeRegisters
- Ipc
- Schedule
- ThreadSwitch
- Mutex
- MemoryCopy
- SpaceSwitch

→ Protocols

- Page fault
- Exception
- Interrupt

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Threads

→ Traditional Thread

- Execution abstraction
- Consist of:
 - Registers (general-purpose and status registers)
 - Stack


→ OKL4 thread also has:

- *Virtual registers*
- Scheduling priority, time slice and time quantum
- Address space

→ OKL4 provides for a fixed overall number of threads

- User threads and system threads (1 idle thread per CPU)
- User thread created by privileged *root task*
- User thread deleted / allocated to address space by holder of master capability

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Virtual Registers

→ Kernel-defined, user-visible thread state

→ Implemented as physical machine registers or memory locations

- Depends on architecture and ABI

→ Two types:

- *Thread control registers* (TCRs)
 - For sharing information between kernel and user
- *Message registers* (MRs)
 - Contain the message transferred in an IPC operation

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Thread Control Block (TCB)

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- TCB contains thread state
 - Kernel-controlled state, must only be modified by syscalls
 - kept in kernel TCB (KTCB)
 - State that can be exposed to user without compromising security
 - kept in *user-level TCB (UTCB)*
 - includes virtual registers
 - *Must only be modified via the provided library functions!*
 - no consistency guarantees otherwise
 - Many fields are only modified as side effect of some operations (IPC)

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User-Level TCB

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- Area of memory directly accessible to thread
- Contains thread control registers:
 - PreemptedIP, PreemptCallbackIP, ErrorCode
 - UserHandle, various flags
- Contains message registers
 - More about this in IPC module
- Convenience APIs:


```
L4_Word_t L4_UserDefinedHandleOf (L4_ThreadId_t target);
void      L4_Set_UserDefinedHandle(L4_ThreadId_t target,
                                  L4_Word_t new_value);
```

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UTCB Array

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- Address space has a fixed region called the UTCB array
 - location fixed at address-space creation time
 - kernel-determined on ARM7/9!
 - no kernel API exists for obtaining its location — *new in 2.1*
 - define user-level protocol if needed
- Each UTCB is allocated at a unique location within array
 - determined at thread-creation time
 - kernel-determined on ARM7/9!

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Thread Capabilities — *New in 2.1*

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- Called *Thread Ids* for historical reasons
- Represent local (to address space) name for a local or external thread
 - no kernel API exists to obtain address-space Id from thread cap
 - ...according to some policy
- Thread-no is index into AS's clist
 - defined by at thread creation
- Two types of thread caps:
 - IPC cap
 - allows sending IPC to thread
 - allows donating time to thread
 - thread (master) cap
 - allows IPC and destroy
 - 2.1: destroy is still privileged
 - *In 2.2 only requires cap; cap controls all thread ops*

Thread ID	
Thread no (18)	1 (14)

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ThreadControl

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- Create, destroy or modify threads
 - Privileged system call (can only be performed by root task)
- Determines thread attributes
 - id of thread permitted to control scheduling parameters
 - this is known as the target thread's *scheduler*
 - *Note: the "scheduler" thread doesn't actually perform scheduling!*
 - page fault handler ("*pager*")
 - exception handler
 - access to hardware resources (eg. FP registers)
 - location of thread's UTCB in UTCB array (at thread creation)
 - not on ARM7/9
- *From OKL4 2.2 on:*
 - Create only requires resources
 - Changing attributes only requires master cap

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Threads and Stacks

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- Kernel does not allocate or manage stacks in any way
 - only preserves IP, SP on context switch
- User level (servers) must manage
 - stack location, allocation, size
 - entry point address
 - thread ID allocation, de-allocation
 - UTCB slot allocation, de-allocation (except on ARM7/9)
- *Be aware of stack overflow!*
 - Very easy to grow stack into other data

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

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ThreadControl

- Create, destroy and threads and modify thread attributes
- C language API:

```
L4_Word_t L4_ThreadControl( L4_ThreadId_t target,  
                           L4_SpaceId_t space,  
                           L4_ThreadId_t scheduler,  
                           L4_ThreadId_t pager,  
                           L4_ThreadId_t excpt_handler  
                           L4_Word_t resources,  
                           void *utcb);
```

Example: Creating a Thread

- Create thread in address space *addr_spc*

```
L4_Word_t number = _; /* Clist slot according to policy */  
L4_ThreadId_t thread = L4_GlobalId(number, 1);  
void *utcb = utcb_base;  
if (!L4_UtcbIsKernelManaged())  
    utcb += L4_GetUtcbSize() * number;  
else  
    utcb = -0UL;  
L4_Word_t resources = 0;  
L4_ThreadControl ( thread, /* new TID */  
                  addr_spc, /* address space to create thread in */  
                  scheduler, /* scheduler of new thread */  
                  pager, /* pager of new thread */  
                  exc_hdlr, /* exception handler */  
                  resources, /* thread resources */  
                  utcb); /* utcb address */
```

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 - Page fault
 - Exception
 - Interrupt

ExchangeRegisters

- Reads, and optionally modifies, kernel-maintained thread state
- Is used for:
 - Activating newly created threads (giving them a valid IP, SP)
 - De-activating threads
 - Multiplexing a kernel thread between several logical threads
 - Maintain a thread pool
 - Saving and restoring thread state
 - E.g. for implementing signals, checkpointing, ...
- Can be executed on a thread:
 - By a thread in the same address space
 - By the thread's pager
 - By the root task

ExchangeRegisters

- C language API:

```
L4_ThreadId_t L4_ExchangeRegisters( L4_ThreadId_t target,  
                                    L4_Word_t control,  
                                    L4_Word_t sp,  
                                    L4_Word_t ip,  
                                    L4_Word_t flags,  
                                    L4_Word_t usr_data,  
                                    L4_ThreadId_t pager,  
                                    L4_Word_t *old_control,  
                                    L4_Word_t *old_sp,  
                                    L4_Word_t *old_ip,  
                                    L4_Word_t *old_flags,  
                                    L4_Word_t *old_usr_data,  
                                    L4_ThreadId_t *old_pager);
```

- *usr_data* is an arbitrary user-defined value
 - can be used to implement thread-local storage
- Flags allows setting processor status bits
- Can also inspect/modify the thread's GP registers
 - contents are in message registers

ExchangeRegisters

- Convenience APIs

```
L4_ThreadId_t L4_Stop( L4_ThreadId_t target);  
void L4_Start_SpIp( L4_ThreadId_t thread,  
                  L4_Word_t sp,  
                  L4_Word_t ip);
```

- Example: starting threads:

```
L4_Start_SpIp(thread, stack, function);
```


IPC Operation

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→ IPC just copies data from sender's to receiver's MRs

- This case is highly optimized in the kernel ("fast path")
- For MRs backed by physical registers, it is a no-op (on same CPU)
- Note:** no page faults possible during transfer (registers don't fault!)

The diagram illustrates the IPC operation. On the left, the 'Sender' has a User Thread (UT) with Message Registers (MR) MR0 through MR7. In the center is the 'GP Register Stack' with registers MR0 through MR5. On the right, the 'Receiver' has a User Thread (UT) with MR0 through MR7. An arrow labeled 'Copy' points from the Sender's MRs to the Receiver's MRs, passing through the GP Register Stack.

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A Word About Protocols

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Any communication requires protocols

→ Human communication protocols:

- meet in certain place at a certain time (14:00 in Room Seminar-Room W)
- use a certain medium (phone, face-to-face)
- use a certain language (English, Swahili, Esperanto...)
- rules about who speaks when (lecture, chaired discussion, ...)

→ Similarly with programs

- identify communication partners (name service, "built-in")
- define message formats
- define message sequences
- define failure modes
- ...

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Message Tag MR₀

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label₍₁₆₎ s r n m ~₍₆₎ U₍₆₎

→ Specifies message content

- u:** number of words in message (excluding MR₀)
- m:** specifies *memcpy* operation (later)
- n:** specifies *asynchronous notification* operation (later)
- r:** blocking receive
 - if unset, fail immediately if no pending message
- s:** blocking send
 - if unset, fail immediately if receiver not waiting
- label:** user-defined (e.g., opcode)
 - kernel protocols define this for some messages

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Reply Caps

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→ Typical client-server scenario:

- Clients are given rights (i.e. caps) for invoking server
- Server shouldn't need to:
 - know which clients it has (i.e. who has caps to it)
 - keep track of past client invocations (unless required by nature of service)
- Server shouldn't be able to:
 - interfere with client except on client's request

→ When client invokes server, server must be able to reply back

- Client could provide server with cap for reply
- However, it couldn't stop server from storing the cap for future use

→ Reply caps address this issue:

- provided to the server by the kernel in a call-type IPC
- can only be used once
- can only be used by the thread (server) which received the call

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Reply Caps

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→ On call-type IPC (and only there), kernel creates a *reply cap*

- delivered to receiver's `from` argument
 - only works with wait-type receive (L4_Wait() or L4_ReplyWait())
- receiver can use this as the cap in a send operation

The diagram shows the interaction between Client, Kernel, and Server. The Client calls L4_Call(Server). The Kernel sends a reply cap to the Server (Server.Client = new reply cap). The Server then calls L4_Send(Client). The Kernel receives this and calls L4_Wait(*Client) on the Client. The Client then calls L4_ReplyWait() on the Kernel.

→ Note: Server will normally use L4_ReplyWait() rather than separate syscalls

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Reply Caps Limitations


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→ Reply caps have "magic" other thread caps do not have:

- a reply cap can only be used once
- a reply cap is manufactured by the kernel on-the-fly
 - as a side effect of an L4_Call() operation
 - not by L4_Send(), L4_ReplyWait()
 - not by any other system call
- a reply cap is not in any clist (and therefore doesn't occupy a clist slot)
- a reply cap can only be used in an IPC send operation
 - L4_Send()
 - L4_ReplyWait()
- a reply cap can only be used by the thread which received it from the kernel
 - cannot be shared with other threads in the same address space
 - cannot be passed to another address space

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Example: Sending 4 words

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label	0	0	0	4
-------	---	---	---	---

```

L4Msg_t  msg;
L4MsgTag_t tag;


L4_MsgClear (&msg);
L4_Set_MsgLabel (&msg, 1);
L4_MsgAppendWord (&msg, word 1);
L4_MsgAppendWord (&msg, word 2);
L4_MsgAppendWord (&msg, word 3);
L4_MsgAppendWord (&msg, word 4);
L4_MsgLoad (&msg);
tag = L4_Send (tid);

```

Note: *u, s, r* are set implicitly by `L4_MsgAppendWord` and convenience function `Delivers MRp, ..., MRt` to thread *tid*
 Note: Should use IDL compiler rather than doing this manually!

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IPC Result MR₀


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label ₍₁₆₎	E	X	~	~	~	U ₍₆₎
-----------------------	---	---	---	---	---	------------------

- Returned from any IPC operation
- E**: error occurred, check `ErrorCode` in UTCB
- Some fields are only useful on a receive operation, and define the received message
 - label**: label of message sent (copy of label specified by sender)
 - u**: number of untyped words received
 - X**: message came from another CPU

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Example: Receiving

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label	0	0	0	4
-------	---	---	---	---

```

L4Msg_t  msg;
L4MsgTag_t tag;


tag = L4_Receive (tid);
L4_MsgStore (&msg);
label = L4_Label (tag);
assert (L4_UntypedWords (tag) == 4);
word1 = L4_MsgWord (&msg, 0);
word2 = L4_MsgWord (&msg, 1);
word3 = L4_MsgWord (&msg, 2);
word4 = L4_MsgWord (&msg, 3);

```

Note: Should use IDL compiler rather than doing this manually!

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IPC Possible Errors

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- Error can be on send or receive
- Error code stored in UTCB. Retrieved by `L4_ErrorCode()`
- Lower bit indicates send or receive phase. (Can't be both!)
- Bits 1-4 indicate cause:
 - Possible cause:
 - NoPartner** - issued when a non-blocking operation was requested and the partner was not ready
 - InvalidPartner** - invalid cap:
 - destination doesn't exist or don't have rights to IPC to it
 - MessageOverflow** - Message size exceeds system limit
 - IpcRejected** - receiver doesn't accept async message
 - IpcCancelled** - Cancelled by another thread before transfer started
 - IPCAborted** - Cancelled by another thread after transfer started
 - consequence of `ExchangeRegisters`

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Asynchronous Notification

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- Remote event notification
 - lightweight signalling mechanism
- Sets bit(s) in receiver's *notify flags* bitmap
 - delivered without blocking sender
 - delivered immediately, directly to receiver's UTCB, without receiver syscall

Sender Kernel Receiver

```

Sender: L4_MsgClear(&msg);
Sender: L4_Set_Notify(&msg);
Sender: L4_MsgAppendWord(&msg, flags);
Sender: tag=L4_Send (Receiver);

Kernel: Receiver.Utcb.NotifyFlags |= msg.w1;


Receiver: flags=L4_Get_Notify_Bits();

```

- receiver must enable asynchronous notification by updating its *acceptor*
- sender-specified flags are OR-ed to receiver's flags
- accumulates: no effect if receiver's bits already set

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Asynchronous Notification

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- Two ways to receive asynchronous notifications:
 - Asynchronously by checking `NotifyFlags` in UTCB
 - but remember it's asynchronous and can change at any time
 - Synchronously by a form of blocking IPC wait
 - receiver specifies mask of notification bits to wait for
 - on notification, kernel manufactures a message in a defined format
- Used by kernel for interrupt delivery — *new in OKL4 2.1*

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IPC: Obsolete Features (from earlier L4 APIs)

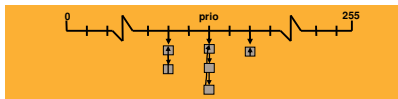
- String item in message
 - Used to send *out-of-line* data, arbitrarily-sized and -aligned buffers
 - Issues with page faults during IPC, recursive kernel invocation...
 - Replaced by more restricted MemCopy() syscall — *New in OKL4 2.1*
- Map/grant item in message
 - Used to send page mappings through IPC
 - High kernel space overhead
 - Long-running operations that are problematic for real-time
 - Replaced by MapControl() syscall
 - Next OKL4 version will have non-privileged, delegatable mappings
- Timeouts on IPC
 - Limit blocking time
 - Practically not very useful for lack of good rules for choosing timeouts
 - Replaced by send/receive block bits (*s*, *r* respectively)
 - Use watchdog time for implementing timeouts at user level

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OKL4 Scheduling

- OKL4 uses 256 hard priorities (0–255):
 - Priorities are strictly observer
 - The highest-priority runnable thread will always be scheduled
- Round-robin scheduling among threads of highest prio
- Aim is real-time scheduling, **not** fairness
 - Kernel on its own will *never* change the priority of a thread
 - Achieving fairness (if desired) is the job of user-level servers
 - Can use Schedule() syscall to adjust priorities



OKL4 Scheduling

- Scheduler is invoked when:
 - the current thread's time slice expires
 - Will only schedule thread of same priority (possibly same again)
 - the current thread yields
 - Will only schedule thread of same priority (possibly same again)
 - an IPC operation blocks caller or unblocks another thread
 - but see below for exceptions...
- Scheduler is **not** invoked when:
 - Interrupt occurs
 - May make higher-priority thread (interrupt-handler) runnable
 - Can determine looking at priorities of current and interrupt thread
 - The highest-prio thread can be determined without the scheduler
 - eg. send unblocks other thread **U** run sender or receiver based on prio
 - switch without scheduler invocation is called *direct process switch*
- Kernel implements *schedule inheritance* — *new in OKL4 2.1*
 - if high-prio thread is blocked on other thread (through IPC, mutex)
 - details later...

Schedule


- The Schedule() syscall does **not** invoke a scheduler!
 - ... nor does it actually schedule any threads
- Schedule sets/reads a thread's scheduling parameters
 - The caller must be registered as the destination's scheduler
 - Set via ThreadControl()
- Can change
 - priority
 - time-slice length
 - processor number
 - Only relevant on multiprocessors
- Can obtain
 - priority
 - time-slice length
 - processor number
 - remaining time slice (time left to next preemption)

Schedule Example

```

□ Set priority:
L4_word_t dummy;
int status;
status=L4_schedule ( tid,
                    0u1, 0u1, 0u1,
                    prio,
                    &dummy, &dummy);
printf("%Id\n", status);
    
```


Pre-emption Callback

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- When its time slice is exhausted, a thread is preempted
 - ... re-scheduled immediately if all other runnable threads are of lower priority
 - Note: no higher priority threads can be runnable due to hard priorities
- Thread can register a **preemption callback**:
 - kernel saves IP in `PreemptedIP` register
 - when re-scheduled, kernel sets thread's IP to registered callback address
 - kernel disables callback (until re-enabled by thread)
 - thread can fix up state and continue
- Can be used for:
 - implementing lock-free synchronization (archs w/o synchronization instructions)
 - real-time threads checking timing invariants

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ThreadSwitch

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- Forfeits the caller's remaining time slice
 - Can donate remaining time slice to specified thread
 - that thread will execute to the end of the time slice on the donor's priority
 - If no recipient specified (or recipient is not runnable):
 - normal "yield" operation
 - kernel invokes scheduler
 - call might receive a new time slice immediately
- Directed donation can be used for
 - explicit scheduling of threads
 - implementing wait-free locks (together with preemption callbacks)

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ThreadSwitch Example

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- Directed switch (time-slice donation):


```
L4_ThreadSwitch(some_thread);
```
- Yield (undirected switch):


```
L4_ThreadSwitch(L4_niltthread);
```

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OKL4 API Overview

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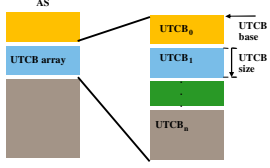
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SpaceControl

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- Create and destroy address spaces
 - Target AS is designated by unique *space ID*
 - within system-defined range
 - Allocated according to user-level policy
- Allocate clist to address space
 - For IPC, thread control rights
- Control layout of new address spaces
 - UTCB area location (not on ARM7/9)
 - Cannot change once address space is created



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SpaceControl

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→ Create create/destroy spaces

```
L4_Word_t L4_SpaceControl( L4_SpaceId_t target,
                          L4_Word_t control,
                          L4_ClistId_t clist,
                          L4_Fpage_t utcb_region,
                          L4_Word_t resources,
                          L4_Word_t *old_resources);
```

→ Can modify address-space resources (hardware-dependent)

- MMU ASID
- ARM9 PID

→ Can specify a *space pager* for the address space

- *OKL4 2.1-only feature*
- pager ID is specified in message register MR₀
- supports un-privileged version of mappings:
 - space pager can map pages into the *target* address space
 - details later...

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Deleting Address Spaces

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→ Deleting an address space frees up all its resources

- Frees its Space ID
- Removes all memory mappings

→ However SpaceControl() does not remove threads!

- Need to be cleaned up explicitly before calling SpaceControl()

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Address Spaces

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→ Address spaces are created empty

- Except UTCB

→ Need to be explicitly populated with page mappings

- Kernel does not map pages automatically (except UTCB)

→ Normally address space populated by pager on demand

- Thread runs, faults on unmapped pages, pager creates mapping

→ OS server(s) can populate pro-actively

- E.g. *Iguana* (default root task) pre-maps contents of executable and initialized data

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MapControl

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→ Creates (maps) or destroys (un-maps) page mappings

→ Normally a privileged system call

- but privilege can be given to address space to map a specific region to others
 - privileged provided via SpaceControl() system call

```
L4_Word_t L4_MapControl( L4_SpaceId_t dest, L4_Word_t control);
```

dest: denominates target address space
control: determines operation of syscall

m	r	0 _(2s)	n _(s)
---	---	-------------------	------------------

r: read operation — returns (pre-syscall) mapping info

- e.g. reference bits where hardware-maintained (x86)

m: modify operation — changes existing mapping

n: number of *map items* used to describe mappings

- map items are contained in message registers MR₀ ... MR_{2n-1}

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Specifying Mappings: Fpages

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→ A *flexpage* or *fpage* is used to specify mapping objects

- Generalisation of hardware pages
- Similar properties:
 - **size** is power-of-two multiple of base hardware page size
 - **base** is aligned to size
- fpage of size=2^s is specified as

base/1024	s ₍₆₎	r ₍₄₎
-----------	------------------	------------------

- Special fpages

0	0x3f	r ₍₄₎
---	------	------------------


0	0 ₍₆₎	0 ₍₄₎
---	------------------	------------------

- On ARM, s ≥ 12

→ Note: *Flexpages will be removed in next release*

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Map Item

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→ Specifies a mapping to be created in destination AS

fpage ₍₂₈₎	0:rwx
Phys adr/1024 ₍₂₆₎	attr ₍₆₎

- **fpage**: specifies where mapping is to occur in destination AS
- **phys adr**: base of physical frame(s) to be mapped
 - Note: shifted 4 bits to support 64MB of physical AS
- **attr**: memory attributes (eg cached/uncached)
- **rwx**: permissions
 - access rights in destination address space
 - can be used to change (up/downgrade) rights (only if mapping is replaced by an otherwise identical one)
 - removing all rights removes the mapping (unmap operation)
 - if specify unsupported permission, kernel widens to smallest superset (x→rx)

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Superpages

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→ Many processors support several page sizes

- OKL4 usually supports all sizes supported by hardware
- actually supported sizes can be obtained from libl4

→ MapControl will automatically choose largest supported size for a mapping


- E.g. mapping a 4MiB region on ARM
 - Kernel will use four 1MiB super-pages

→ Note: *next OKL4 release will require caller to specify page size*

- Example of removing policy from kernel

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Task

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→ OKL4 API does not define a concept of a “task”

→ We use it informally to mean:

- an address space, having:
 - space id
 - UTCB area
 - clist
 - other resources such as space pager, ASID, ...
- a set of threads inside that address space, each having:
 - local thread id (clist index)
 - UTCB location
 - IP, SP
 - pager
 - scheduler
 - exception handler
- code, data, stack(s) mapped into that address space

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Steps in Creating a Task

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→ Create a new address space (AS)

- SpaceControl() system call
- determines space ID and address-space layout according to policy
- associates a clist with the AS
- reserves virtual-memory region for UTCB array

→ Map memory into AS

- MapControl() system call
- maps text, data, stack(s)
- can also be done lazily (by pager in response to page faults)

→ Create threads


- ThreadControl() system call
- as discussed earlier

→ Start first thread

- ExchangeRegisters() system call
- gives thread IP, SP to make it runnable
- first thread may start any further threads itself

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Creating a Task...


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→ Define UTCB area location in new address space

```
L4_SpaceControl( task,
                /* new TID */
                L4_SpaceCtrl_new, /* control */
                clist, /* capability list */
                utcb_fpage /* location of UTCB array */
                0, /* no resources */
                &old_resources);
```

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Mapping Memory to Task

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```
L4_Fpage_t
fpage = L4_Fpage(vaddr, size);
fpage = L4_FpageAddRights(fpage, L4_Readable);
L4_PhysDesc_t
physdesc = L4_PhysDesc(paddr, L4_DefaultMemory);
L4_MapFpage(space, fpage, physdesc);
```

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Adding Threads to Task

→ Use ThreadControl() to add new threads to AS

```
threadno = ...; /* according to policy */
thread = L4_GlobalId(threadno, 1);
utcb = ...; /* according to policy, ignore on ARM9/11 */
L4_ThreadControl(tid, task, me, pager, me, res, utcb);
```

→ Note: Maximum number of threads defined at address-space creation time

- via the size of the UTCB area

Starting first Thread in Task

```
L4_Start_SpIp (thread, stack_pointer, function);
```

- convenience function, uses the ExchangeRegisters() system call
- thread can be started by its pager
- alternatively, can be started by another thread in the same address space

Practical Considerations

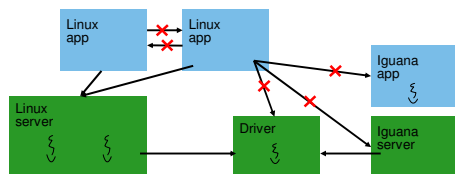
- Sequence for creating tasks may seem cumbersome
 - price to be paid for leaving policy out of kernel
 - any shortcuts imply policy
- A system built on top of L4 will inherently define policies
 - can define and implement library interfaces for task and thread creation
 - incorporating system policy
- Actual apps would not use raw L4 system calls, but
 - use libraries
 - use IDL compiler (Magpie)
- Note: *Some older L4 APIs do not support space IDs*

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 - lpc
 - Schedule
 - ThreadSwitch
 - Mutex
 - MemoryCopy
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- Protocols
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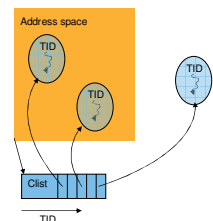
Capabilities

- Caps specify communication rights
 - supports information-flow control
 - in future versions of OKL4 this will be extended to all system resources
- Threads can always receive messages from anywhere
- Threads can only send messages to threads whose IPC caps they hold




Capabilities and Clists

- Each address space has one *clist*
 - holds all caps of that address space
 - caps provide local names for kernel objects
- Clist is a kernel object
 - not directly accessible to user code
- Clists created/destroyed by CapControl()
 - only empty clists can be destroyed
- Thread caps created by ThreadControl()
 - deposits thread cap in slot in caller's clist
 - identified by thread-no field in thread cap
- IPC caps created by CapControl()
 - creates an IPC cap from a thread cap
 - deposits the IPC cap in specified clist
- Thread/IPC caps are location-transparent
 - cannot infer thread's address space from cap



Managing Clists

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```
ok = L4_CreateClist( clist, /* id of new clist */
                   n_entries); /* clist size */

ok = L4_CreateIpcCap(tid, /* thread cap */
                    tid_clist, /* clist of tid */
                    dest, /* new IPC cap */
                    dest_clist); /* clist for dest cap */
```

- Those convenience functions use CapControl()
- As clists determine access rights, in general an address space doesn't have access to its own clist
 - this is presently ensured by CapControl() being a privileged system call
 - in future versions, clists will be subject to access control instead

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Mutex

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- Kernel-supported mutual-exclusion mechanism
- Two kind of mutexes supported
 - **kernel mutex**: lock/unlock are system calls
 - legacy, do not use
 - system call overhead too high for uncontended locks
 - **hybrid mutex**: combination of library and syscall — *new in OKL4 2.1*
 - user-level implementation of lock/unlock (in shared memory) if uncontended
 - syscall if contended
 - thread waiting on lock is put to sleep, with schedule inheritance, fairness
- Three operations:
 - **lock**: acquire blocking
 - **trylock**: acquire non-blocking
 - **unlock**: release

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Mutex Use

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MutexControl() convenience functions:

```
okl4_mutex_t mutex;
ok = okl4_mutex_init( mutex); /* alloc kernel mutex and initialise */
ok = okl4_mutex_free( mutex); /* free kernel mutex etc */
```


Mutex operation:

```
ok = okl4_mutex_lock( mutex);
ok = okl4_mutex_trylock( mutex);
ok = okl4_mutex_unlock( mutex);
```

- Hybrid mutex variable contains user-level state + reference to kernel mutex
 - if lock operation finds mutex locked, performs Mutex() syscall to sleep
 - if unlock operation finds mutex locked contended, performs Mutex call to unlock
- Note: *hybrid mutexes are only simulated in OKL4 2.1* (always do syscall)

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User-to-User Memory Copy

New in OKL4 2.1

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- Supports bulk data transfer without limitations of alternatives:
 - copy server
 - requires trusted third party
 - higher synchronisation overhead
 - shared memory buffer
 - page-alignment requirement
 - space overhead of at least one page per pair of address spaces
- Replacement for "long IPC" feature of L4 V2, V4
 - avoids drawbacks of long IPC:
 - page faults during syscall, recursive syscalls
 - tricky corner cases in semantics, high implementation complexity

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MemoryCopy Operation

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- Semi-synchronous copy between address spaces
 - similar in style to asynchronous notification:
 - one thread sets up
 - other thread invokes transfer
 - synchronous to invoker, asynchronous to initiator
- Sandwiched between IPCs
 - serve for
 - setup
 - synchronization
 - don't touch buffer
 - sender between IPCs
 - receiver after final IPC
- Copy direction
 - independent of IPC direction

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MemoryCopy Use

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- Initiator:


```
L4_MsgClear( &msg);
L4_Set_MemoryCopy( &msg); /* Set m bit in tag word */
L4_MsgAppendWord( &msg, &buf); /* buffer address */
L4_MsgAppendWord( &msg, n); /* buffer size (byte) */
L4_MsgAppendWord( &msg, L4_MemoryCopyBoth<<30); /* send/recv */
tag = L4_Send( transferer);
```
- MemoryCopy descriptor is in message registers, after any untyped words
 - specifies address and size of buffer
 - specifies permitted copy direction (from, to or both)
- Transferer:


```
L4_MemoryCopy( initiator, &rec_buf, n_rec, L4_MemoryCopyFrom);
L4_MemoryCopy( initiator, &snd_buf, n_snd, L4_MemoryCopyTo);
```

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SpaceSwitch — New in OKL4 2.1

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- Migrates a thread between address spaces
 - previously part of ThreadControl() functionality
- This is a *privileged* system call (despite no "Control") in its name
 - but limited switch privilege is delegatable via SecurityControl()

```
L4_SpaceSwitch( L4_ThreadId_t tid, /* target thread */
               L4_SpaceId_t space, /* where to */
               void *utcb); /* new slot */
```

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OKL4 API Overview

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InterruptControl — New in OKL4 2.1

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- Manages interrupts
 - association/dissociation of handler threads with IRQs
 - interrupt acknowledgement
 - right to use must be delegated to address space via SecurityControl()
 - mostly replaces interrupt IPC protocol of earlier L4 versions
- Actual interrupt delivery is by asynchronous notification
 - different from earlier L4 versions, but more in line with hardware behaviour
 - allows handler to decide whether to block or poll
- 5 different operations
 - register: associates IRQ(s) to thread
 - unregister: removes association of thread with IRQ(s)
 - acknowledge: acknowledge and clear interrupt at hardware
 - acknowledgeOnBehalf: ack by a different thread in same address space
 - acknowledgeWait: ack and wait for next interrupt notification

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InterruptControl Use  Be open. Be safe.

```

L4_Register_Interrupt (
    L4_ThreadId_t  thread, /* handler thread, local to address space */
    L4_Word_t     n_bit,  /* number of bit used for interrupt notification */
    L4_Word_t     mrs,    /* number of highest msg reg for parameters */
    L4_Word_t     request); /* additional parameter */


L4_AcknowledgeInterrupt( L4_Word_t mrs, L4_Word_t request);

```

→ Details of parameters are platform-specific

- defined by board support package
- typically deal with one IRQ at a time
- platform-defined parameter format
 - parameters in $MR_0 \dots MR_{n-1}$
 - typically $mrs=0$, parameter word contains IRQ number
 - additional `request` parameter not needed by most platforms

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OKL4 API Overview  Be open. Be safe.

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SecurityControl — New in OKL4 2.1  Be open. Be safe.


→ Used to delegate certain privileges to an address space

- enables unprivileged address space to perform limited privileged operations
- logically derives a capability and grants this to target address space
- will become redundant once all resources are explicitly capability-controlled

→ Deals with 5 different privileges

- **platform**: grants right to invoke PlatformControl()
- **space-switch**: grants right to switch threads to another address space
 - specifies the allowed target address space
- **interrupt**: assigns specified interrupts to an address space
 - enabling it to associate those using InterruptControl()
- **map**: grants rights to an address space to map memory to a different space
 - specifies the physical memory region the address space can map
 - enables the address space to invoke MapControl() for that region
 - but only map to an address space whose *space pager* is the caller
- **domain**: grants right to set up shared regions using a common domain ID
 - supports high-performance sharing on ARM9 (architecture-specific)

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CacheControl  Be open. Be safe.

→ Controls state of CPU caches

- may operate on complete cache
- may operate on all cache lines holding data of a certain memory region
- may operate on instruction or data cache
- may operate on all or specified levels of cache


→ 6 different operations

- **flush**: clean any modified lines corresponding to region, then invalidate
- **lock**: lock lines corresponding to region
- **unlock**: unlock lines corresponding to region
- **flushI**: clean and invalidate complete instruction cache
- **flushD**: clean and invalidate complete data cache
- **flushAll**: clean and invalidate all caches

→ Example: Driver flushes I/O buffer prior to DMA

- L4_CacheFlushDRange(space, start_addr, end_addr);

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→ Protocols

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PlatformControl

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- Platform-specific system call
 - used for platform-specific functionality
- Presently used only for power management
 - used to set core voltage and frequency
- *Right to use may be granted to unprivileged address space using SecurityControl()*
- Possible use:


```
I4_PlatformControl(0, bus_freq, cpu_freq, voltage);
```

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OKL4 Protocols

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- Page fault
- Exception
- Interrupt

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Page Fault Handling

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- Address-spaces are populated in response to page faults
- Page faults are converted into IPC messages:
 1. Thread triggers page fault
 2. Kernel exception handler generates IPC from fault to pager
 3. Pager establishes mapping
 - Calls MapControl()
 - if not privileged to do this, has to ask root task
 4. Pager replies to page-fault IPC
 5. Kernel intercepts message, discards
 6. Kernel restarts faulting thread

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Page Fault Message

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- Format of kernel-generated page fault message

Fault IP	MR ₂
Fault address	MR ₁
-2 0rwx 0 ₍₄₎ 0 ₍₈₎ 2	MR ₀
- E.g. page fault at address 0x2002: Kernel sends

Fault IP	MR ₂
0x2002	MR ₁
-2 0rwx 0 ₍₄₎ 0 2	MR ₀
- Application could manufacture same message if it had a cap to the pager
 - ... provided it has a cap to IPC to the pager (which it generally does not have)
 - Pager could not tell the difference
 - Could mess up OS bookkeeping (has page been mapped?)
 - Better not to give apps a cap to their pager (possible in OKL4 2.1)

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Pager Action

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- E.g. pager handles write page fault at 0x2002
 - Map item to map 4KB page at PA 0xc000

0x8	12	0
0x300	0	

 - Note: *phys addr* must be aligned to *page* size
- Next, pager replies to page-fault message
 - Content of message completely ignored
 - Serves for synchronisation: informing kernel that fault can be restarted
 - If pager did not establish mapping, client will trigger same fault again

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OKL4 Protocols

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- Page fault
- Exception
- Interrupt

Operating System

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Exception Protocols

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- Other exceptions (invalid instructions, division by zero...) result in a kernel-generated IPC to thread's *exception handler*
- Exception IPC
 - Kernel sends (partial) thread state

Exception word _{k+1}	MR _{k+1}
Exception word ₀	MR ₂
Exception IP	MR ₁
label	MR ₀

0	0	0	k
---	---	---	---

- Label:
 - -4: Standard exception, architecture independent
 - -5: Architecture-specific exception

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Exception State

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- Thread state sent to exception handler depends on exception
- **General exception:** kernel sends:
 - IP, SP, CPSR, exception number
 - Error code (exception specific)
- **VFP exception (ARM):** kernel sends:
 - IP, SP, CPSR, exception number
 - Error code (Exception specific)
 - Faulting FP instruction, next instruction, FP SCR (status word)
- **Syscall exception:** kernel sends:
 - IP, SP, LR, CPSR, R0, ..., R7
 - **On ARM:** syscall instruction

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Exception Reply

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- Thread remains blocked until exception handler replies
 - Logically performs call() IPC
- Reply has same format
 - Kernel uses to overwrite thread state
 - To leave unchanged, send same message back
 - Obviously kernel will not let you modify privileged state (eg in status register)

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Exception Handling

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- Possible responses of exception handler:
 - retry:** reply with unchanged state
 - Possibly after removing cause
 - Possibly changing other parts of state (registers)
 - continue:** reply with IP+=4 (assuming 4-byte instructions)
 - emulation:** compute desired result, reply with appropriate register value and IP+=4
 - handler:** reply with IP of local exception handler code to be executed by the thread itself
 - ignore:** will block the thread indefinitely
 - kill:** use `ExchangeRegisters()` (if local) or `ThreadControl()` to restart or kill thread

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OKL4 Protocols


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- Page fault
- Exception
- Interrupt

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What is in a device?

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- Registers
 - The interface to the device
 - Provides the mechanism for modifying device state
 - Provides the mechanism for querying the device state
- Interrupts
 - Mechanism for device to notify CPU of events
- Direct Memory Access
 - Allows device to access memory efficiently
 - Compare with programmed I/O (PIO)

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Device Registers

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- Memory mapped
 - Mapped into the hardware address space
 - Can be access using normal memory operations
 - map into driver address space using MapControl()
 - should map with caching disabled!
- I/O Ports (x86 only)
 - Separate I/O address space
 - Uses special instructions (INB, OUTB)
- Register size
 - Usually *word* size
 - Can be smaller: e.g: 8-bit or 16-bit
 - Important to use the correct types to avoid incorrect operation

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Interrupts

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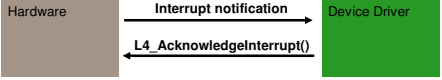
- Used to signal event
 - network packet arrived
 - disk operation completed
- Device is usually connected to an *interrupt controller*
 - interrupt controller multiplexes many interrupt sources onto CPU interrupt line
 - two different options for L4:
 - export just the CPU interrupt, demux interrupt sources at user level
 - kernel demux interrupt source, export each individual interrupt source
 - Both have pros and cons: decision is platform specific
 - on x86 decodes interrupt source inside the kernel
 - on ARM typically have separate interrupt for each source

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Interrupts

UNSW  Be open. Be safe.

- Modelled as asynchronous notification sent by hardware
 - received by interrupt handler thread registered for that interrupt
 - handler associated via InterruptControl()
 - handler uses InterruptControl() to acknowledge interrupt




```

graph LR
    Hardware[Hardware] -- "Interrupt notification" --> DeviceDriver[Device Driver]
    DeviceDriver -- "L4_AcknowledgeInterrupt()" --> Hardware
  
```

- Board-support package may update interrupt descriptor in handler's UTCB
 - can be used to pass additional information to driver

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Interrupt Handlers

UNSW  Be open. Be safe.

- Typical setup: Interrupt handler is "bottom-half" device driver
- Interrupt handling:
 1. Interrupt is triggered, hardware disables interrupt and invokes kernel
 2. Kernel masks interrupt, determines interrupt number and notifies handler
 3. Handler has been blocked waiting on notify, is unblocked
 4. Handler identifies interrupt cause by inspecting notify mask, possibly inspects interrupt descriptor in handler's UTCB (if set by BSP)
 5. Handler acknowledges interrupt via InterruptControl()
 6. Handler queues request to top-half driver
 7. Handler sends notification to top-half, waits for next interrupt (*reply-and-wait* IPC)

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Direct Memory Access

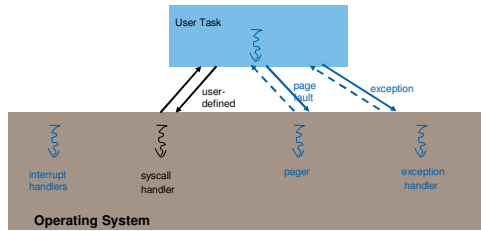
UNSW  Be open. Be safe.

- DMA is important for performance of bulk-IO devices
 - actual IO happens bypasses the CPU
 - however still impacts performance because I/O consumes memory bus cycles
- DMA is not necessarily *cache coherent*
 - DMA engine works directly on the physical memory, bypasses the CPU cache
 - potential for incorrect data to be read by the device
 - IA32: The exception, DMA is cache coherent
- Must explicitly flush cache before performing DMA (except on IA32!)
 - use CacheControl()
 - not needed on x86
- Device driver must translate a virtual addresses to physical addresses
 - can use L4_MapControl to query pagetable
 - usually root server keeps track of these mappings to avoid a kernel call

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OKL4 Protocols

- Page fault
- Exception
- Interrupt



OKL4 API Overview

→ Privileged system calls

- ThreadControl
- SpaceControl
- MapControl
- CapControl
- MutexControl
- InterruptControl
- SecurityControl
- CacheControl
- PlatformControl

→ Unprivileged system calls

- ExchangeRegisters
- Ipc
- Schedule
- ThreadSwitch
- Mutex
- MemoryCopy
- SpaceSwitch

→ Protocols

- Page fault
- Exception
- Interrupt

Final Remarks

Beer o'clock!