School of Computer Science & Engineering

COMP9242 Advanced Operating Systems

2019 T2 Week 01a

Introduction: Microkernels and seL4

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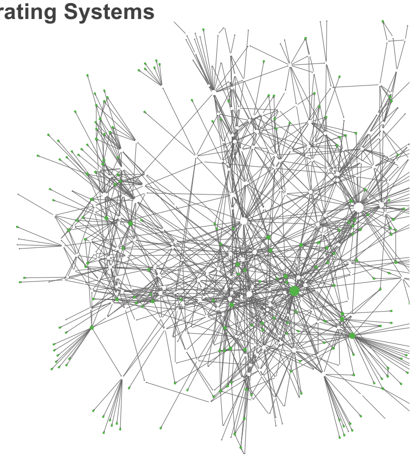

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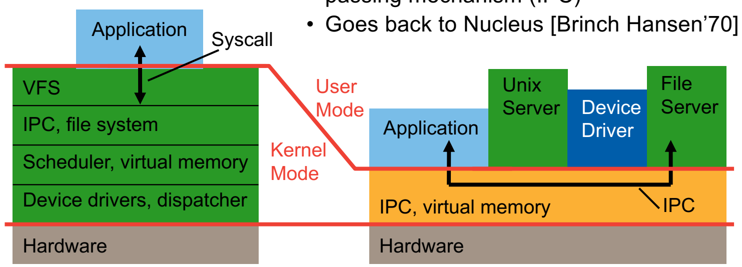
Microkernels: Reducing the Trusted Computing Base

IPC performance is critical!

- Idea of microkernel:
  - Flexible, minimal platform
  - Mechanisms, not policies
  - OS functionality provided by usermode servers
  - Servers invoked by kernel-provided message-passing mechanism (IPC)
  - Goes back to Nucleus [Brinch Hansen'70]



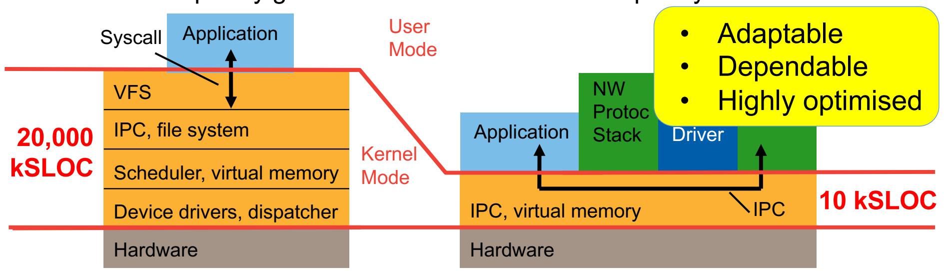
Monolithic vs Microkernel OS Evolution

Monolithic OS

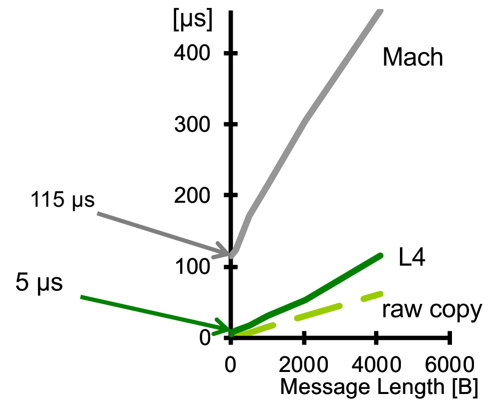
- New features add code kernel
- New policies add code kernel
- Kernel complexity grows

Microkernel OS

- Features add usermode code
- Policies replace usermode code
- Kernel complexity is stable



1993 “Microkernel”: IPC Performance



i486 @
50 MHz

Culprit: Cache footprint [Liedtke’95]

Microkernel Principle: Minimality

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. [SOSP’95]

- Advantages of resulting small kernel:
  - Easy to implement, port?
  - Easier to optimise
  - Hopefully enables a minimal *trusted computing base*
  - Easier debug, maybe even *prove* correct?
- Challenges:
  - API design: generality despite small code base
  - Kernel design and implementation for high performance

Limited by arch-specific micro-optimisations

Small attack surface, fewer failure modes

Microkernel Evolution

First generation

Mach [’87], QNX, Chorus

- Memory Objects
- Low-level FS, Swapping
- Devices
- Kernel memory
- Scheduling
- IPC, MMU abstr.

180 syscalls, 100 kSLOC
100 µs IPC

Second generation

L4 [’95], PikeOS, Integrity

- Kernel memory
- Scheduling
- IPC, MMU abstr.

~7 syscalls, ~10 kSLOC
~ 1 µs IPC

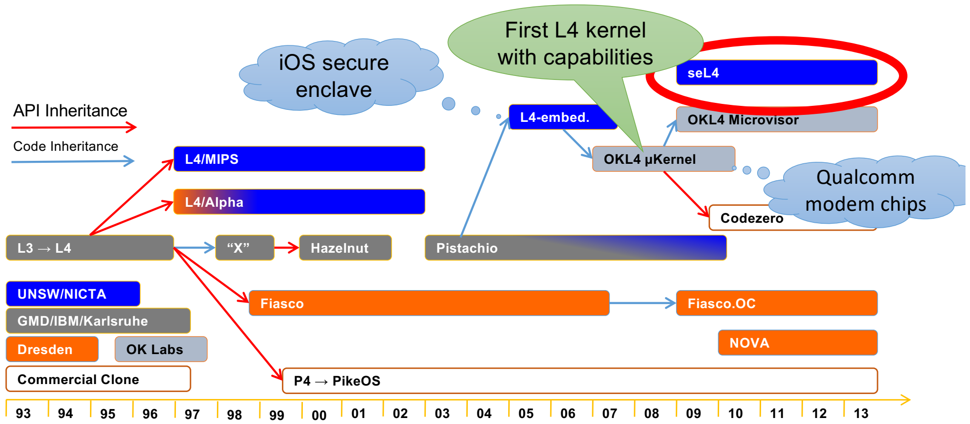
Third generation

seL4 [’09]

- Memory-mangmt library
- Scheduling
- IPC, MMU abstr.

~3 syscalls, ~10 kSLOC
0.1 µs IPC
Capabilities
Design for isolation

L4: 25 Years High Performance Microkernels



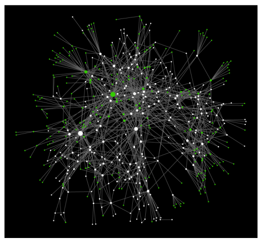
Issues With 2G Microkernels

- L4 solved microkernel performance [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
  - No delegation of authority ⇒ limited flexibility, performance issues
  - Unprincipled management of time
- Addressed by seL4
  - Designed to support safety- and security-critical systems
  - Principled time management (MCS branch)

The seL4 Microkernel

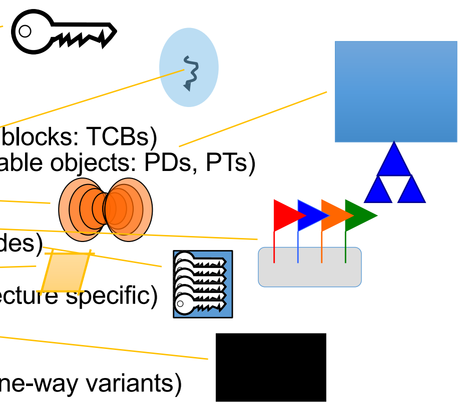
seL4 Principles

- Single protection mechanism: capabilities
  - Now also for time [Lyons et al, EuroSys'18]
- 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]



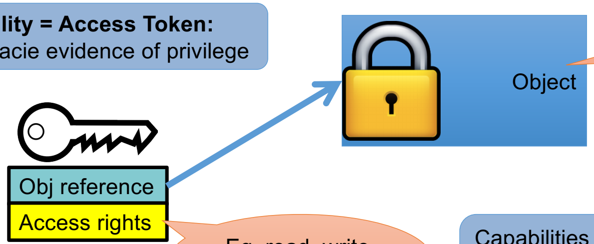
seL4 Concepts

- Capabilities (Caps)
  - mediate access
- Kernel objects:
  - Threads (thread-control blocks: TCBs)
  - Address spaces (page table objects: PDs, PTs)
  - Endpoints (IPC)
  - Notifications
  - Capability spaces (CNodes)
  - Frames
  - Interrupt objects (architecture specific)
  - Untyped memory
- System calls:
  - Call, Reply&Wait (and one-way variants)
  - Yield



What Are (Object) Capabilities?

Capability = Access Token:
Prima-facie evidence of privilege



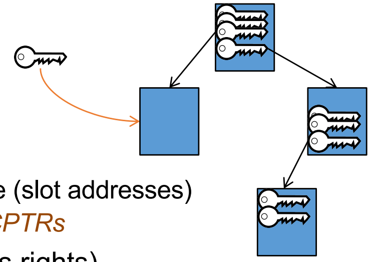
Eg. thread, address space

Eg. read, write, send, execute…

Capabilities provide:
- Fine-grained access control
- Reasoning about information flow

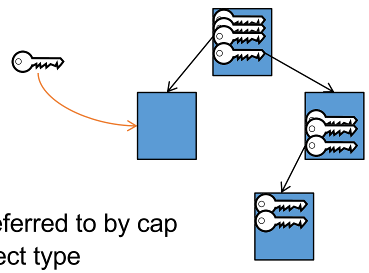
Any system call is invoking a capability:
err = cap.method(args);

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`, `Execute`, `Grant` (cap transfer)

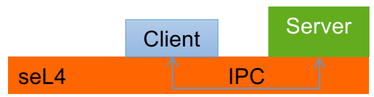
Capabilities



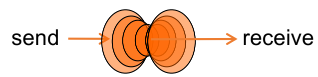
- Main operations on caps:
  - *Invoke*: perform operation on object referred to by cap
    - Possible operations depend on object type
  - *Copy*/ *Mint*/ *Grant*: create copy of cap with *same*/*lesser* privilege
  - *Move*/ *Mutate*: transfer to different address with same/lesser privilege
  - *Delete*: invalidate slot (cleans up object if this is the only cap to it)
  - *Revoke*: delete any derived (eg. copied or minted) caps

Cross-Address-Space Invocation (IPC)

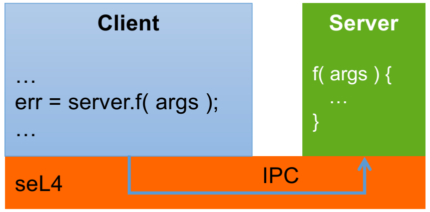
Fundamental microkernel operation
- Kernel provides no services, only mechanisms
- OS services provided by (protected) user-level server processes
- invoked by IPC



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



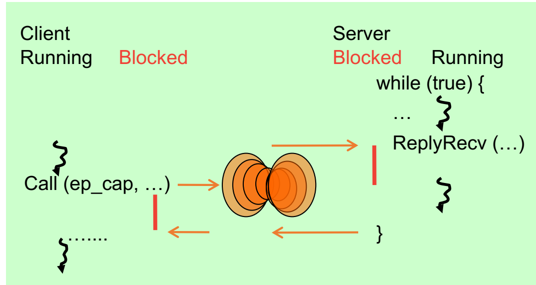
seL4 IPC: Cross-Domain Invocation



seL4 IPC is **not**:
- A mechanism for shipping data
- A synchronisation mechanism

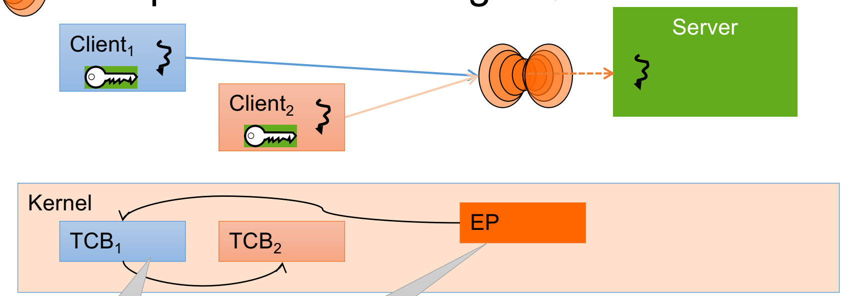
seL4 IPC **is**:
- A protected procedure call
- A user-controlled context switch

IPC: Endpoints



- Threads must rendez-vous
  - 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!

Endpoints are Message Queues

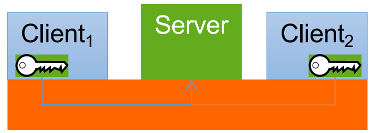


Further callers of same direction queue behind

First invocation queues caller

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

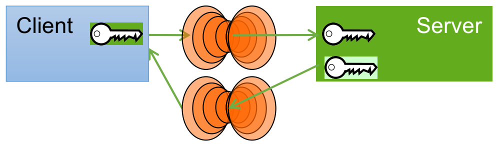
Server Invocation & Return



- 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
  - allows server to reply to client
  - cannot be copied/minted/re-used but can be moved
  - one-shot (automatically destroyed after first use)

MCS kernel removes the magic

Call Semantics



Client | **Kernel** | **Server**

ep=ReplyRecv(ep,&args)

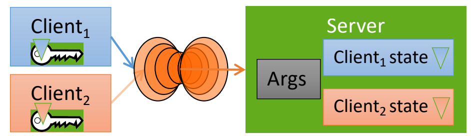
Call(srv, args) → *mint* reply cap

deliver to server → *process*

deliver to client ← ep=ReplyRecv(ep,&args)

process ← *destroy reply cap*

Stateful Servers: Identifying Clients



- Server 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 (session) caps to clients
    - separate endpoints for opening session, further invocations
  - server tags client state with badge
  - 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
    - 4 on ARM & x64, 2 on ia32
  - 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()

Better model in "MCS" branch – merge soon

IPC Operations Summary

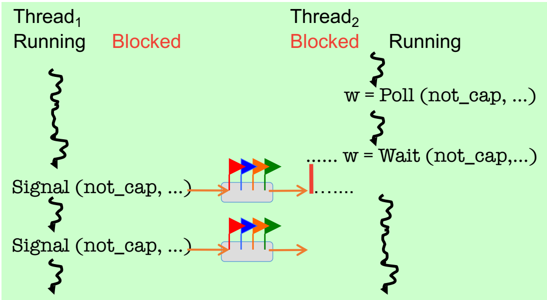
- Call (ep_cap, ...)
  - *Atomic*: guarantees caller is ready to receive reply
  - Generates reply cap on-the-fly
- ReplyRecv (ep_cap, ...)
  - Consumes reply cap
- Send (ep_cap, ...), Recv (ep_cap, ...), Reply(...)
  - For initialisation and exception handling
  - needs Write, Read permission, respectively
- NBSend (ep_cap, ...)
  - Polling send, message lost if receiver not ready

Need error handling protocol !

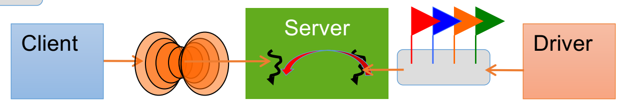
No failure notification where this reveals info on other entities!

Notifications

- Logically, a Notification is an array of binary semaphores
  - Multiple signalling, select-like wait
  - Not a message-passing IPC operation!
- Implemented by *data word* in Notification
  - 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* Notification



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 events
  - Notification is *bound* to thread with `TCB_BindNotification()`
  - thread waits on Endpoint
  - Notification delivered as if caller had been waiting on Notification