School of Computer Science & Engineering

COMP9242 Advanced Operating Systems

2024 T3 Week 01 Part 1

Introduction: Microkernels and seL4

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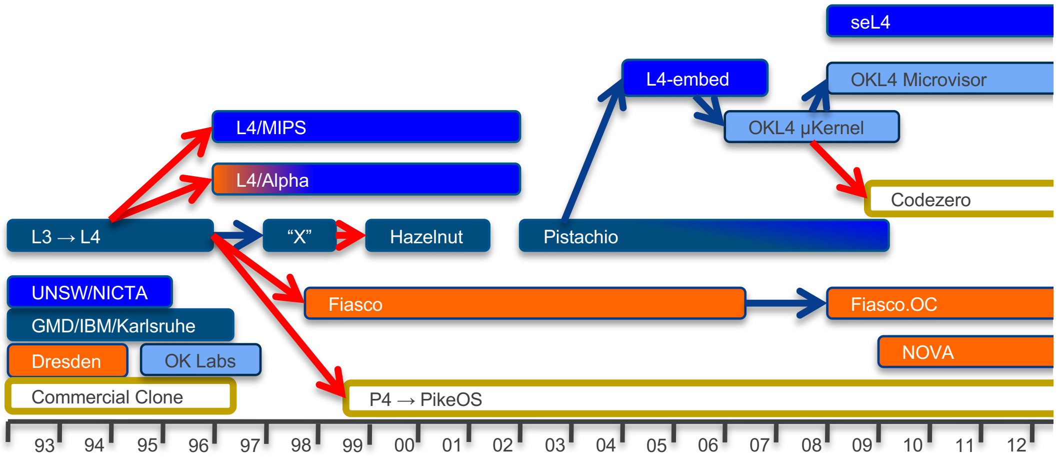

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Why Advanced Operating Systems?

- Understand OS (especially microkernels) in real depth
- Understand how to design an OS
- Learn to build a sizable system with great deal of independence
- Learn to cope with the complexity of systems code
- Tackle a real challenge
- Get a glimpse of OS research, and preparation for it
- Obtain skills highly sought-after in industry
- **Have fun while working hard!**

Today’s Lecture

- Whirlwind intro to microkernels and the context of seL4
- seL4 principles and concepts
- seL4 Mechanisms
  - PPC
  - Notifications

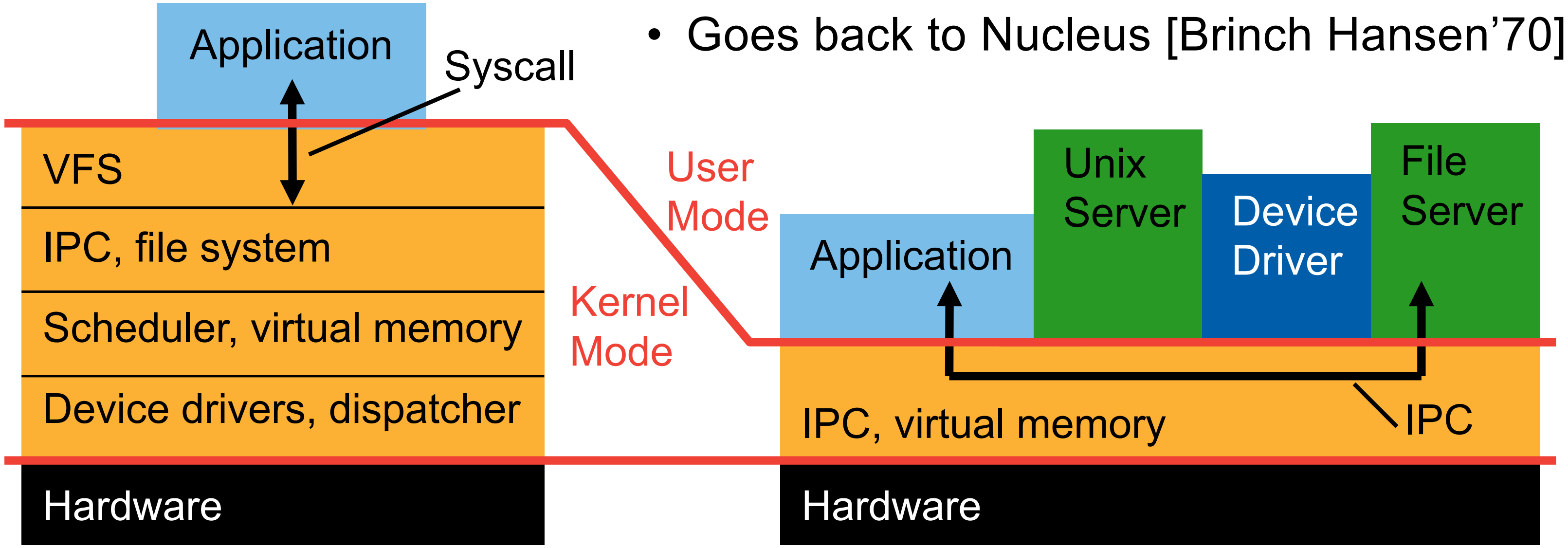
Aim: Get you ready for the project quickly

Microkernels

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 (called “IPC”)
  - Goes back to Nucleus [Brinch Hansen’70]



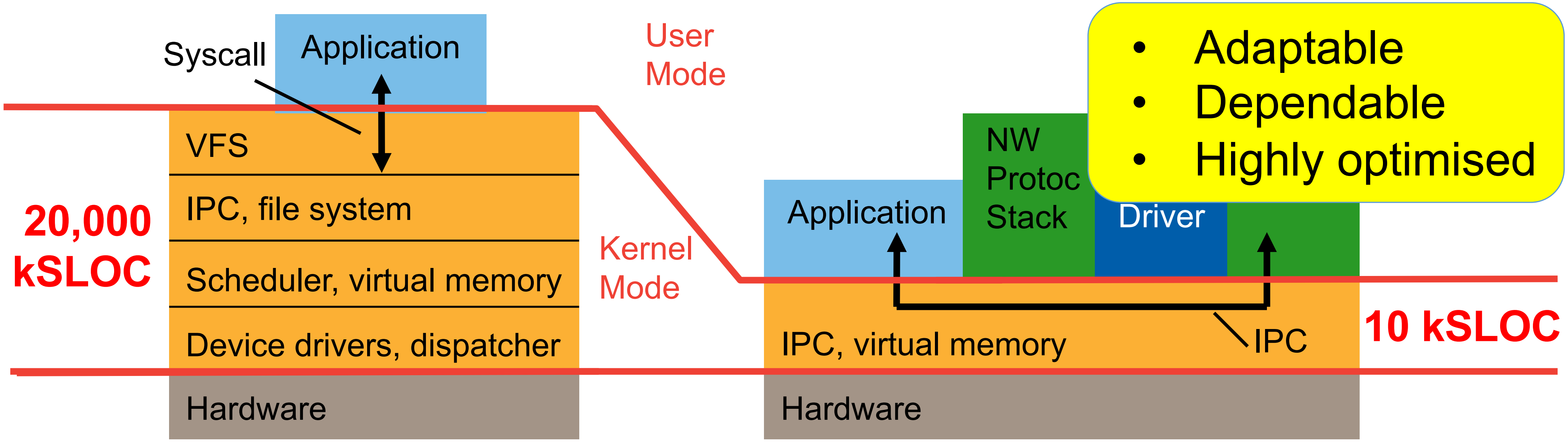
Monolithic vs Microkernel OS Evolution

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



- Adaptable
- Dependable
- Highly optimised

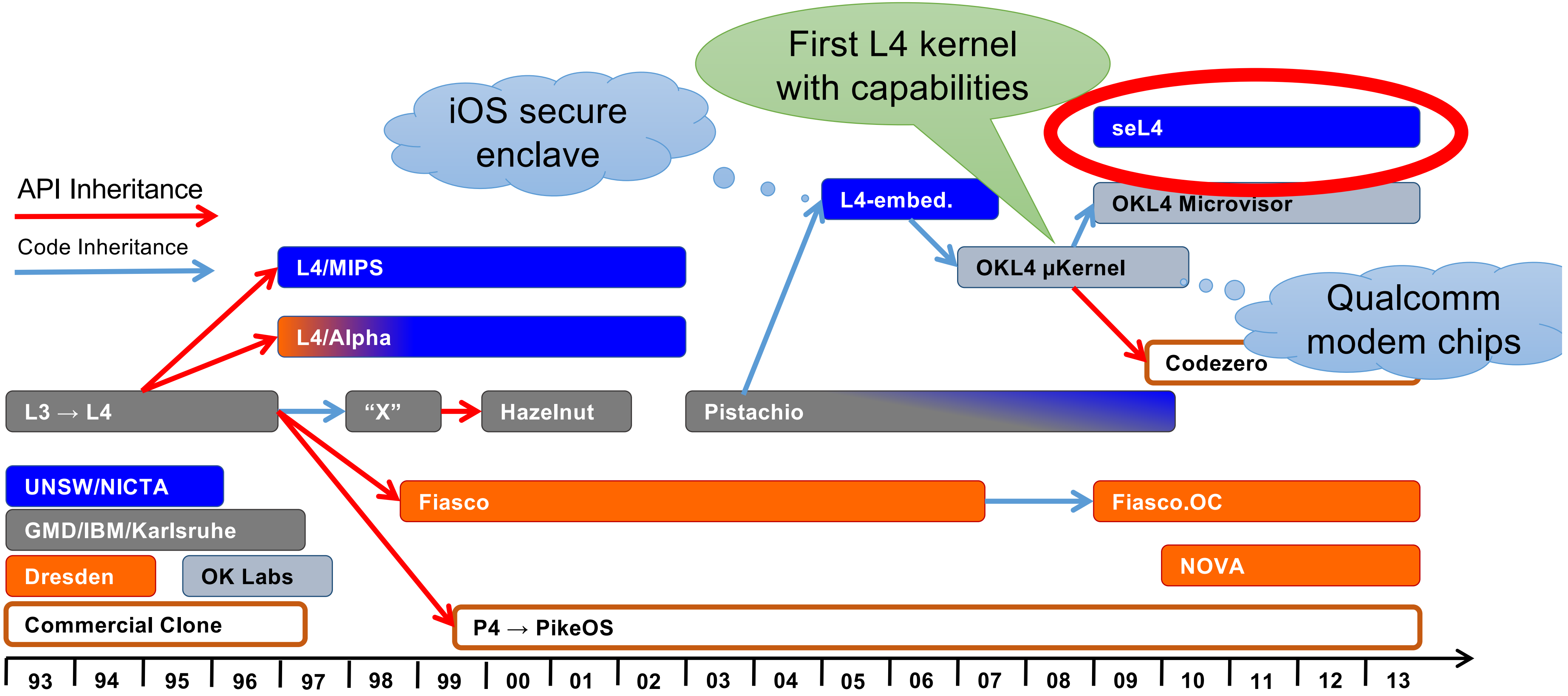
Microkernel Principle: Minimality

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. [Lietdke SOSP'95]

- Small *trusted computing base*
  - Easier to get right
  - Small attack surface
- Challenges:
  - API design: **generality** despite small code base
  - Kernel design and implementation for high performance

Needs policy-freedom!

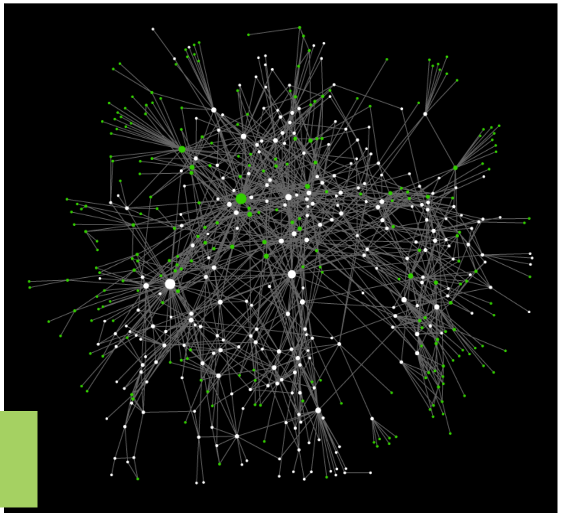
L4: 30 Years High-Performance Microkernels



The seL4 Microkernel

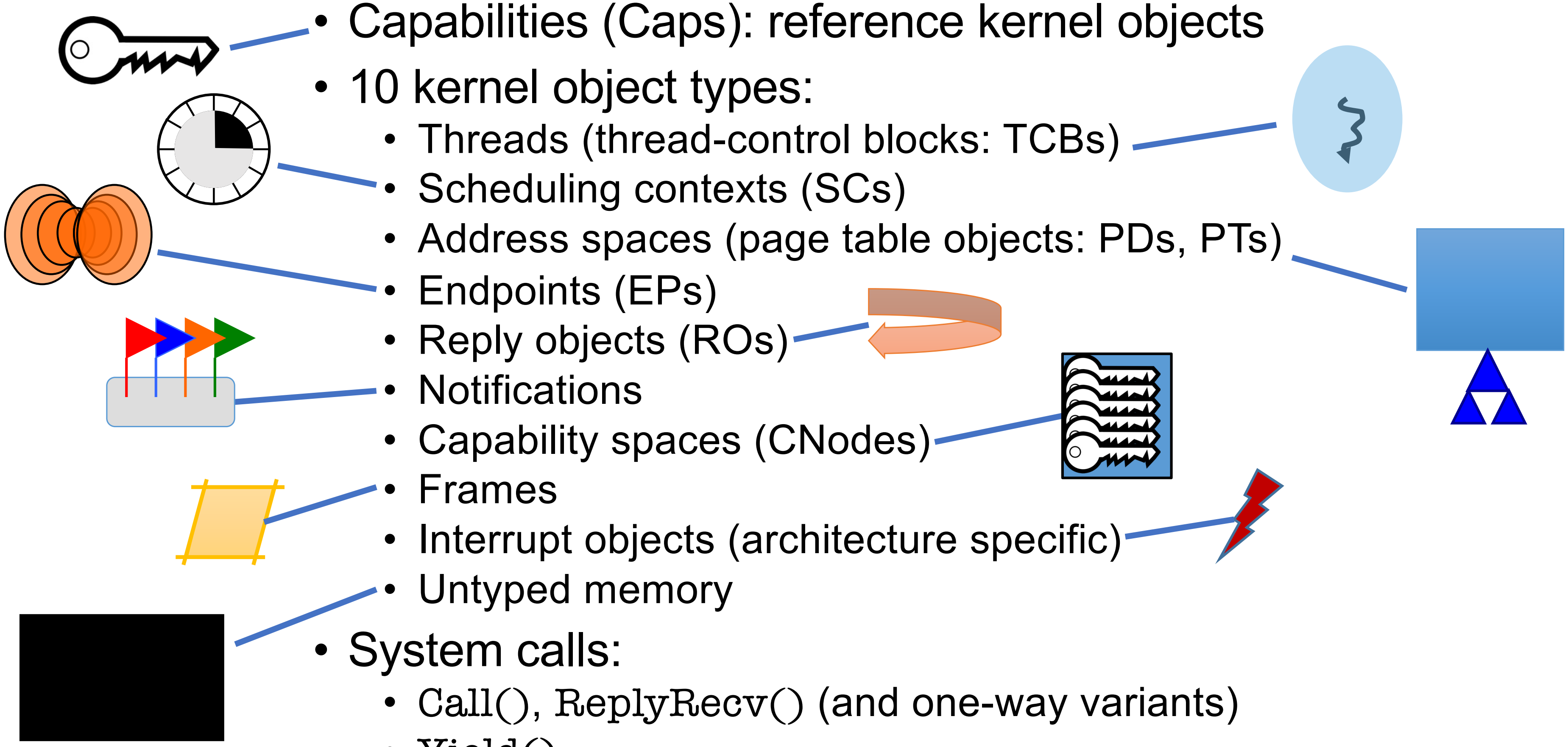
seL4 Principles

- Single protection mechanism: capabilities
  - Now also for time: MCS configuration [Lyons et al, EuroSys'18]
- All resource-management policy at user level
  - Painful to use
  - Need to provide memory-management library for COMP9242
    - 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/UNSW [Klein et al, SOSP'09]



More on principles in my blog: https://bit.ly/34uI8Fl

Concepts in a Slide



- Capabilities (Caps): reference kernel objects
- 10 kernel object types:
  - Threads (thread-control blocks: TCBs)
  - Scheduling contexts (SCs)
  - Address spaces (page table objects: PDs, PTs)
  - Endpoints (EPs)
  - Reply objects (ROs)
  - Notifications
  - Capability spaces (CNodes)
  - Frames
  - Interrupt objects (architecture specific)
  - Untyped memory
- System calls:
  - `Call()`, `ReplyRecv()` (and one-way variants)
  - `Yield()`

Not a Concept: Hardware Abstraction

Why?

- Hardware abstraction *violates minimality*
- Hardware abstraction *introduces policy*

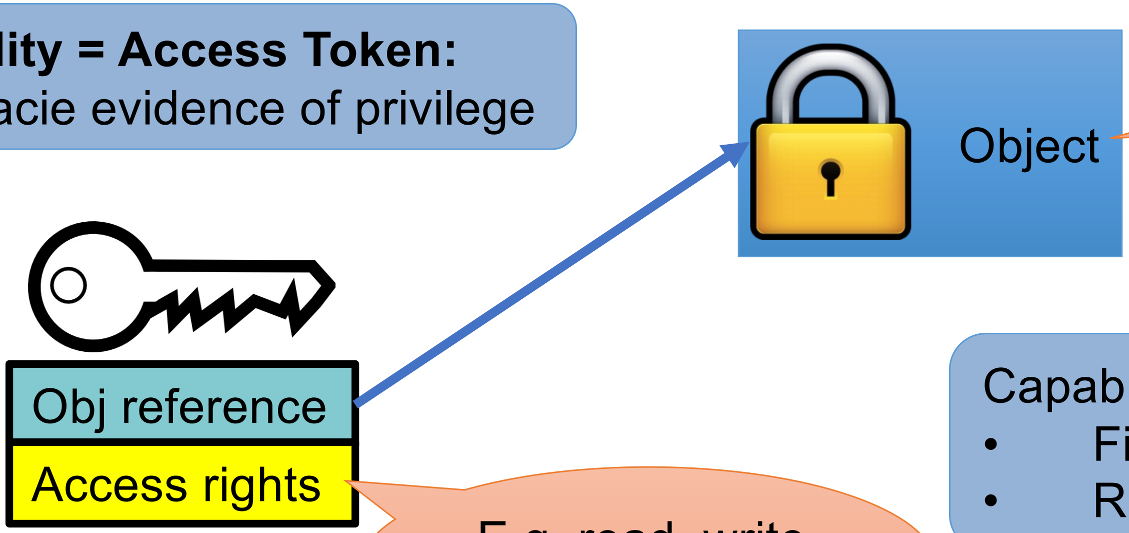
Limits generality!

True microkernel:

- Minimal wrapper of hardware, just enough to safely multiplex
- policy-free
- "CPU driver" [Charles Gray]
  - Similarities with Exokernels [Engeler '95]

What Are (Object) Capabilities?

Capability = Access Token:
Prima-facie evidence of privilege



E.g. thread, address space

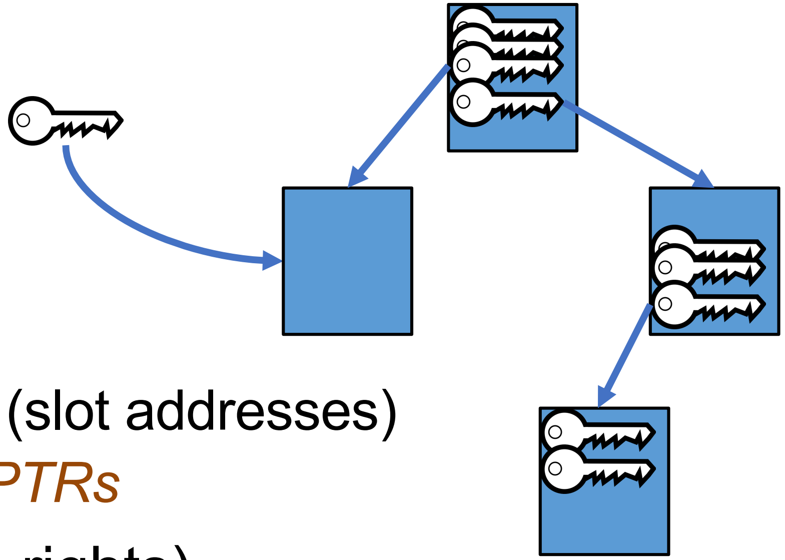
E.g. read, write, send, execute…

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`, `GrantReply` (Call), `Grant` (cap transfer)
- Can invoke a cap or derive cap of less or equal strength
  - Details later

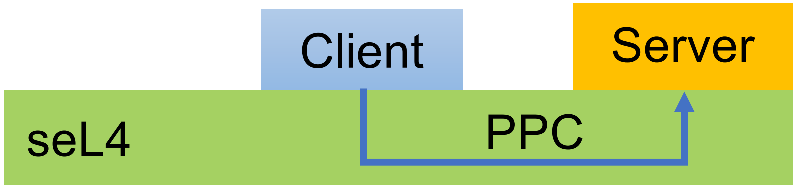
seL4 Mechanisms

PPC & Notifications

Protected Procedure Calls (PPC)

Fundamental microkernel operation

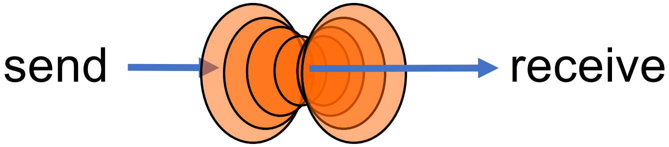
- Kernel provides no services, only mechanisms
- OS services provided by (protected) user-level server processes
- Invoked by *protected procedure call* (PPC)



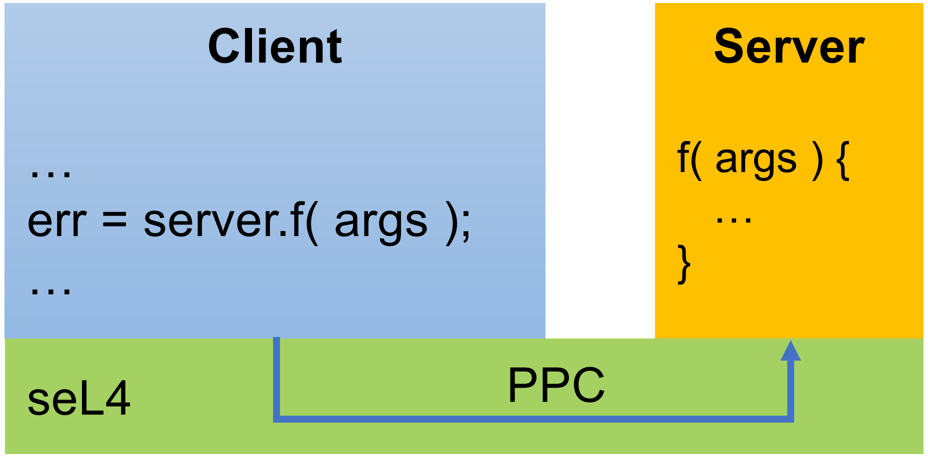
Historically called “IPC” – bad term!

seL4 PPC uses a handshake through *Endpoints*:

- Transfer points without storage capacity
- Arguments must be transferred instantly
  - Single-copy user ➞ user by kernel



seL4 PPC: Cross-Domain Invocation

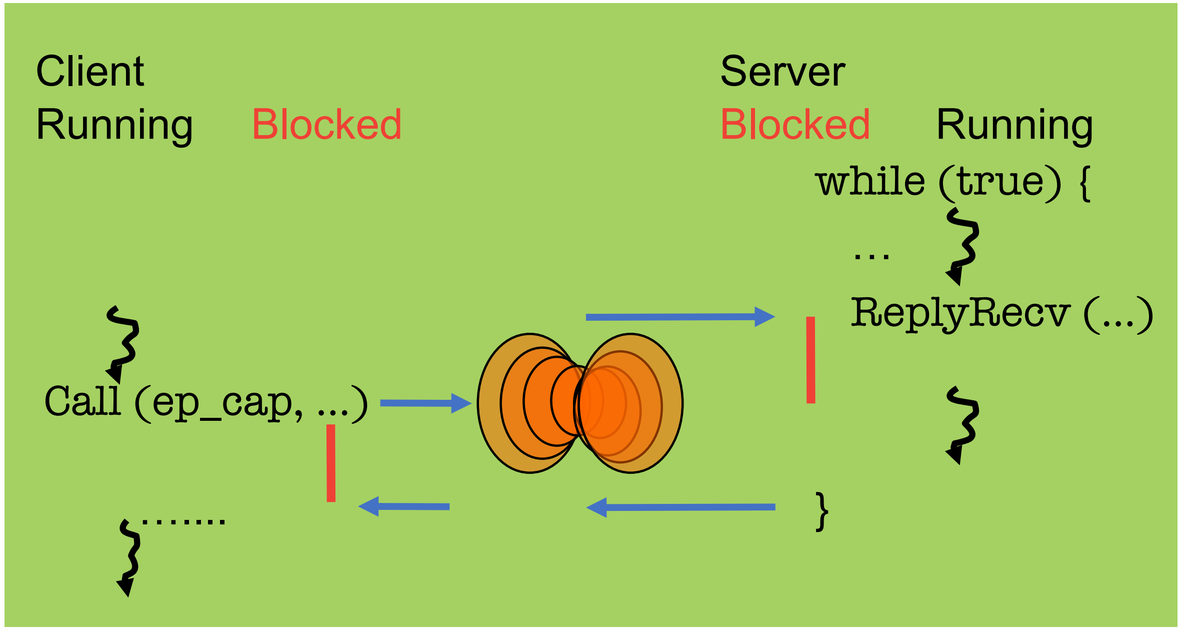


seL4 PPC is **not**:
- A mechanism for shipping data
- A synchronisation mechanism
    - side effect, not purpose

seL4 PPC **is**: A user-controlled context switch “with benefits”:
- change protection context
- pass arguments / result

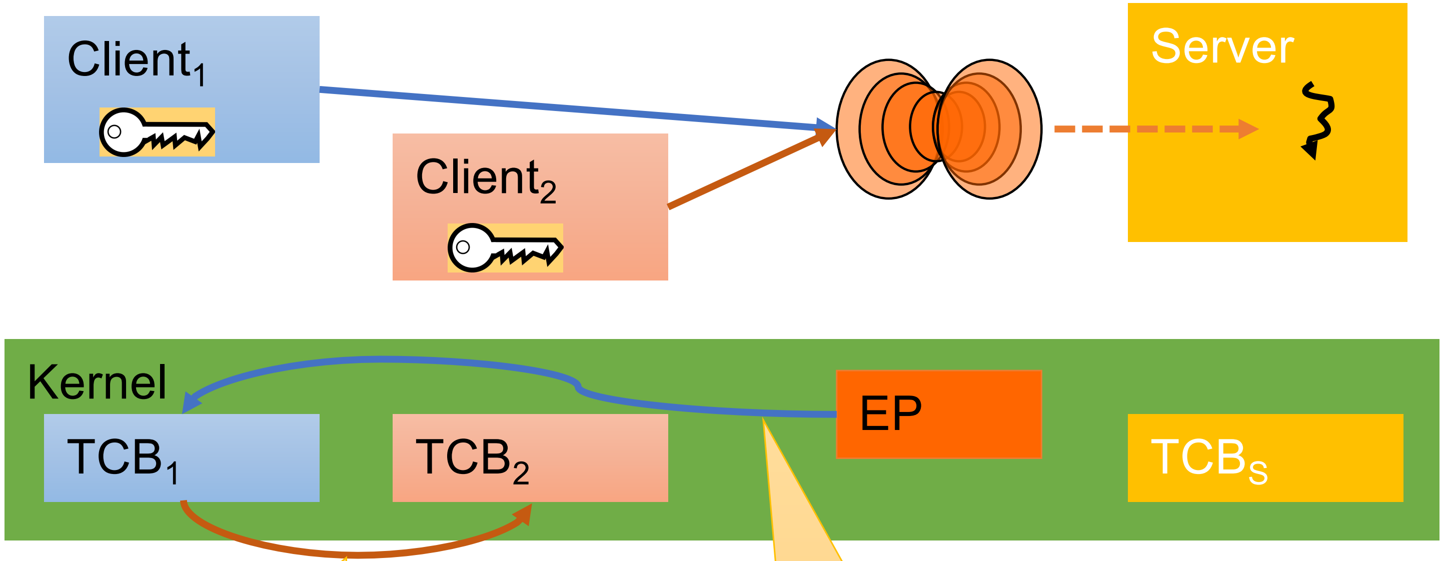
PPC: Endpoints

- Involves 2 threads, but always one blocked
- logically, thread moves between address spaces



- Threads must rendezvous
  - One side blocks until the other is ready
  - Implicit synchronisation
- Arguments copied from sender's to receiver's *message registers*
  - Combination of caps (by-reference arguments) and data words (by-value)
    - Presently max 121 words (484B on 32-bit archs, incl message "tag", more on 64-bit)
    - Should never use anywhere near that much!

Endpoints are Thread Queues



Further callers of same direction queue by priority

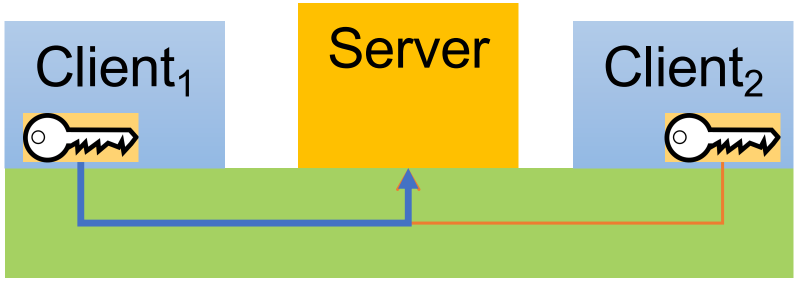
First invocation queues caller

Note: On single core should not get queues – server should be higher priority!

But: Reasonable for single-threaded (“passive”) server on multicore!

- EP has no sense of direction
- May queue clients or servers
  - never both at the same time!
- *Server invocation needs 2 EPs!*

Server Invocation & Return



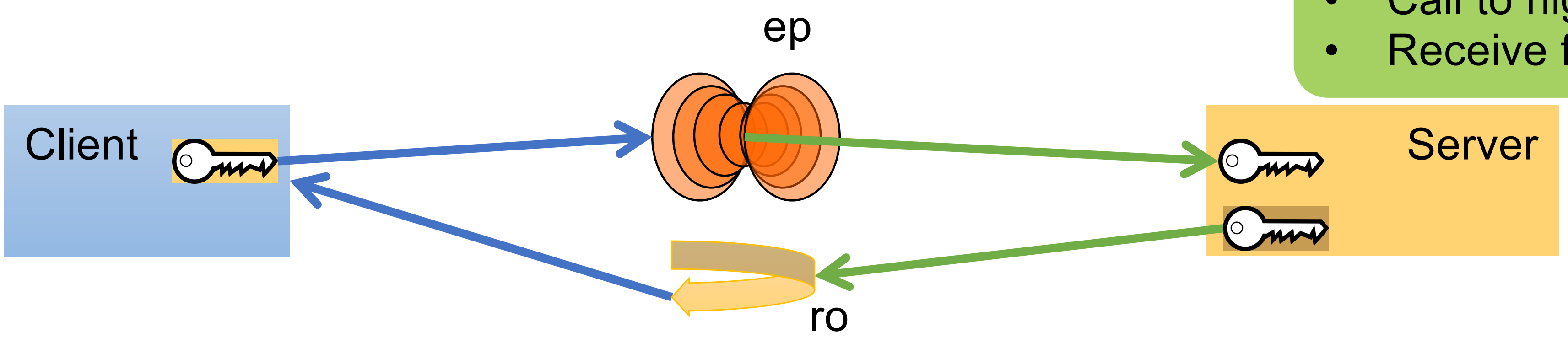
- Asymmetric relationship:
  - Server widely accessible, clients not
  - How can server reply back to client (distinguish between them)?
- Client can pass session cap in first request
  - server needs to maintain session state
  - forces stateful server design

New MCS kernel semantics!

- seL4 solution: Kernel creates reply channel in *reply object* (RO)
  - server provides RO in `ReplyRecv()` operation
  - kernel blocks client on RO when executing receive phase
  - server invokes RO for send phase (only one send until refreshed)
  - only works when client invokes with `Call()`

Call Semantics

Priorities:
- Call to high
- Receive from low!



Client

Kernel

Server

ReplyRecv(ep,... ,ro)

Call(ep, args)

deliver args to server

block client on RO

One per client for blocking calls!

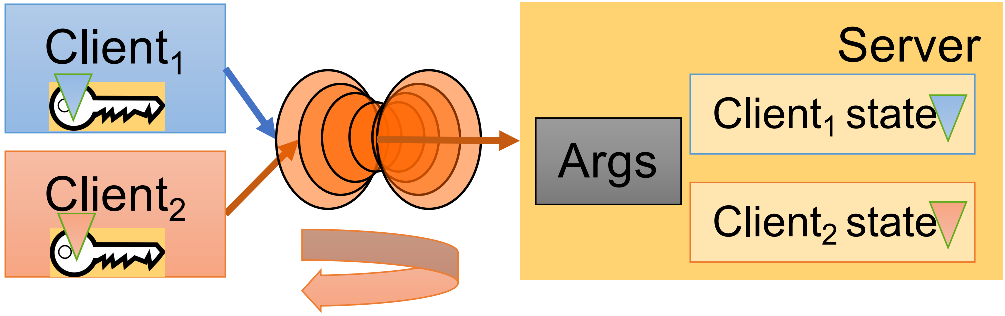
process

ReplyRecv(ep,... ,ro)

deliver result to client

process

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 would require mechanism to wait on a set of EPs (like Unix `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

PPC Mechanics: Virtual Registers

- Like physical registers, virtual registers are thread state
  - context-switched by kernel
  - map to physical registers or thread-local memory (“IPC buffer”)
- Message registers
  - contain arguments/results transferred in PPC
  - architecture-dependent subset mapped to physical registers
    - presently 1 on x86, 4 on x64, Arm, RISC-V
    - library interface hides details
    - 1st transferred word is special, contains *message tag*
  - API: `MR[0]` refers to next word (not the tag!)
  - Use helper functions `seL4_SetMR`, `seL4_GetMR`

PPC Operations Summary

- Call (ep_cap, …)
  - *Atomic*: guarantees caller is ready to receive reply
  - Sets up server’s reply object
- ReplyRecv (ep_cap, …)
  - Invokes RO (non-blocking), waits on EP, re-inits RO
- Recv (ep_cap, …), Reply(…), Send (ep_cap, …)
  - For initialisation and exception handling
  - needs Read, Write, Write permission, respectively
- NBSend (ep_cap, …)
  - Polling send, message lost if receiver not ready

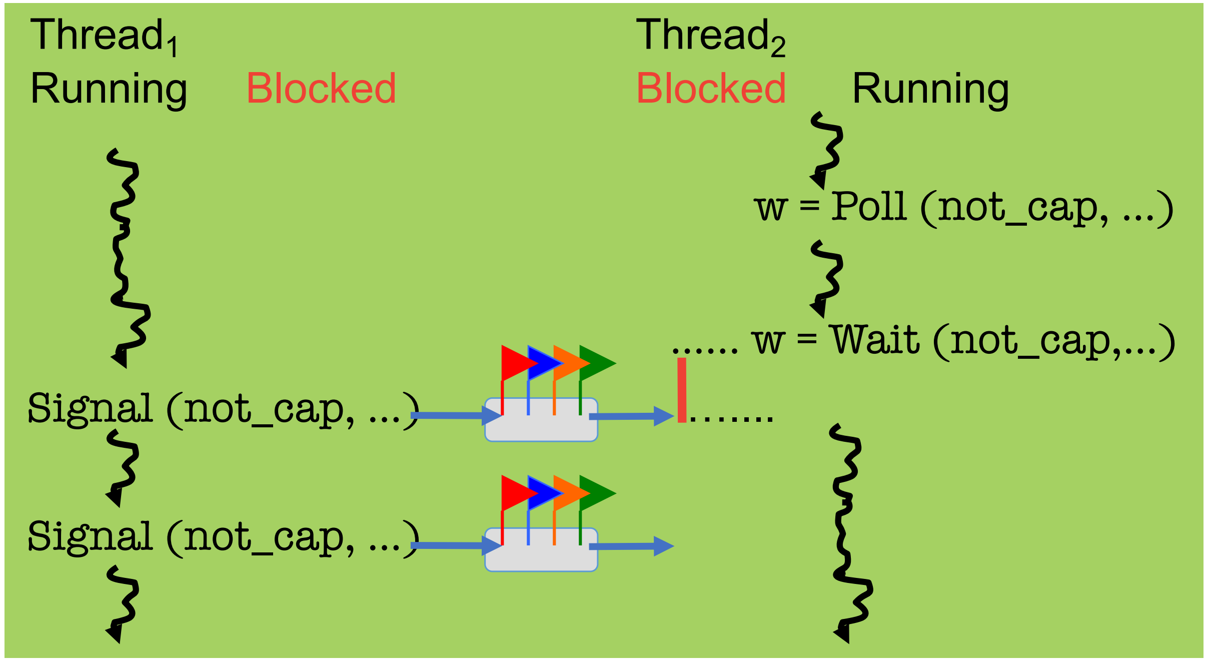
Not really useful

Need error handling protocol !

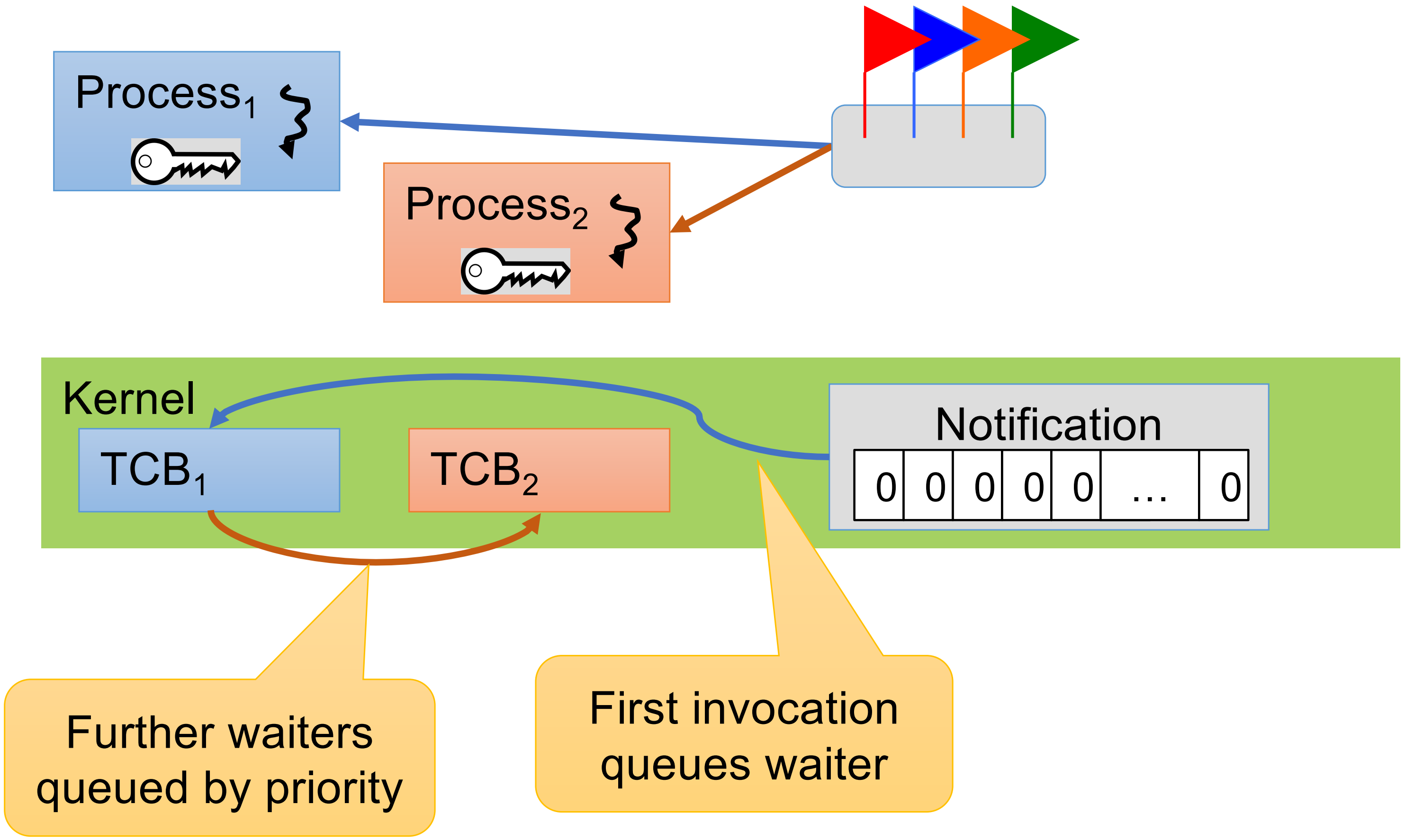
No failure notification where this reveals info on other entities!

Notifications – Synchronisation Objects

- Logically, a Notification is an array of binary semaphores
  - Multiple signalling, select-like wait
  - Not a message-passing 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



Notification Queues



Process$_1$

Process$_2$

Kernel

TCB$_1$

TCB$_2$

Notification

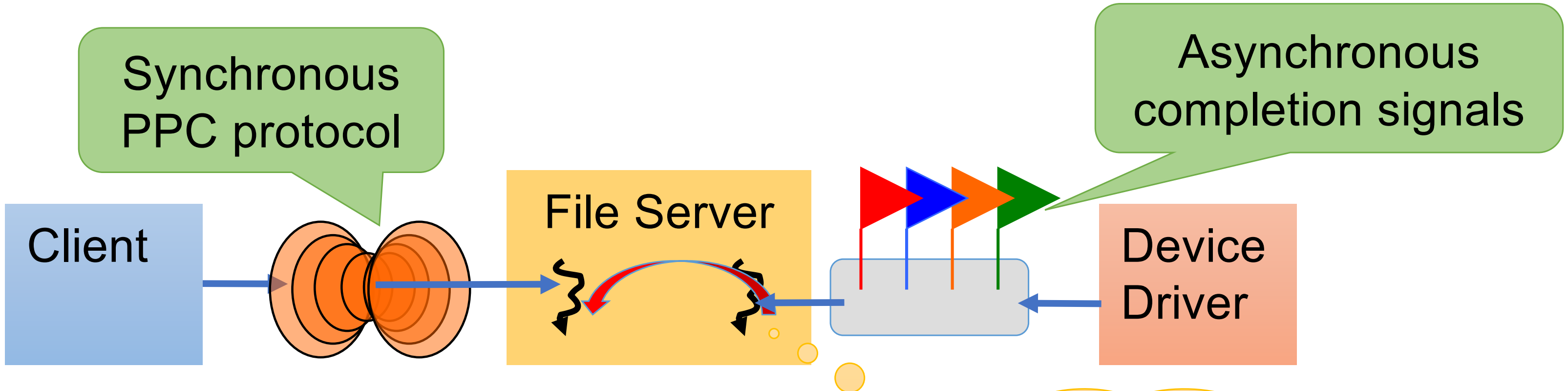
0	0	0	0	0	…	0

Further waiters queued by priority

First invocation queues waiter

Receiving from EP *and* Notification

Server with synchronous and asynchronous interface



Better: single thread for both interfaces

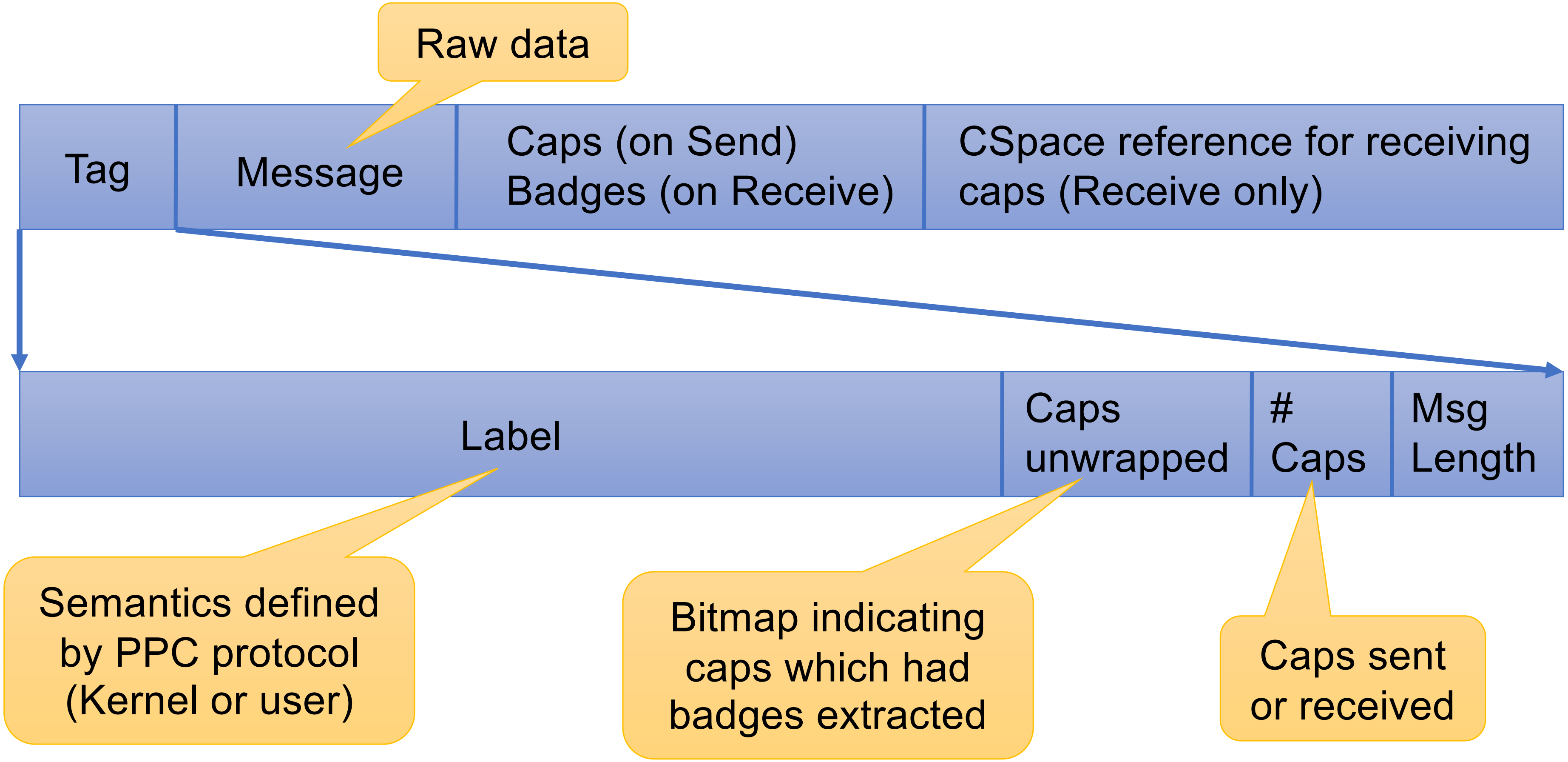
- Notification "bound" to TCB
- Signal delivered as "PPC" from EP

Separate thread per interface?

Concurrency control, complexity!

Must partition badge space to distinguish!

PPC Message Format



Raw data

Tag

Message

Caps (on Send)
Badges (on Receive)

CSpace reference for receiving caps (Receive only)

Label

Caps unwrapped

Caps

Msg Length

Semantics defined by PPC protocol (Kernel or user)

Bitmap indicating caps which had badges extracted

Caps sent or received

Client-Server PPC Example

Client

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

Set message register #0

Server

```
ut_t* reply_ut = ut_alloc(seL4_ReplyBits, &cspace);
seL4_CPtr reply = cspace_alloc_slot(&cspace);
err = cspace_untyped_retype(&cspace, reply_ut->cap, reply,
                            seL4_ReplyObject, seL4_ReplyBits);
seL4_CPtr badged_ep =  cspace_alloc_slot(&cspace);
cspace_mint(&cspace, badged_ep, &cspace, ep, seL4_AllRights, 0xff);
…
seL4_Word badge;
seL4_MessageInfo_t msg = seL4_Recv(ep, &badge, reply);
…
seL4_MessageInfo_t response = seL4_MessageInfo_new(0, 0, 0, 1);
seL4_NBSend(reply, response);
```

CSpace helper functions in libsel4cspace

Allocate slot & retype to RO

Derive cap with badge 0xff

Wait on EP, receiving badge, setting RO

Reply to sender identified by RO

Note: this is for clarity, in reality should use ReplyRecv!

Proper Server Loop

Reasons for no reply:
- Initialisation
- Received bound Notification

EP to wait on

Return value

Client badge

Reply object

```
bool have_reply=FALSE;
seL4_MessageInfo_t msg;
while (1) {
   if (have_reply) {
      msg = seL4_ReplyRecv(ep, response, &badge, reply);
   } else {
      msg = seL4_Recv(ep, &badge, reply);
   }
   … // process request, prepare response}
}
```