School of Computer Science & Engineering

COMP9242 Advanced Operating Systems

2022 T2 Week 01 Part 1

Introduction: Microkernels and seL4

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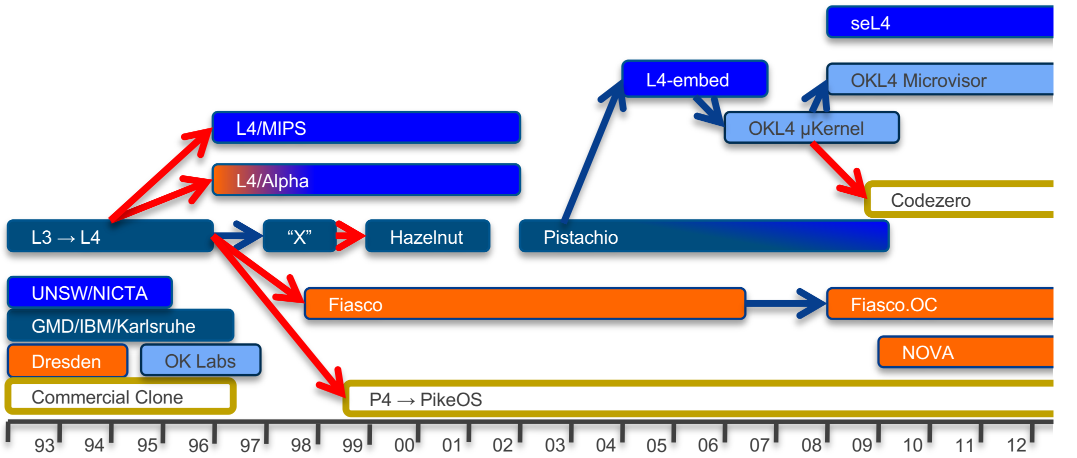

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Why Advanced Operating Systems?

- 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
  - IPC and Notifications

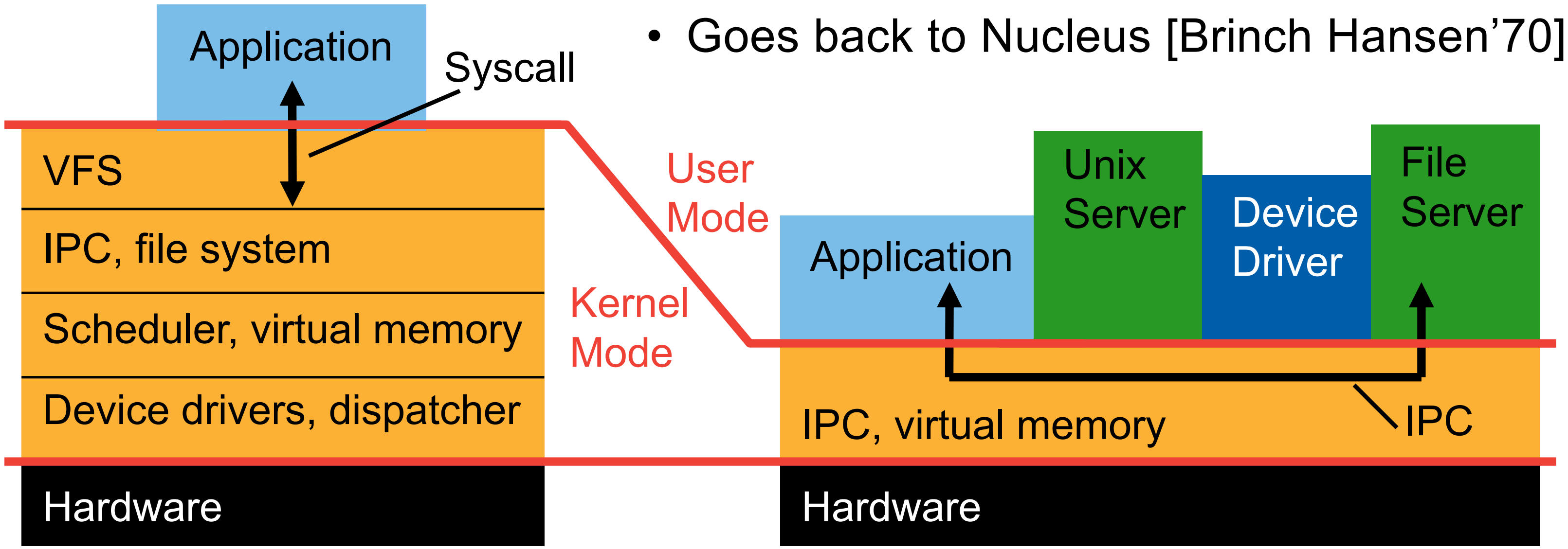
Aim: Get you ready for the project quickly

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 (IPC)
  - Goes back to Nucleus [Brinch Hansen'70]



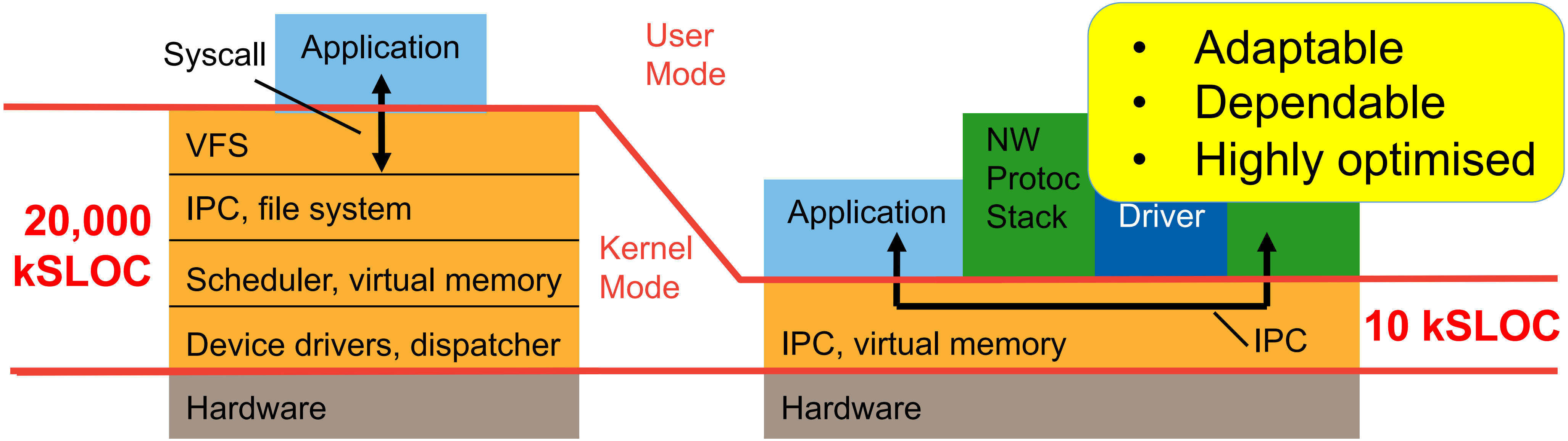
Monolithic vs Microkernel OS Evolution

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



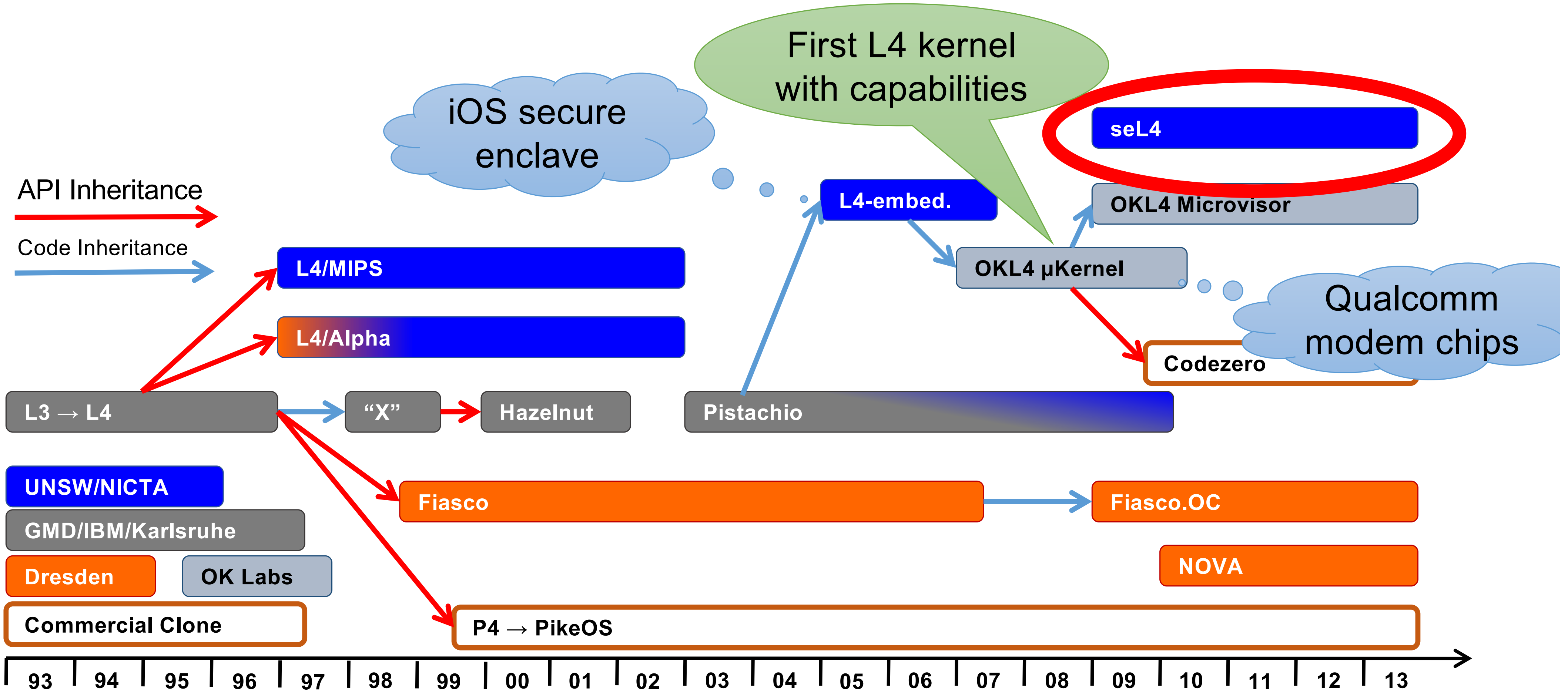
- Adaptable
- Dependable
- Highly optimised

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

L4: 30 Years High-Performance Microkernels



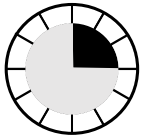
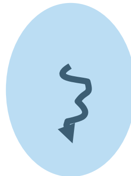
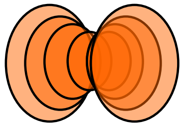
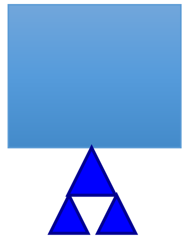
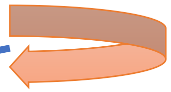
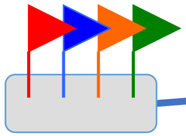
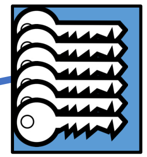
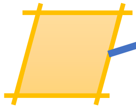
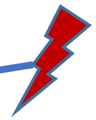
The seL4 Microkernel

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 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]

More on principles in my blog: https://bit.ly/34uI8FI

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 (IPC)
  - 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?

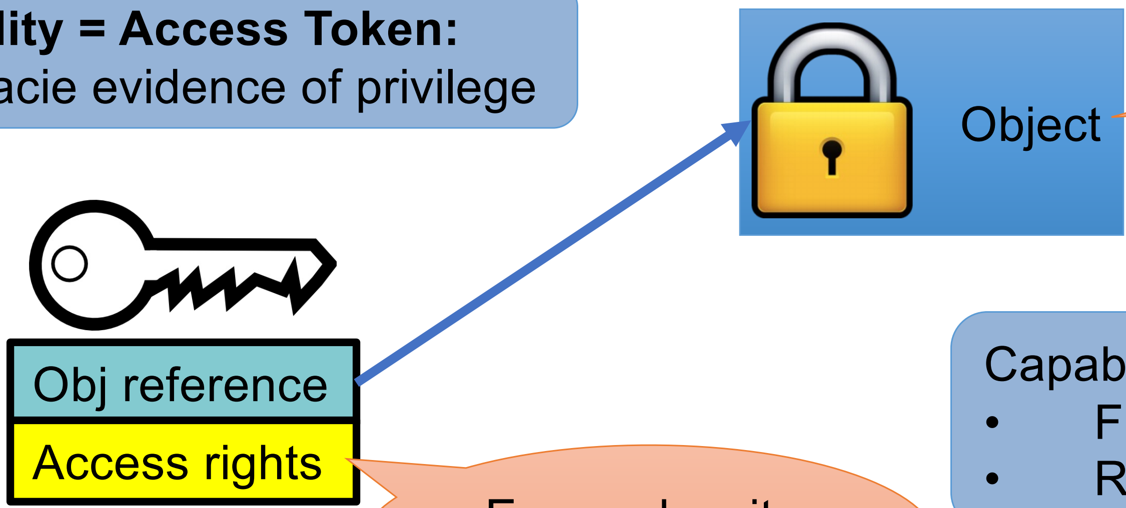
- Hardware abstraction violates minimality
- Hardware abstraction introduces policy

True microkernel:

- Minimal wrapper of hardware, just enough to safely multiplex
- “CPU driver” [Charles Gray]
- Similarities with Exokernels [Engeler ’95]

What Are (Object) Capabilities?

Capability = Access Token:
Prima-facie evidence of privilege



Eg. thread, address space

Eg. read, write, send, execute…

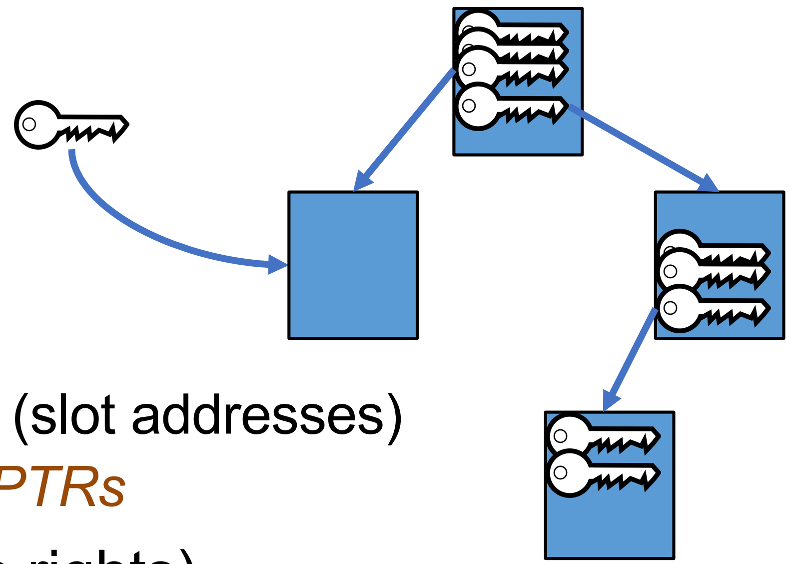
Capabilities provide:
- Fine-grained access control
- Reasoning about information flow

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



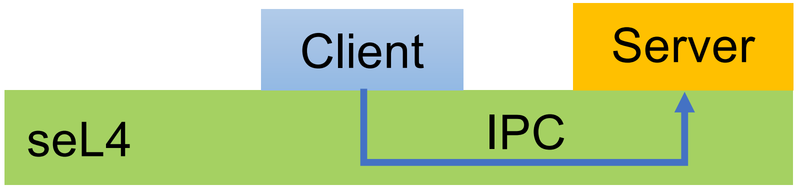
seL4 Mechanisms

IPC & Notifications

Protected Procedure Calls (IPC)

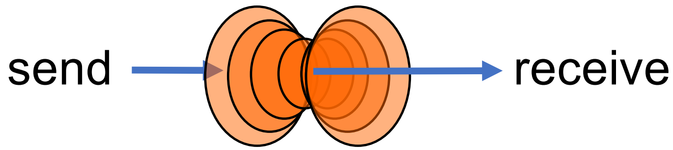
Fundamental microkernel operation

- Kernel provides no services, only mechanisms
- OS services provided by (protected) user-level server processes
- Invoked by *protected procedure call* (called “IPC” for historical reasons)

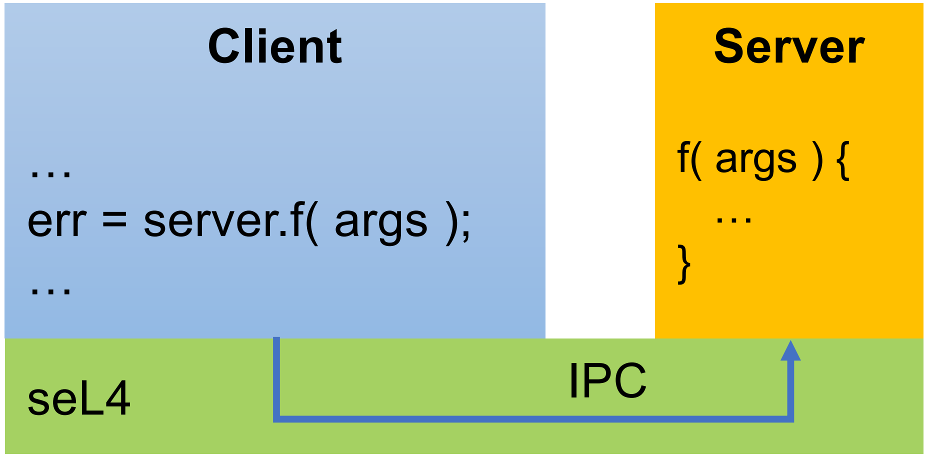


seL4 IPC uses a handshake through *Endpoints*:

- 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**:

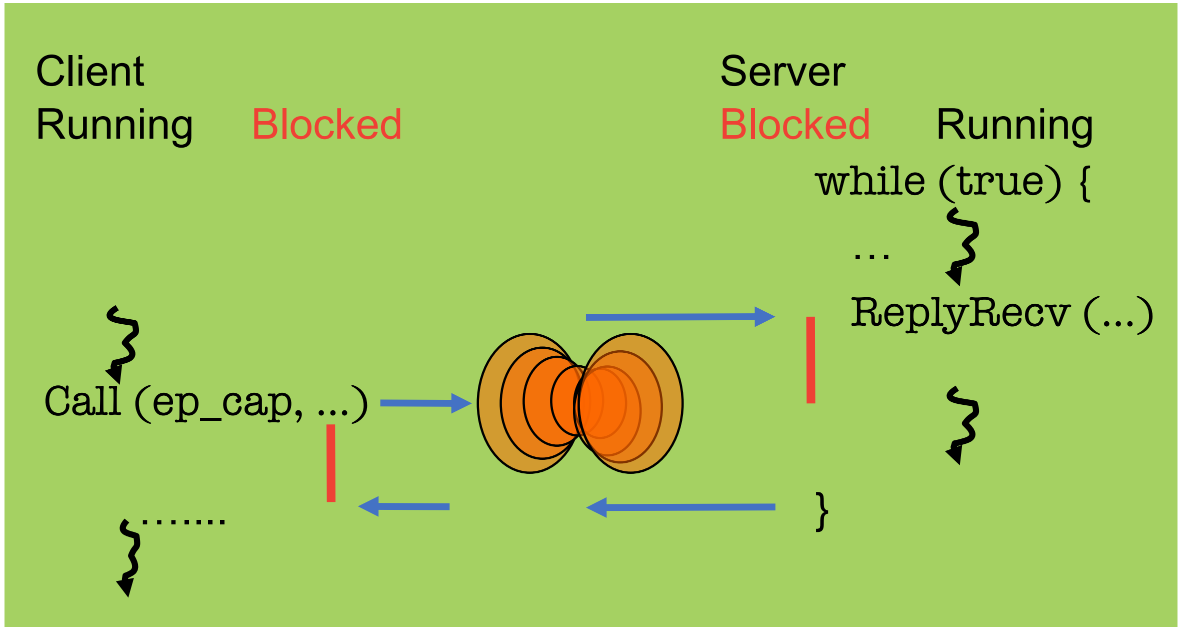
- A mechanism for shipping data
- A synchronisation mechanism
  - side effect, not purpose

seL4 IPC **is**: A user-controlled context switch “with benefits”:

- change protection context
- pass arguments / result

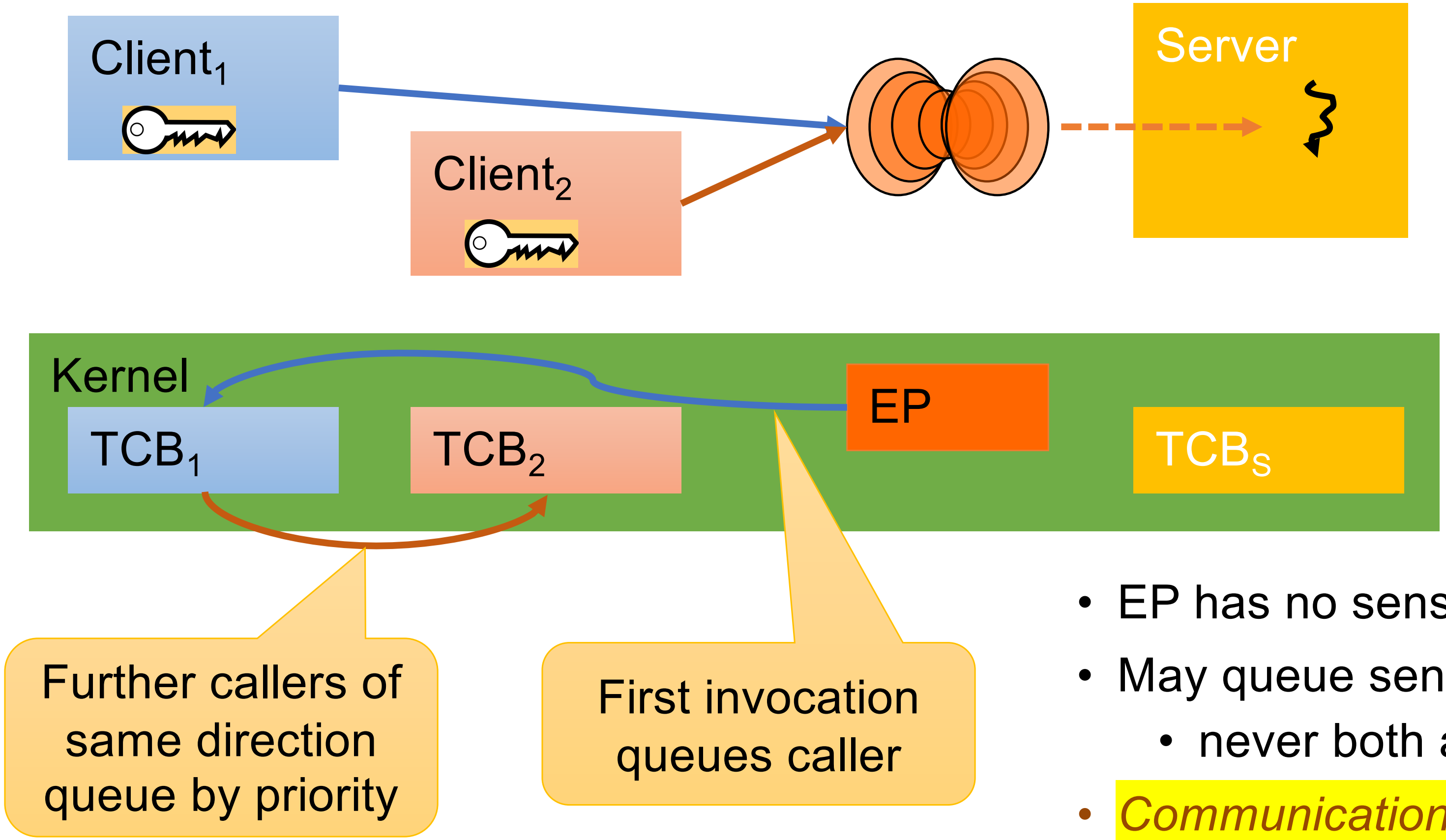
IPC: Endpoints

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



- Threads must rendez-vous
  - 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, incl message "tag")
    - Should never use anywhere near that much!

Endpoints are Message Queues



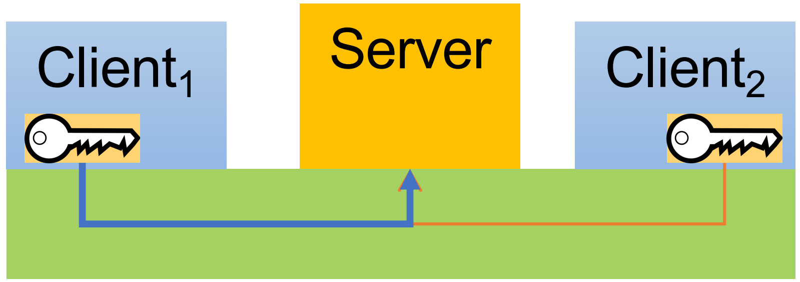
Note: On single core should not get queues – server should be highest priority!

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

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

Server Invocation & Return

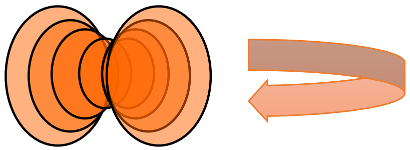
- Asymmetric relationship:
  - Server widely accessible, clients not
  - How can server reply back to client (distinguish between them)?



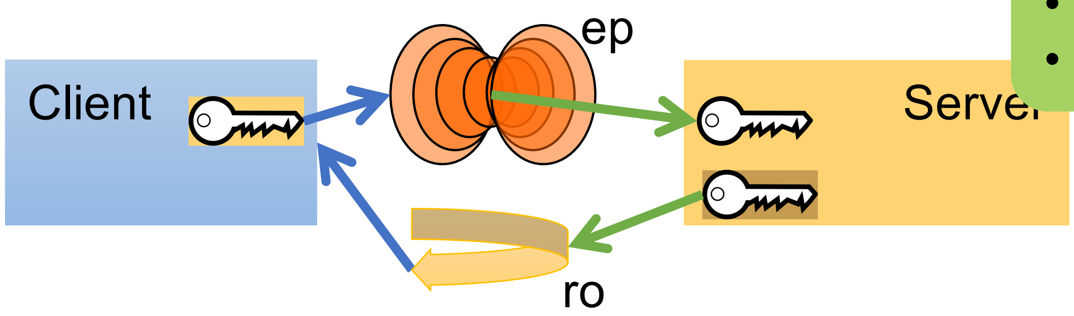
- Client can pass session cap in first request
  - server needs to maintain session state
  - forces stateful server design

New MCS kernel semantics!

- seL4 solution: Kernel creates 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(ro,ep,&args)

Call(ep, args)

deliver to server

block client on RO

One per client for blocking calls!

process

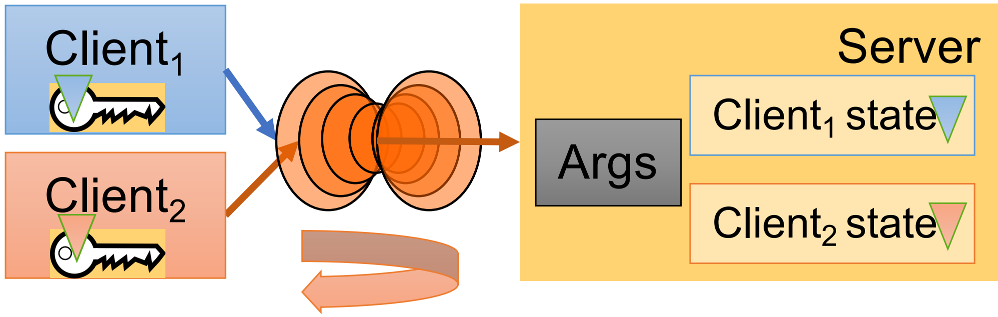
ReplyRecv(ro,ep,&args)

deliver 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

IPC 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 message transferred in IPC
  - 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!)

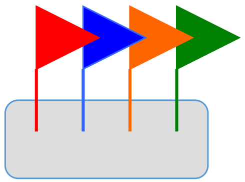
IPC Operations Summary

- `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

No failure notification where this reveals info on other entities!

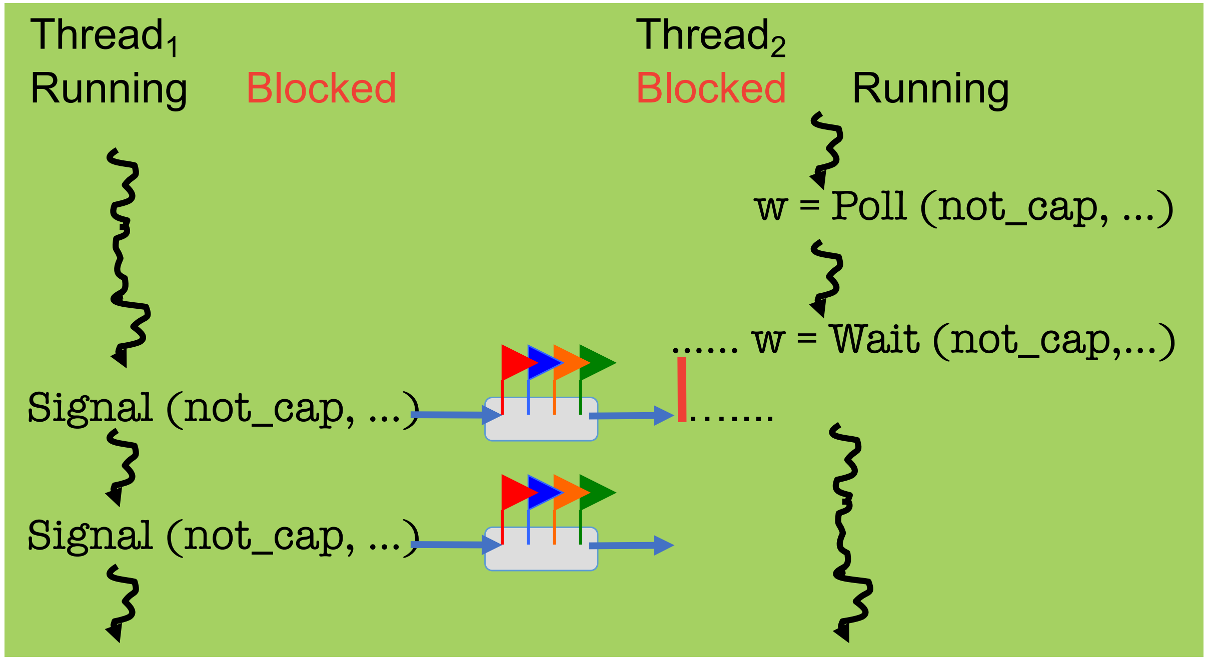
Not really useful

Need error handling protocol !

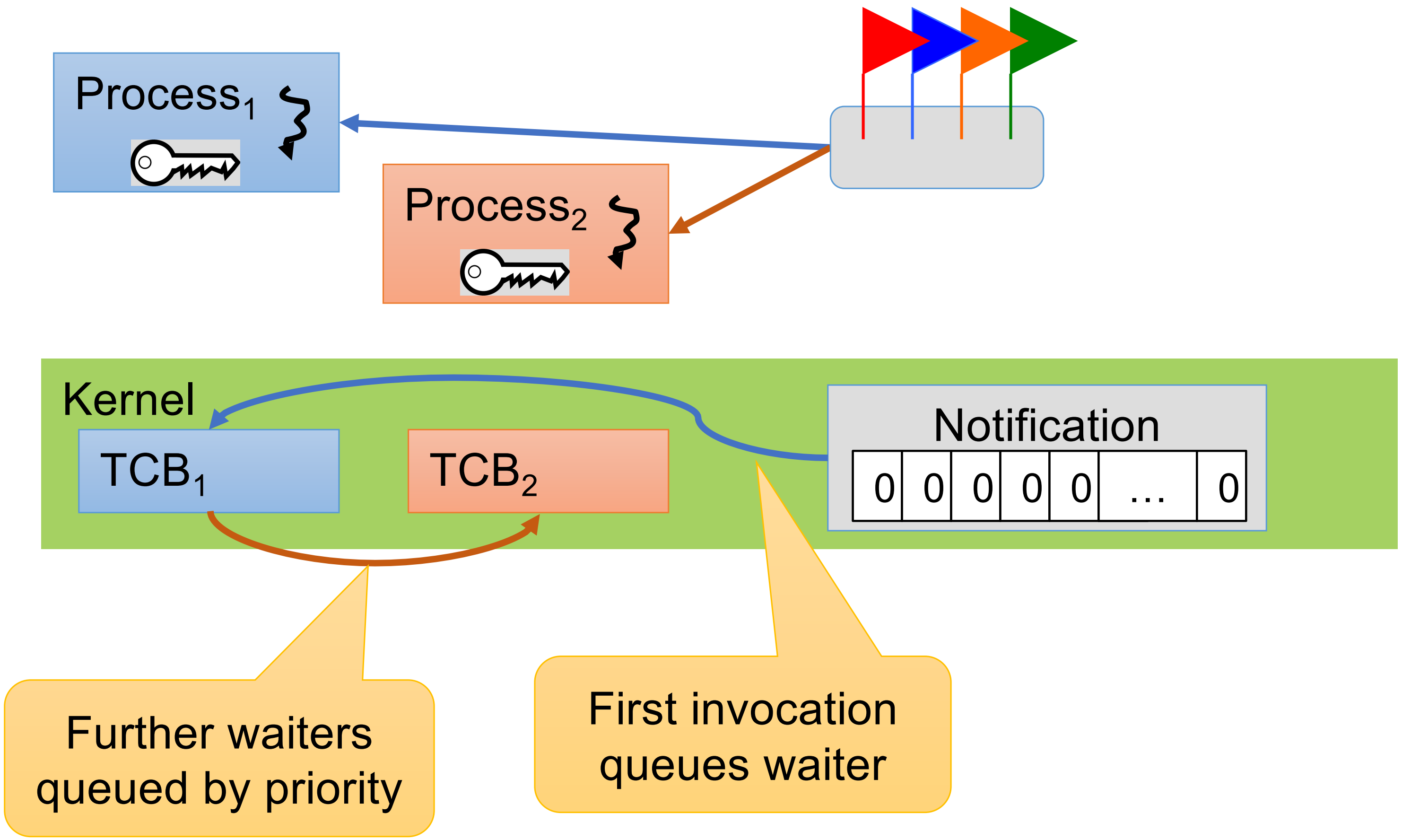


Notifications – Synchronisation Objects

- 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

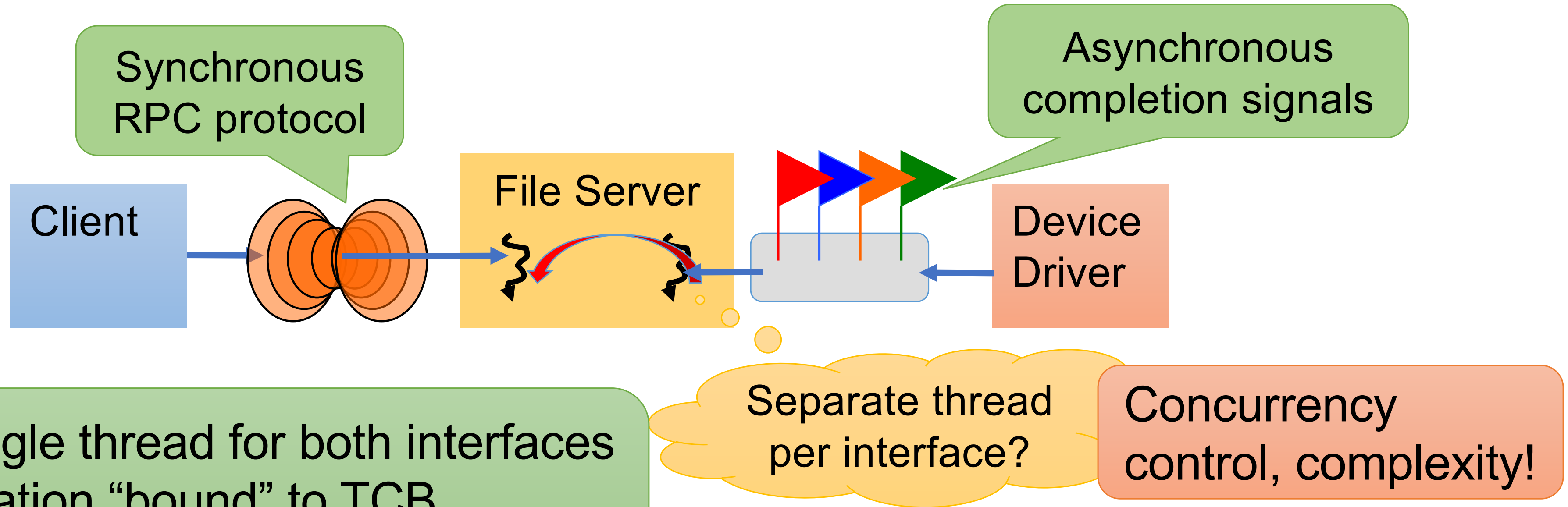


Notification Queues



Receiving from EP *and* Notification

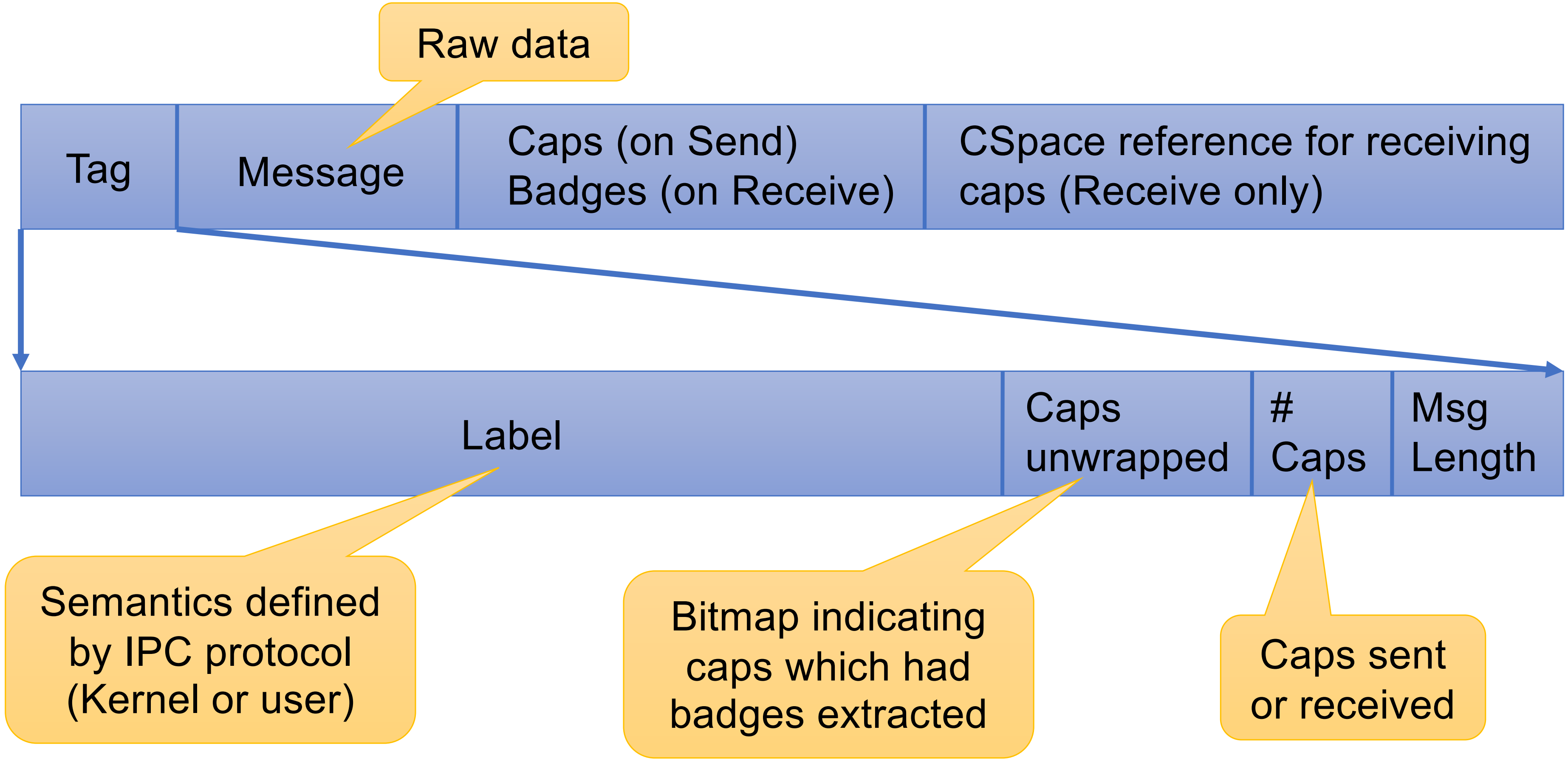
Server with synchronous and asynchronous interface



Better: single thread for both interfaces
- Notification “bound” to TCB
- Signal delivered as “IPC” from EP

Must partition badge space to distinguish!

IPC Message Format



Client-Server IPC 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);
```

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

EP to wait on

Return value

Reply object

```
...
while (1) {
   seL4_MessageInfo_t msg = seL4_ReplyRecv(ep, response, &badge, reply);
   ...
   seL4_MessageInfo_t response = seL4_MessageInfo_new(0, 0, 0, 1);
}
```

Client badge