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Faculty of Computer Science Institute for System Architecture, Operating Systems Group

Inter-Process Communication

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So far...

- Microkernels as a design alternative
  - Flexibility
  - Security
- Case Study: Fiasco.OC
  - Mechanisms: Tasks, Threads, Communication
  - Capabilities to denote kernel objects

Today

- Inter-Process Communication (IPC)
  - Purpose
  - Implementation
  - How to find a service?
  - Tool/Language support
  - Security – Who speaks to whom?
  - Shared memory

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Why do we need to Communicate?

- IPC is a fundamental mechanism in a µ-kernel-based system:
  - Exchange data
  - Synchronization
  - Sleep, timeout
  - Hardware / software interrupts
  - Grant access to resources (memory, I/O ports, capabilities)
  - Exceptions
- Liedtke: *"IPC performance is the master."*

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Exploring the Design Space

- Asynchronous IPC (e.g., Mach)
  - “Fire and forget”
  - In-kernel message buffering
  - Two problems:
    - Data copied twice
    - DoS attack on kernel memory (never receive data) – can use quotas, though

- Synchronous IPC (e.g., L4)
  - IPC partner blocks until other one gets ready
  - Direct copy between sender and receiver
  - E.g., Remote Procedure Call (RPC)

L4 IPC - Basics

- Basic data types:
  - Bulk data
  - Memory references
  - Resource mappings (flexpages)

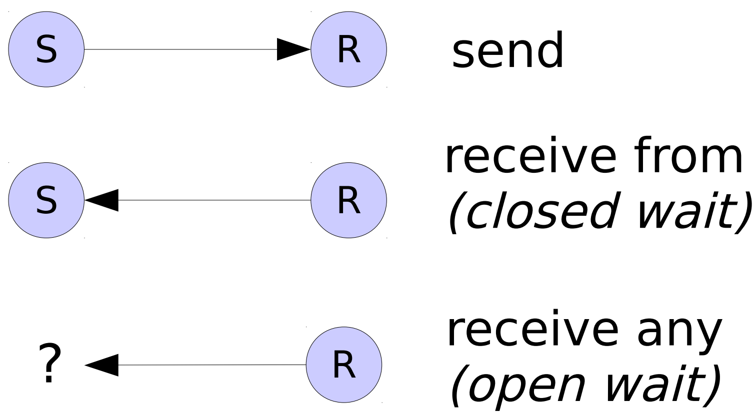
- Types
  - Send
  - Closed wait
  - Open wait
  - Call
  - Reply & wait

L4 IPC – Advanced Features

- Timeouts
  - 0 (non-blocking IPC)
  - NEVER or specific value – block until partner gets ready or timeout occurs
  - sleep() is implemented as IPC to NIL (non-existing) thread with timeout
- Exceptions
  - Certain conditions need external interaction
    - Page faults
    - L4Linux system calls
    - Virtualization faults (-> lectures on virtualization)

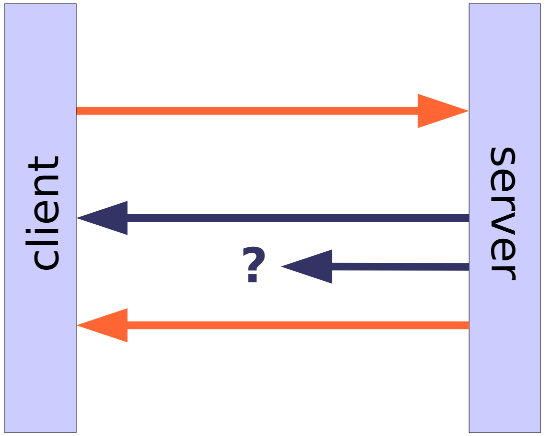
L4 IPC Flavors

Basics



- Why is there no broadcast?

Special cases for client/server IPC



- **call** := <u>atomic</u> send + recv from
- **reply and wait** := <u>atomic</u> send + recv any
- E.g.: Allows server reply with timeout 0, client will be ready to receive

Break

Purpose

Implementation

Tool/Language support

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How to find a service?

Shared memory

IPC Building Blocks – IPC Gate

- Referenced through a capability (local name)
- Created using *factory* object
  - Each L4Re task is assigned a **factory object**
  - Factory creates other objects (e.g., kernel objects)
  - Can enforce quotas / perform accounting / ...
- Bound to a thread (receiver)
  - IPC channels are uni-directional
  - Anyone with the gate capability may send, only bound thread receives
- Add a label
  - A thread may receive from multiple gates
  - Label allows to identify where a message came from

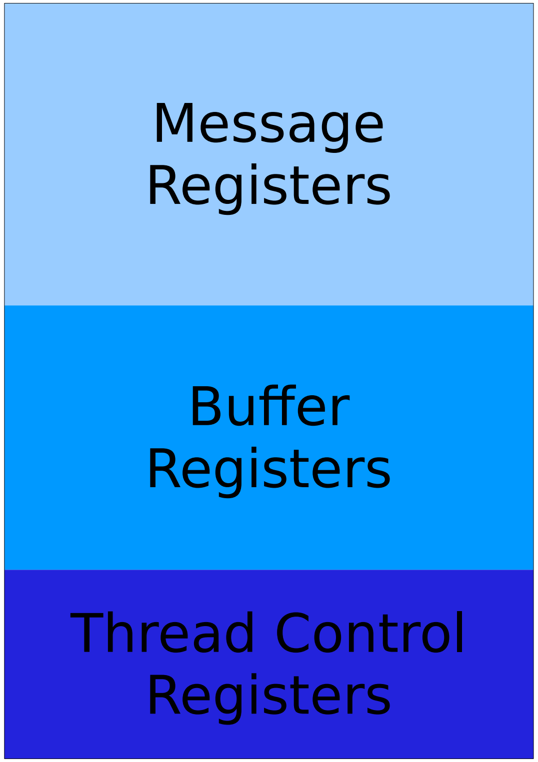
IPC Building Blocks – IPC Gate

- Receiving:
  - Receiver calls open wait.
  - Waits for message on any of its gates
  - Receive system call returns label of the used gate (but not the sender's capability!)

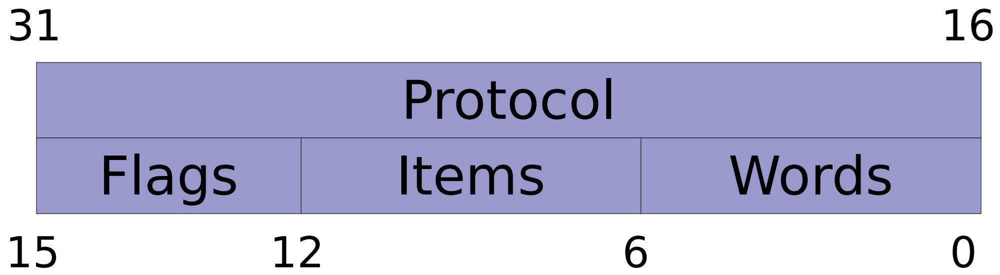
- Replying
  - Receiver doesn't know sender.
  - Kernel provides implicit reply capability (per-thread)
    - Valid until reply sent or next wait started.

IPC Building Blocks – UTCB

- **U**ser-level **T**hread **C**ontrol **B**lock
- Set of “virtual” registers
- Message Registers
  - System call parameters
  - IPC: direct copy to receiver
- Buffer registers
  - Receive flexpage descriptors
- Thread Control Registers
  - Thread-private data
  - Preserved, not copied

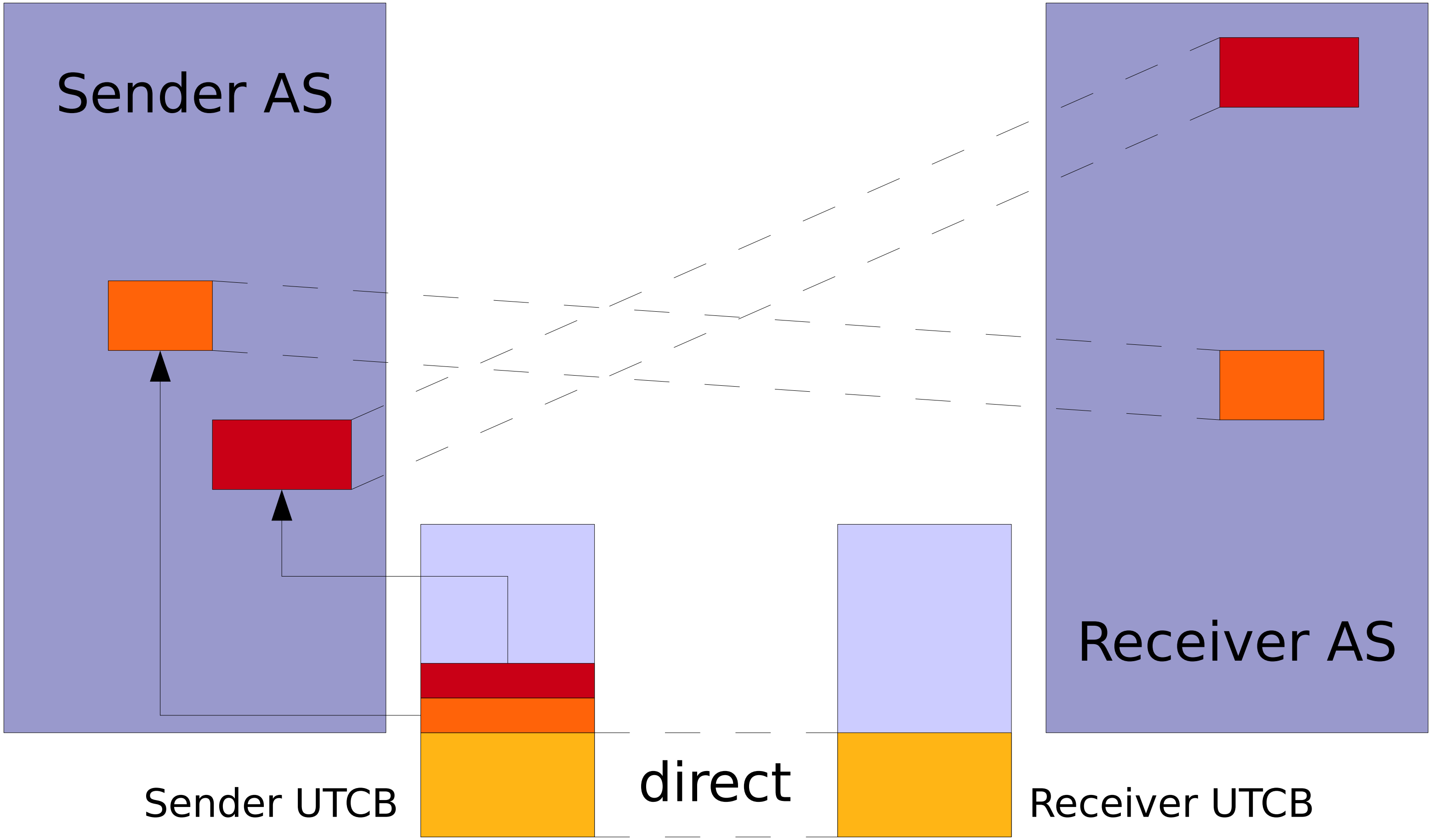


IPC Building Blocks – Message Tag



- UTCB contents for IPC described by message tag
- Protocol:
  - User-defined type of communication
  - Pre-defined system protocols (Page fault, IRQ, ...)
- Flags
  - Special-purpose communication flags
- Items
  - Number of indirect items to copy (flexpages in UTCB buffer registers)
- Words
  - Number of direct items to copy (message registers)

Direct vs. indirect copy



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How to find a service?

Shared memory

Client-Server RPC Broken down

Client

Marshall data

Assign Opcode

IPC call →

Unmarshall exception or reply

Server

IPC wait

Unmarshall Opcode

Unmarshall Data

Execute function

Marshall return value or error

IPC reply

Goto begin

Writing IPC code Manually

```
/* Arguments: 1 integer parameter, 1 char array with size */
int FOO_OP1_call(l4_cap_idx_t dest, int arg1, char *arg2, unsigned size) {
    int idx = 0; // index into message registers

    // opcode and first arg go into first 2 registers
    l4_utcb_mr()->mr[idx++] = OP1_opcode;
    l4_utcb_mr()->mr[idx++] = arg1;

    // tricky: memcpy buffer into registers, adapt idx according
    //          to size (XXX NO BOUNDS CHECK!!!)
    memcpy(&l4_utcb_mr()->mr[idx], arg2, size);
    idx += round_up(size / sizeof(int));

    // create message tag (prototype, <idx> words, no bufs, no flags)
    l4_msgtag_t tag = l4_msg_tag(PROTO_FOO, idx, 0, 0);
    return l4_ipc_call(dest, l4_utcb(), tag, TIMEOUT_NEVER);
}
```

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Writing IPC code Manually

- Now repeat the above steps for
  - N > 20 functions with
    - varying parameters
    - varying argument size
    - complex use of send/receive flexpages
    - correct error checking
    - …

- Dull and error-prone!

How About Some Automation?

- Specify the interface of server in *Interface Definition Language* (IDL)
  - High-level language

```
interface FOO {
    int OP1(int arg1,
            [size_is(arg2_size)] char *arg2,
            unsigned arg2_size);
};
```

- Use IDL Compiler to generate IPC code
  - Automatic assignment of RPC opcodes
  - Generated marshalling/unmarshalling code
  - Built-in error handling
  - Client/server stub functions to fill in

- For L4: Dice – **D**ROPS **I**DL **C**ompil**e**r

IDL vs. Manual code

- Use of high-level language and IDL compiler makes things easier

- Additionally:
  - Type checking: generated code stubs make sure that client sends the correct amount of data, having proper types
  - IDL compiler can optimize code
  - Use IDL interfaces to generate
    - Documentation
    - Unit tests
    - ...

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Using Fancy Language Features

- C++: streams
- Overload `operator<<` to access the UTCB
  - Copying of basic data types and arrays into message registers
  - Dedicated objects representing flexpages copied into buffer registers
  - Automatic updates of positions in buffer
- Do the reverse steps for `operator>>`

Fancy Language Features - Client

```
int Foo::op1(l4_cap_idx_t dest, int arg1,
             char *arg2, unsigned arg2_size)
   {
       int res = -1;
       L4_ipc_iostream i(l4_utcb());
       i << Foo::Op1
         << arg1
         << Buffer(arg2, arg2_size);
       int err = i.call(dest);
       if (!err)
          i >> result;
       return i;
   }
```

Fancy Language Features - Server

```
int Foo::dispatch(L4_ipc_iostream& str, l4_msgtag_t tag) {
  // check for invalid invocations
  if (tag.label() != PROTO_FOO)
    return -L4_ENOSYS;

  int opcode, arg1, retval;
  Buffer argbuf(MAX_BUF_SIZE);

  str >> opcode;
  switch(opcode) {
    case Foo::Op1:
      str >> arg1 >> argbuf;
      // do something clever, calculate retval
      str << retval;
      return L4_EOK;
    // .. more cases ..
  }}
```

Dynamic RPC Marshalling in Genode

- C++-based operating system framework
- Abstract from the underlying kernel
  - Runs on Linux, Fiasco.OC, OKL4, L4::Pistacchio, Nova, CodeZero
  - IPC mechanisms differ (built-in mechanism in L4.Fiasco vs. UDP sockets in Linux)
- Communication abstraction: IPC streams
  - Use C++ templates to allow writing arbitrary (*primitively serializable!*) objects to IPC message buffer
  - Special values (Genode::IPC_CALL) lead to calls to underlying system's mechanism

DynRPC Summary

- C++ compiler can heavily optimize IPC path
- No automatic (un)marshalling
  - Use whatever serialization mechanism you like
- No builtin type checking
  - Developer needs to care about amount, type and order of arguments
- Orthogonal to use of IDL compiler
  - Generate IPC stream code from C++ class definitions (Prototype: Liasis IDL compiler by Stefan Kalkowski, 2008)

Break

Purpose

Implementation

Tool/Language support

Security

How to find a service?

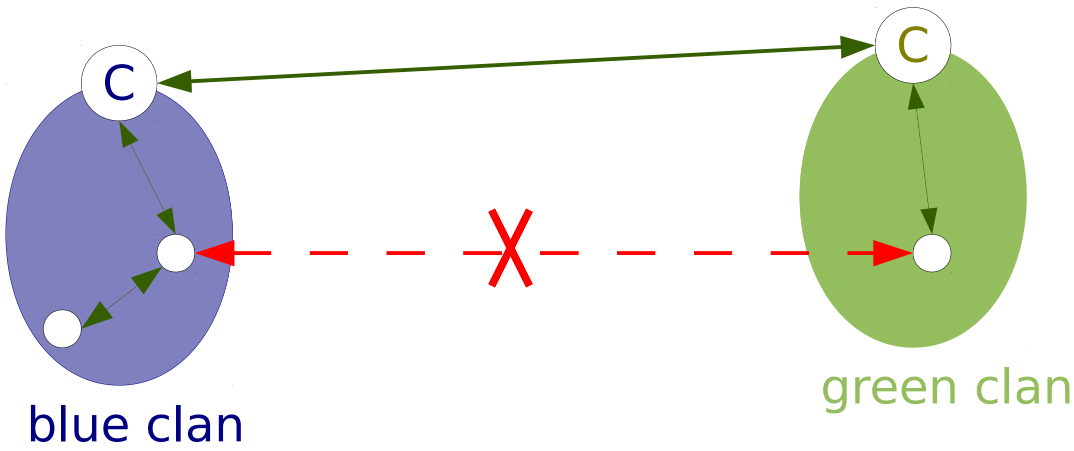
Shared memory

IPC & Security

- Problem: How to control data flow?
- Crucial problem to solve when building real systems
- Many proposed solutions

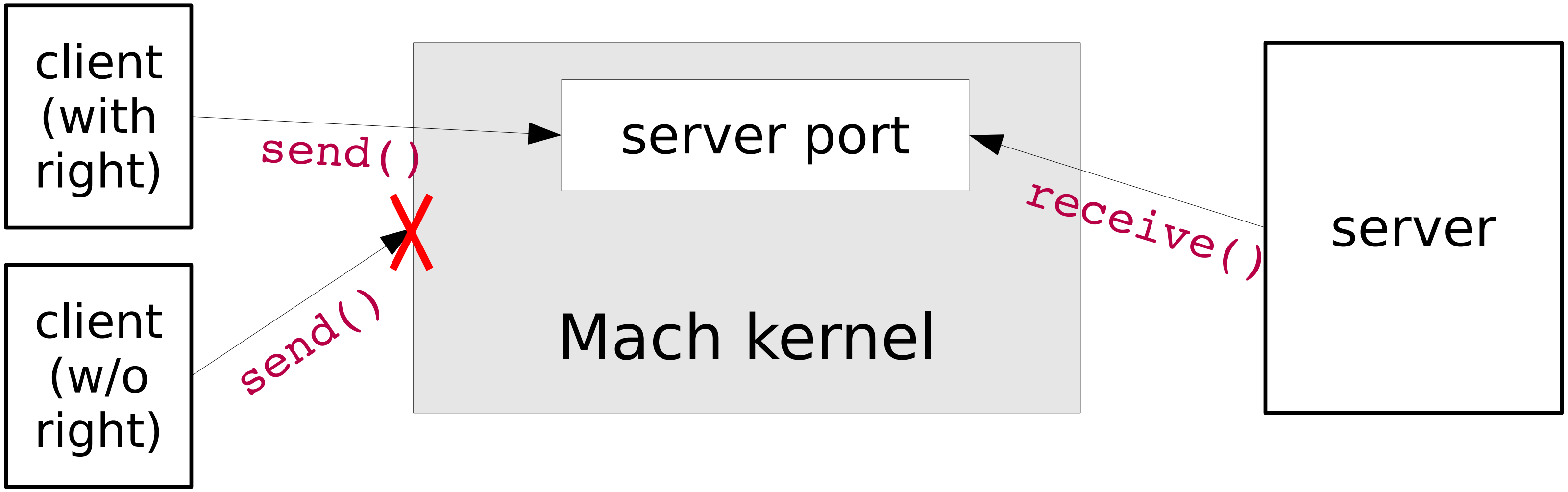
L4v2: Clans & Chiefs

- Tasks are owned by a chief.
- Clan := set of tasks with the same chief
- No IPC restrictions inside a clan
- Inter-clan IPC redirected through chiefs
- Performance issue
  - One IPC transformed into three IPCs
  - Decisions are not cached.



Mach: Ports

- Dedicated kernel objects
- Applications hold send/recv rights for ports
- Kernel checks whether task owns sufficient rights before doing IPC



L4/Fiasco: Reference Monitors

- New abstraction: communication is allowed if certain flexpage has been mapped to sender

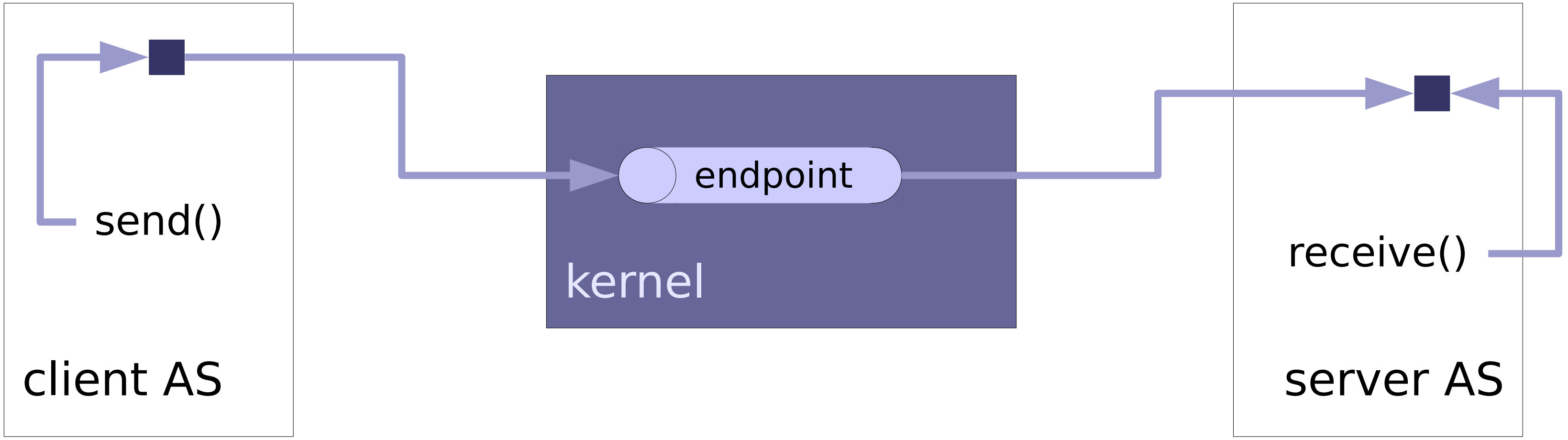
- Every task gets a reference monitor assigned.

- Communication:
  - IPC right mapped?
    - Yes: perform IPC
    - No: raise exception at reference monitor
  - Reference monitor can answer exception IPC with a mapping and thereby allow IPC

- Fine-grained control
- No per-IPC overhead, only exception in the beginning

L4.Sec, L4Re: Dedicated Kernel Objects

- Idea:
  - Invoke IPC on a kernel-object (IPC gate) -> endpoint (capability)
  - Kernel object mapped to a virtual address (local name space)
    - task only knows object's local name → no information leaks through global names

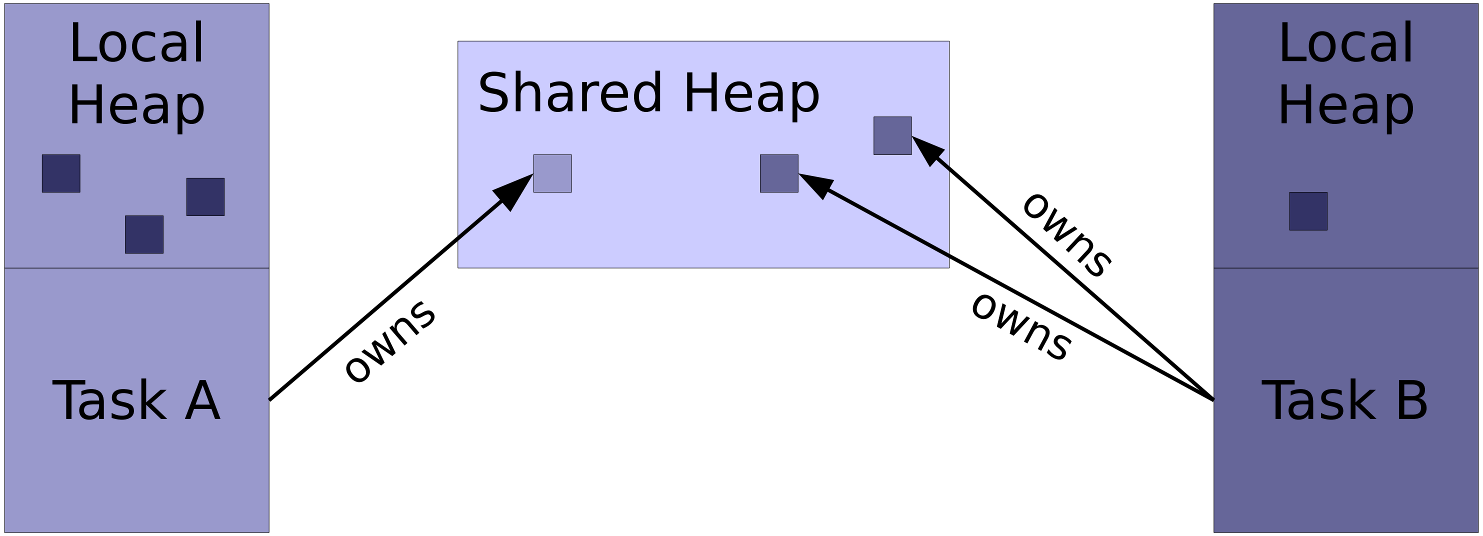


Singularity

- Singularity
  - Research microkernel by MS Research
  - Written in a dialect of C# (Sing#)
  - Topic of a paper reading exercise
- All applications run in privileged mode.
  - No system call overhead – syscalls are real function calls
- Enforce system safety at compile time.
  - Isolation completely realized using means of the used programming language -> Language-Based Isolation

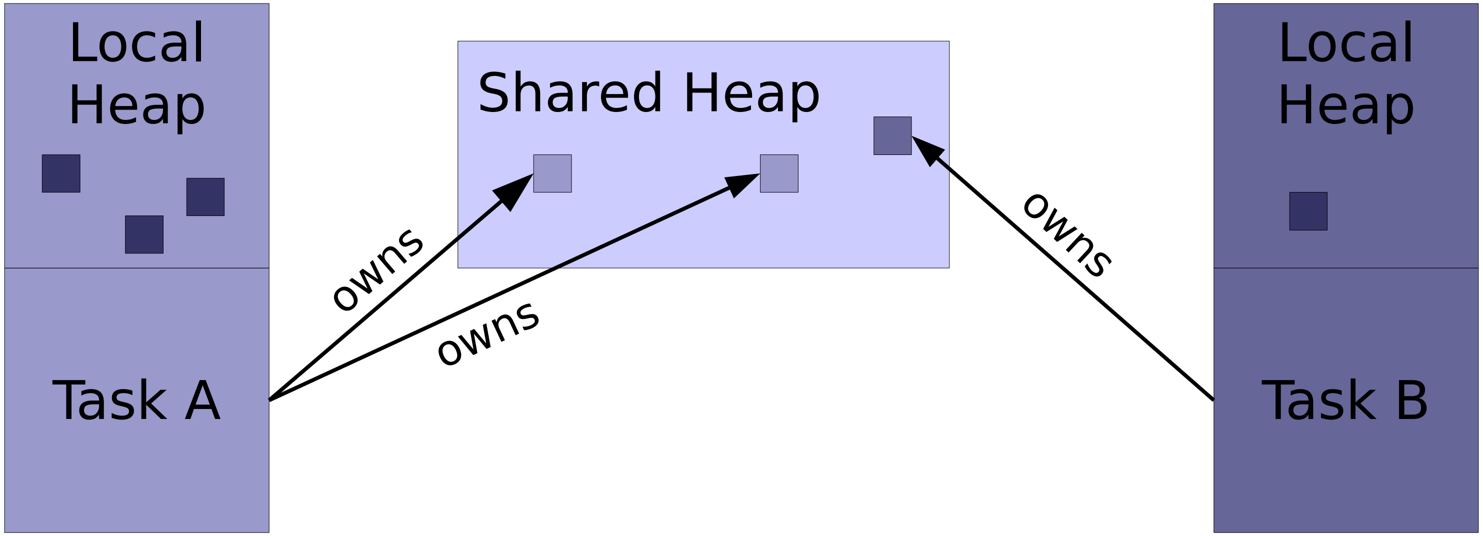
IPC & Language-Based Isolation

- Singularity IPC is always performed through shared memory.
- Only certain objects can be transferred.
  - Allocated from a special memory pool -> shared heap



IPC & Language-Based Isolation (2)

- Only one task may own objects in SH.
- IPC := transfer ownership of an object in SH.
- IPC protocols are specified by state machines – contracts
- Contracts are verified at compile-time



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Break

- Mechanisms for controlling information flow
  - Special IPC control mechanism (traditional L4)
  - Reuse other kernel mechanism (e.g., mapping of memory pages) for IPC control (L4.Fiasco)
  - Special kernel objects for IPC (Mach, L4.Florence, L4Re)
  - Static compile-time analysis of communication behavior (Singularity)

Break

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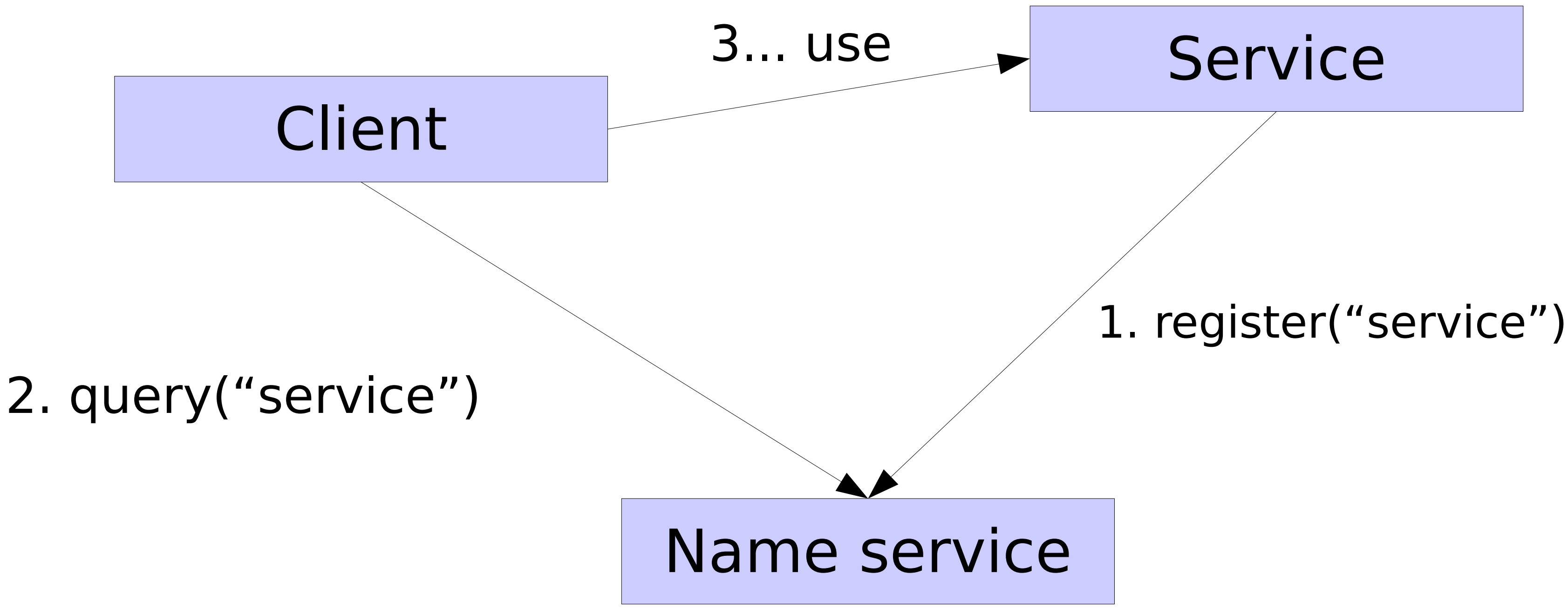
How to find a service?

Shared memory

How to find a service

- Need to get some kind of identification of service provider in order to perform IPC.
  - L4Re: need to get a capability mapped into my local capability space
- Idea borrowed from the internet: translate human-readable-names into IDs.
- Need a name service provider.

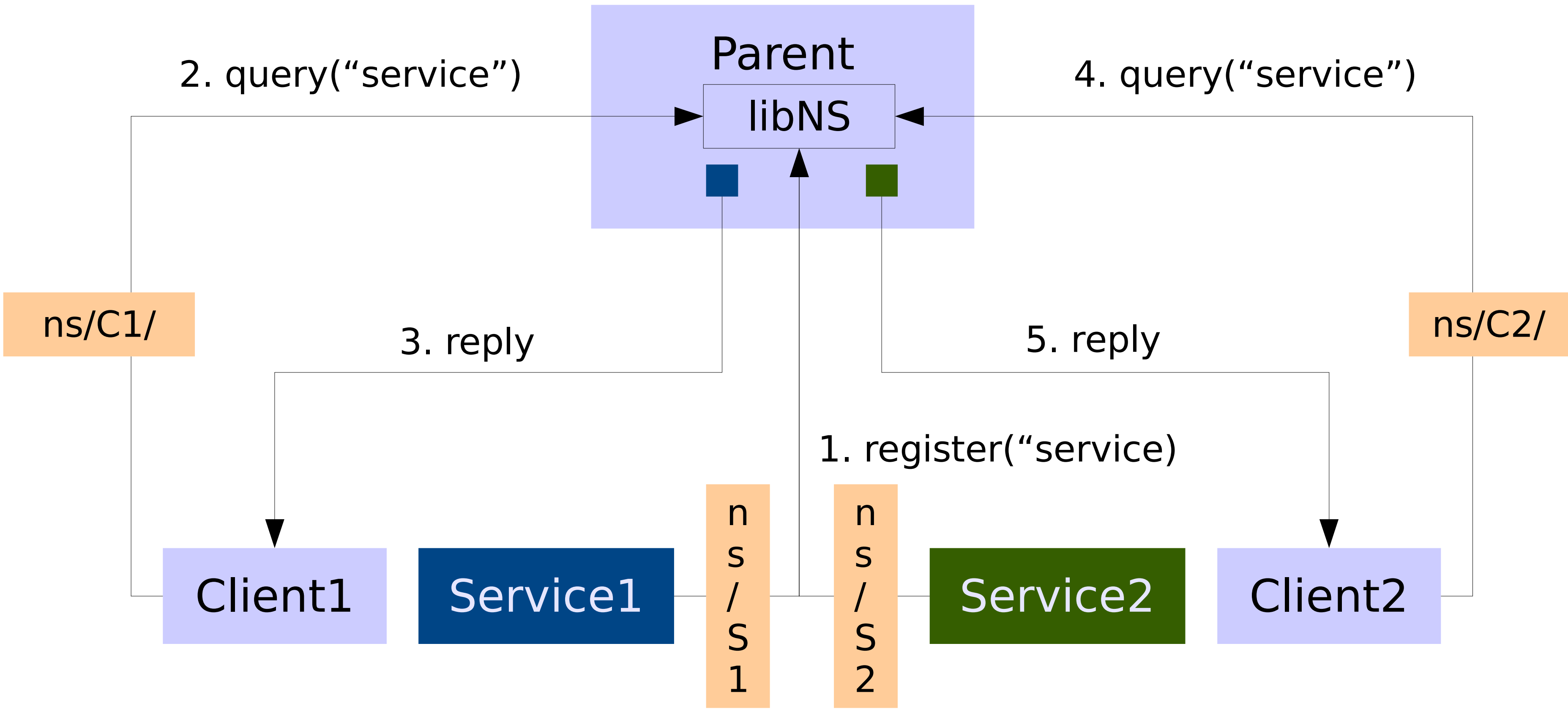
Global name service



- **Race condition:** Evil app can register name before real one.
- **Information leak:** Query name service for names and gain information about running services → contradicts resource separation

→ *Names are a resource and must be managed!*

Hierarchical naming



Hierarchical Naming

- Race Condition
  - Parent controls name space and program startup
  - Knows who is registering a service
- Information leak
  - Parent only provides name space content to each application
- Problem: configuration can be a mess.

Break

- Purpose
- Implementation
- Tool/Language support
- Security
- How to find a service?
- **Shared memory**

Asynchronous IPC & Shared Memory

- Some applications need high throughput for a lot of data.
  - Sharing memory between tasks can provide better performance

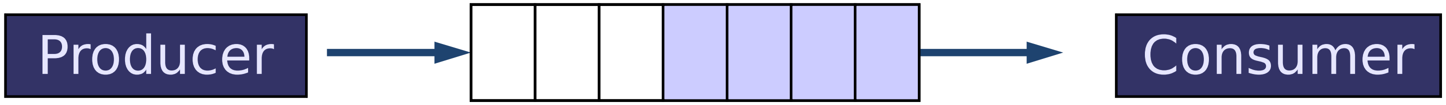
- Many workloads need asynchronous communication.
  - Fiasco.OC: IRQ kernel object

Shared Memory

- Zero-copy communication
  - Producer writes data in place
  - Consumer reads data from the same physical location
- Kernel seldom involved
  - At setup time: establish memory mapping (flexpage IPC + resolution of pagefaults)
  - Synchronization only when necessary
- Ergo: Shared mem communication is fast (if the scenario allows it)
  - High throughput, large amount of data
  - Example: streaming media applications

Example: Consumer-Producer Problem

- Shared buffer between consumer and producer
- Wake up notifications using IPC
  - If new data for consumer is ready
  - If free space for producer is available
- How to handle these notifications?



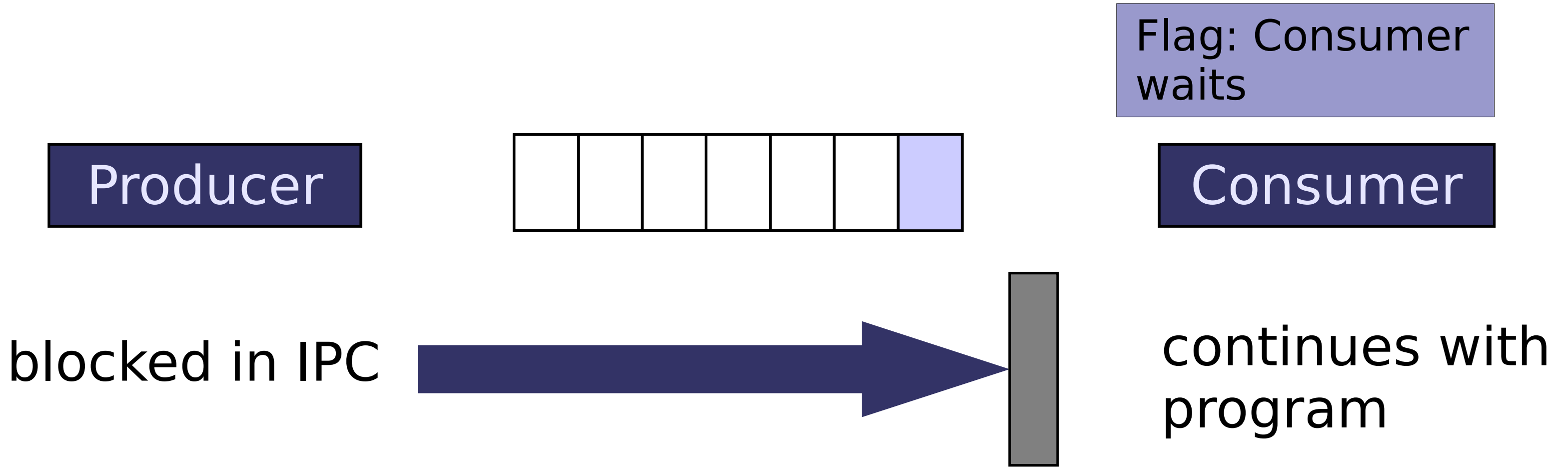
generate data (recv from network, keyboard events, ...)

FIFO queue

process data

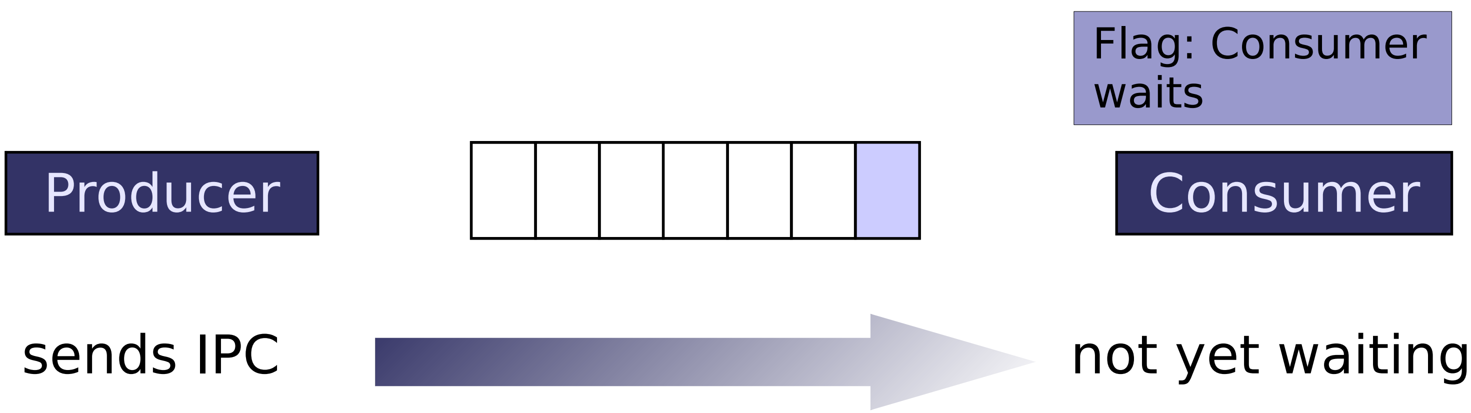
1st try: Consumer sets flag

- Consumer indicates “I am ready to receive.” using a flag (in shared memory) and waits for IPC.
- Producer sends notification IPC with infinite timeout.
- Evil consumer: sets flag, but doesn't wait
- Producer remains blocked forever -> DoS



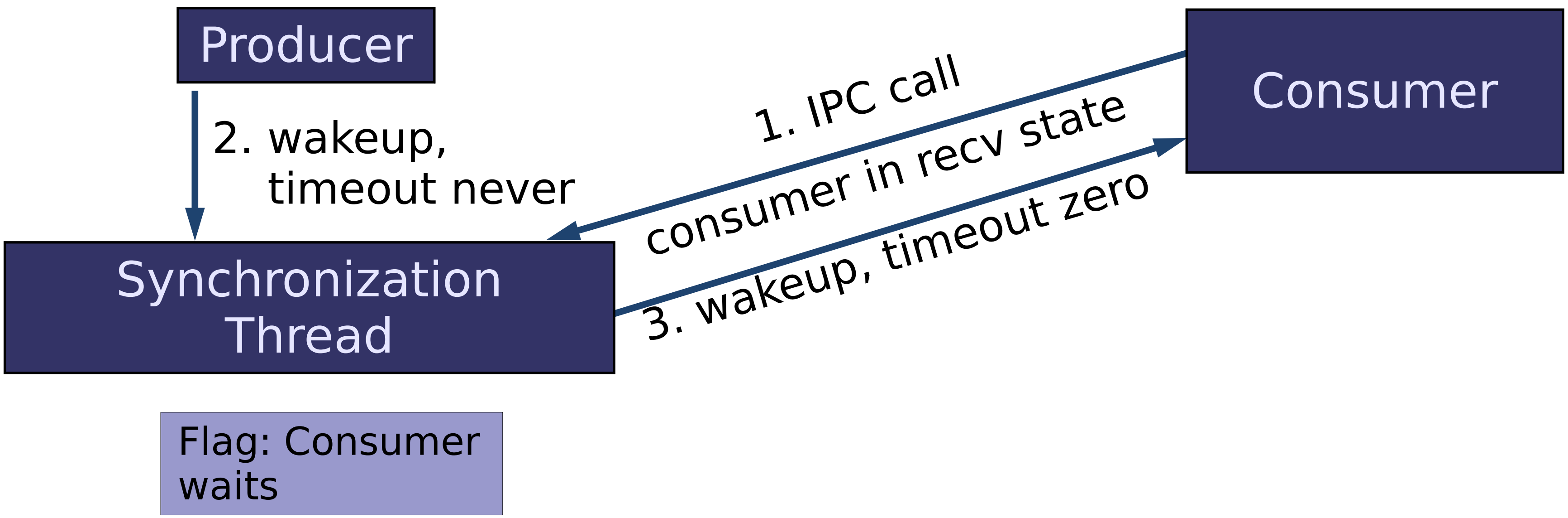
2^{nd} try: Notify with zero Timeout

- Consumer flags “I am ready.”
- Producer sends notification with timeout zero
- Consumer in bad luck: sets flag and gets interrupted right before waiting for IPC
- Producer sends notification
- Consumer is blocked forever



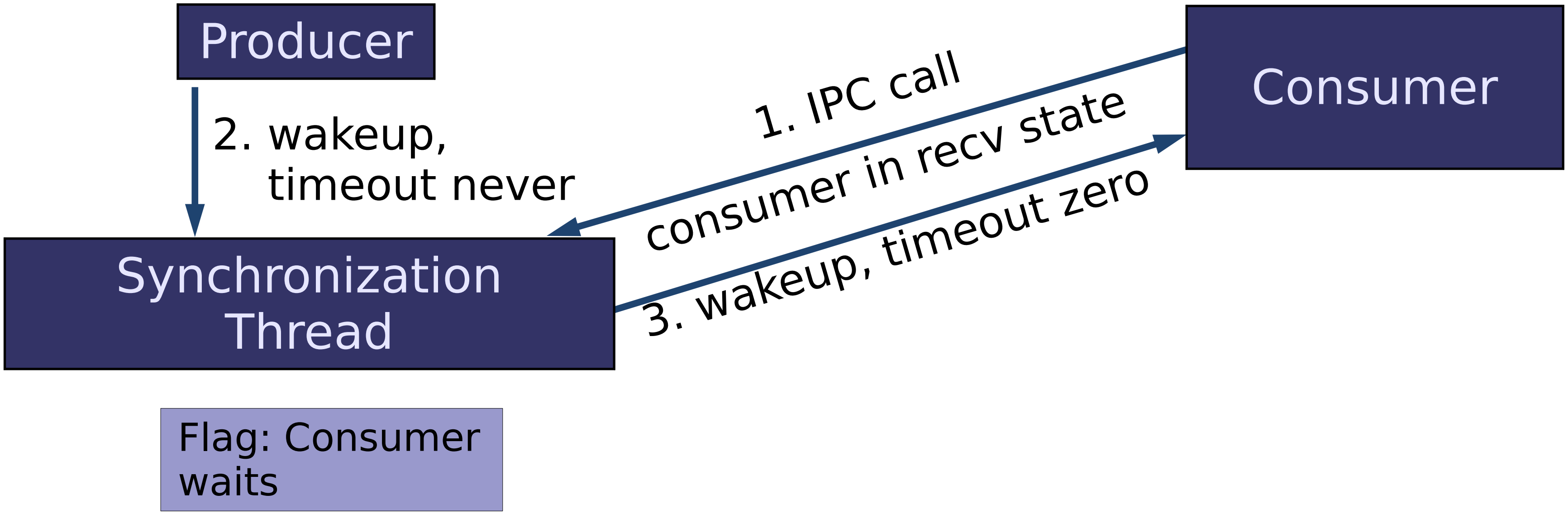
The Problem: Atomicity

- Idea: set flag and enter wait state atomically
  - (Delayed preemption; not discussed here)
  - Atomic L4 IPC call to synchronization thread, which sets the flag and wakes consumer later



The Problem: Atomicity

- Idea: set flag and enter wait state atomically
  - (Delayed preemption; not discussed here)
  - Atomic L4 IPC call to synchronization thread, which sets the flag and wakes consumer later
- Note: this is just consumer notification; producer side and full/empty detection must be handled, too



Further Reading

- L4 kernel manual:
  http://l4hq.org/docs/manuals/Ln-86-21.pdf
- Dice manual: http://os.inf.tu-dresden.de/dice/manual.pdf
- Genode Dynamic RPC Marshalling:
  N. Feske: *"A case study on the cost and benefit of dynamic RPC marshalling for low-level system components"*
- Singularity IPC:
  Faehndrich, Aiken et al.: *"Language support for fast and reliable message-based communication in Singularity OS"*

Coming soon

- Next week:
  - Lecture: Memory
  - No exercise