



TECHNISCHE
UNIVERSITÄT
DRESDEN

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

Inter-Process Communication

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Dresden, 2023-10-17

- No lecture/exercise next week!
- Reminder: consider visiting the MOS lab!
 - Hacking on L4
 - Pong game
 - You implement memory management, keyboard driver, and graphical console
 - Subscribe to the mailing list:
<https://tudos.org/mailman/listinfo/moslab2023>



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



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

- IPC is a fundamental mechanism in L4:
 - Exchange data
 - Synchronization
 - Sleep, timeout
 - Hardware / software interrupts
 - Grant access to resources (memory, I/O ports, kernel objects)
 - Exceptions
- Liedtke: *“IPC performance is the master.”*

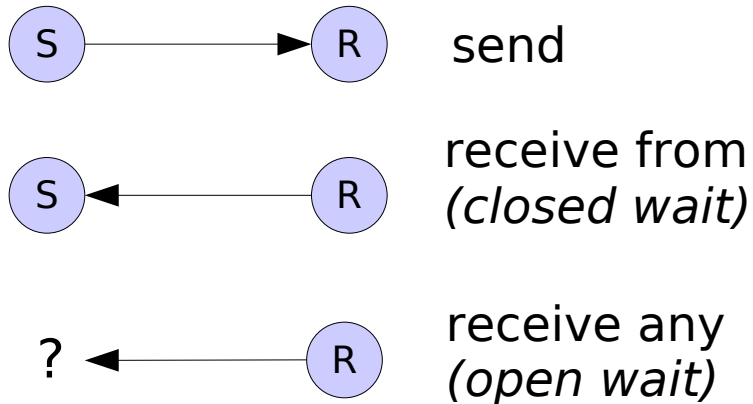
- Asynchronous IPC (e.g., Mach)
 - “Fire and forget”
 - In-kernel message buffering
 - Two problems:
 - Data copied twice
 - DoS attack on kernel memory (never receive data) – can use quotas, though
- Synchronous IPC (e.g., L4)
 - IPC partner blocks until other one gets ready
 - Direct copy between sender and receiver



- What you can send:
 - Plain data
 - Resource mappings
- Types
 - Send
 - Closed wait
 - Open wait
 - Call
 - Reply & wait

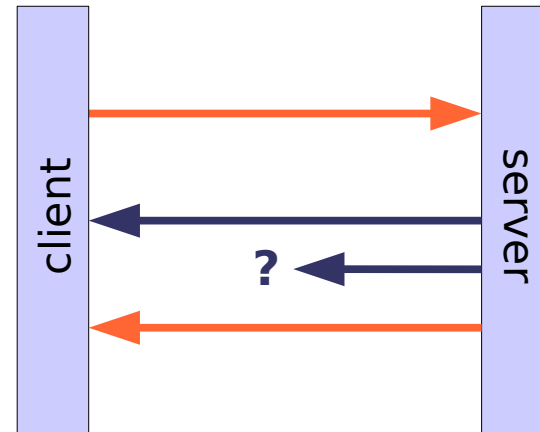
- Timeouts
 - 0 (non-blocking IPC)
 - NEVER or specific value – block until partner gets ready or timeout occurs
 - sleep() is implemented as IPC to NIL (non-existing) thread with timeout
- Exceptions
 - Certain conditions need external interaction
 - Page faults
 - L4Linux system calls
 - Virtualization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

Basics



- Why is there no broadcast?

Special cases for client/server IPC



- **call** := send + rcv from
- **reply and wait** := send + rcv any



Purpose

Implementation

Tool/Language support

Security

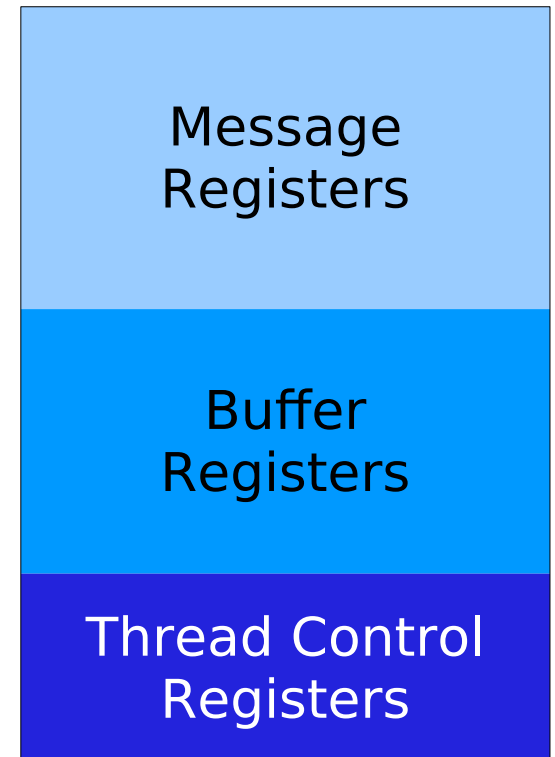
How to find a service?

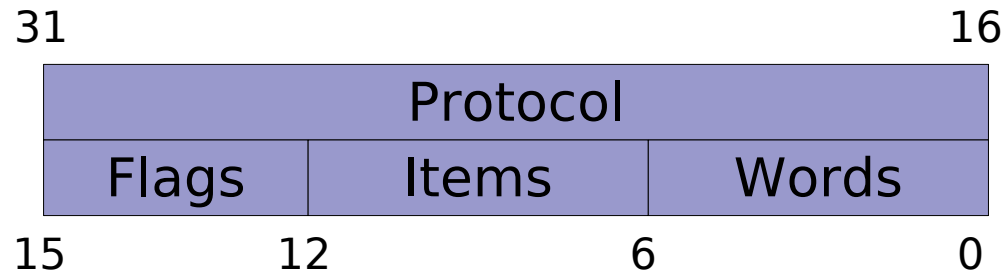
Shared memory

- 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

- Sending:
 - Sender calls send or call
 - Blocks until message has been sent or reply has been received
- 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 have IPC Gate to sender.
 - Kernel provides implicit reply capability (per-thread)
 - Valid until reply sent or next wait started.

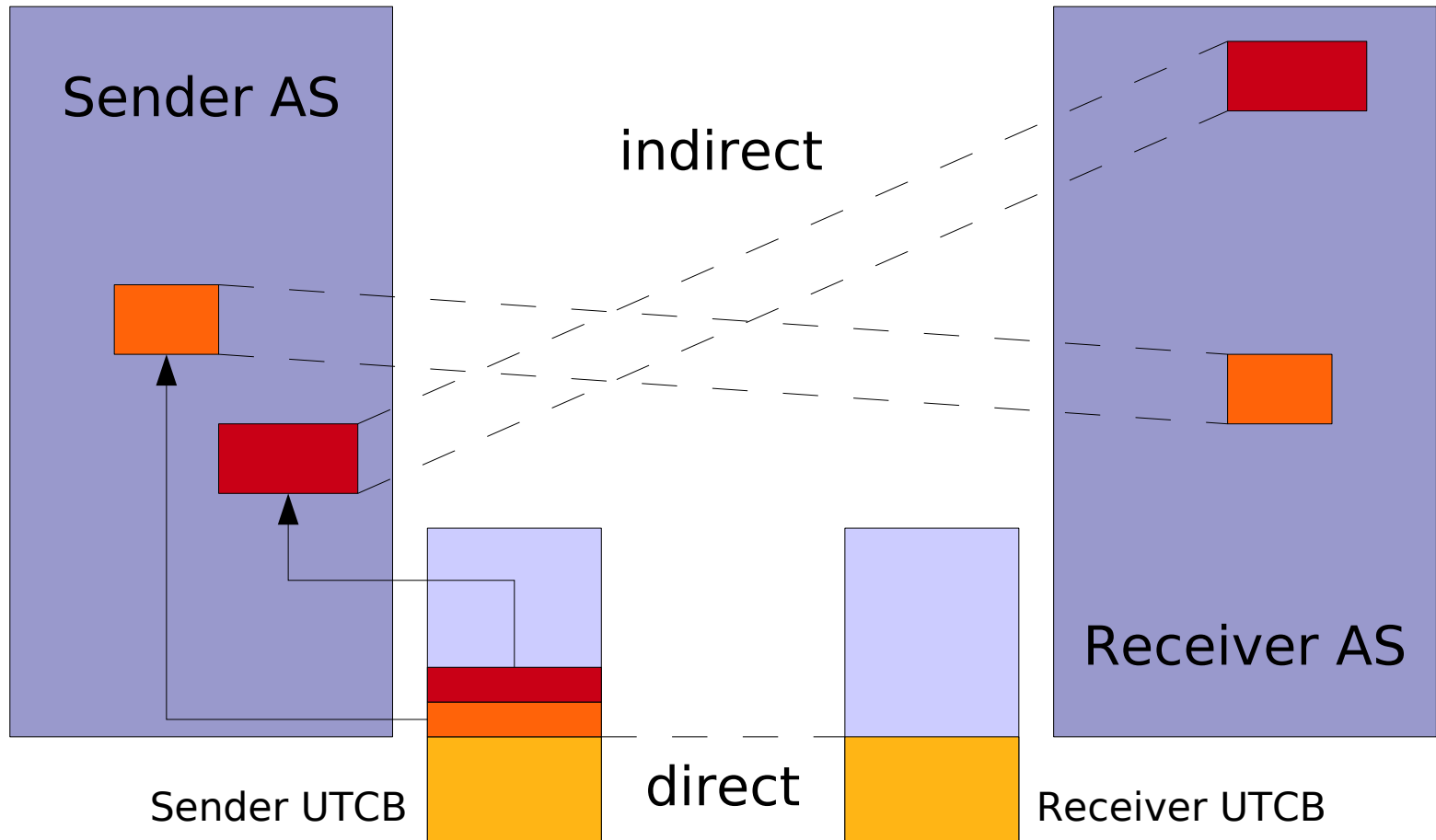
- **U**ser-level **T**hread **C**ontrol **B**lock
- Set of “virtual” registers
- Message Registers
 - System call parameters
 - IPC: direct copy to receiver
- Buffer registers
 - Contains flexpage descriptors
- Thread Control Registers
 - Thread-private data
 - Preserved, not copied





- 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 (resource mappings)
- Words
 - Number of direct items to copy (plain data)

Direct vs. indirect copy





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How to find a service?

Shared memory

Client

Marshall data
Assign Opcode
IPC call

Server

IPC wait
Unmarshall Opcode
Unmarshall Data
Execute function
Marshall reply or error
IPC reply
Goto begin

Unmarshall error or reply



```
/* 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);
}
```

- 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!**

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

```
interface F00 {  
    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**ompiler

- 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
 - ...

- 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>>

```
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 >> res;
    return res;
}
```

```
int Foo::dispatch(L4_ipc_iostream& str, l4_msgtag_t tag) {
    // check for invalid invocations
    if (tag.label() != PROTO_F00)
        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 ..
    }
}
```


- 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

- 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)



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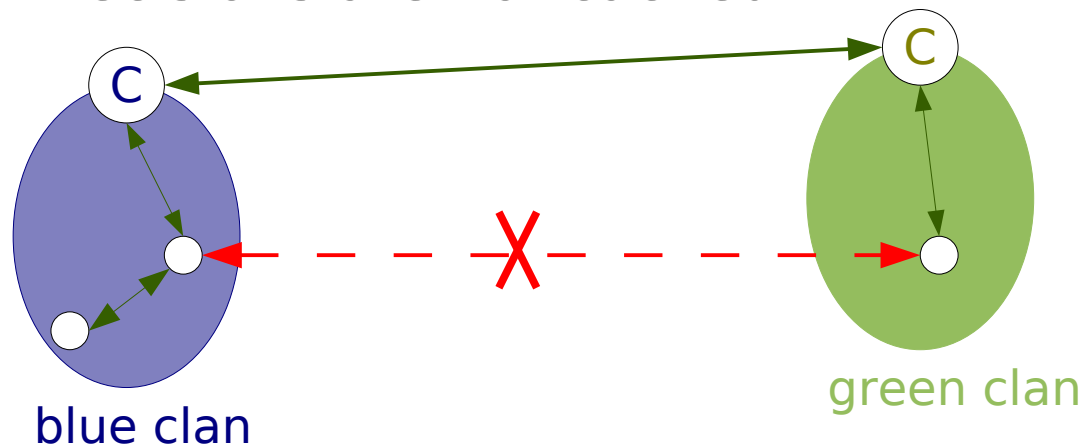
How to find a service?

Shared memory

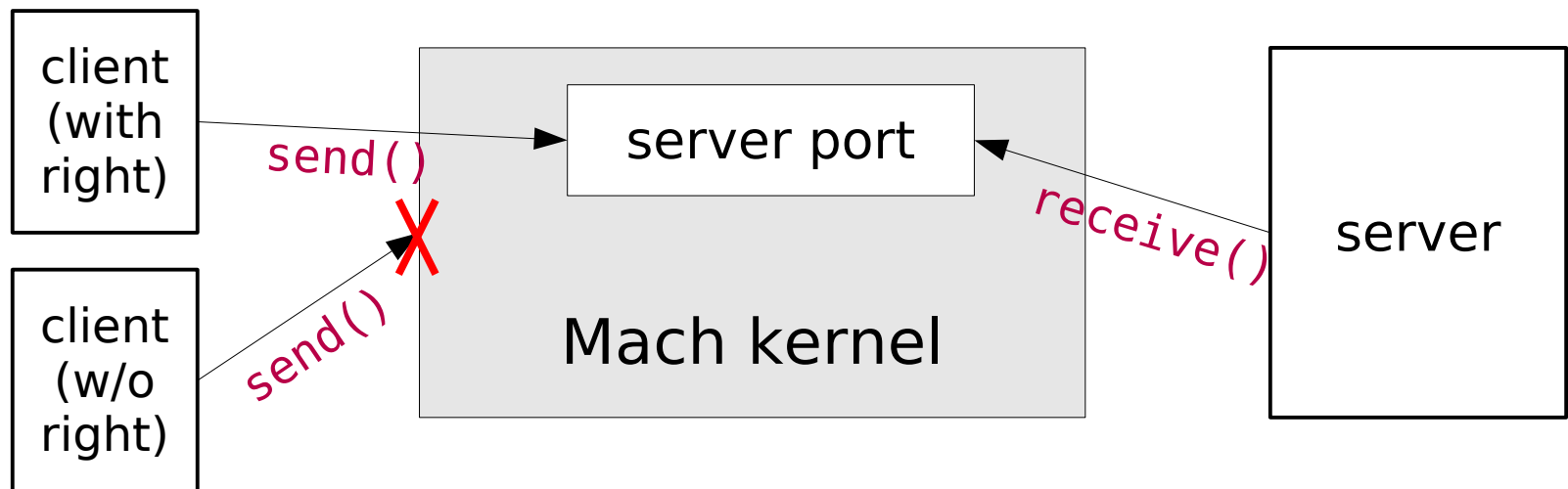


- Problem: How to control data flow?
- Crucial problem to solve when building real systems
- Many proposed solutions

- 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.



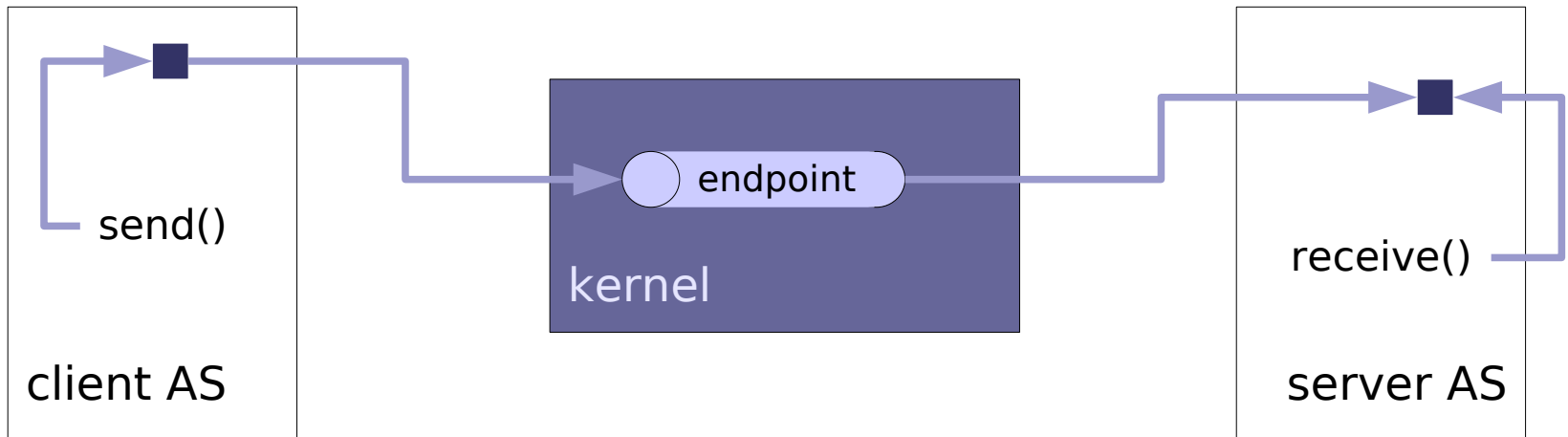
- Dedicated kernel objects (global)
- Applications hold send/recv rights for ports
- Kernel checks whether task owns sufficient rights before doing IPC



- 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

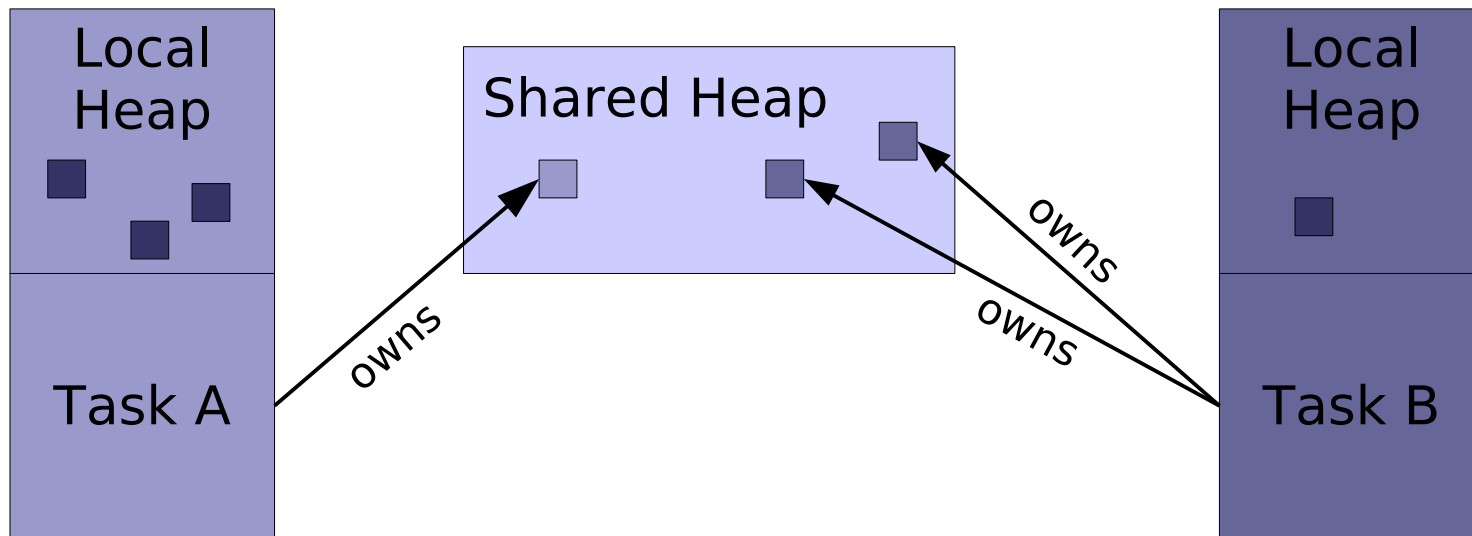
- Idea:

- 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

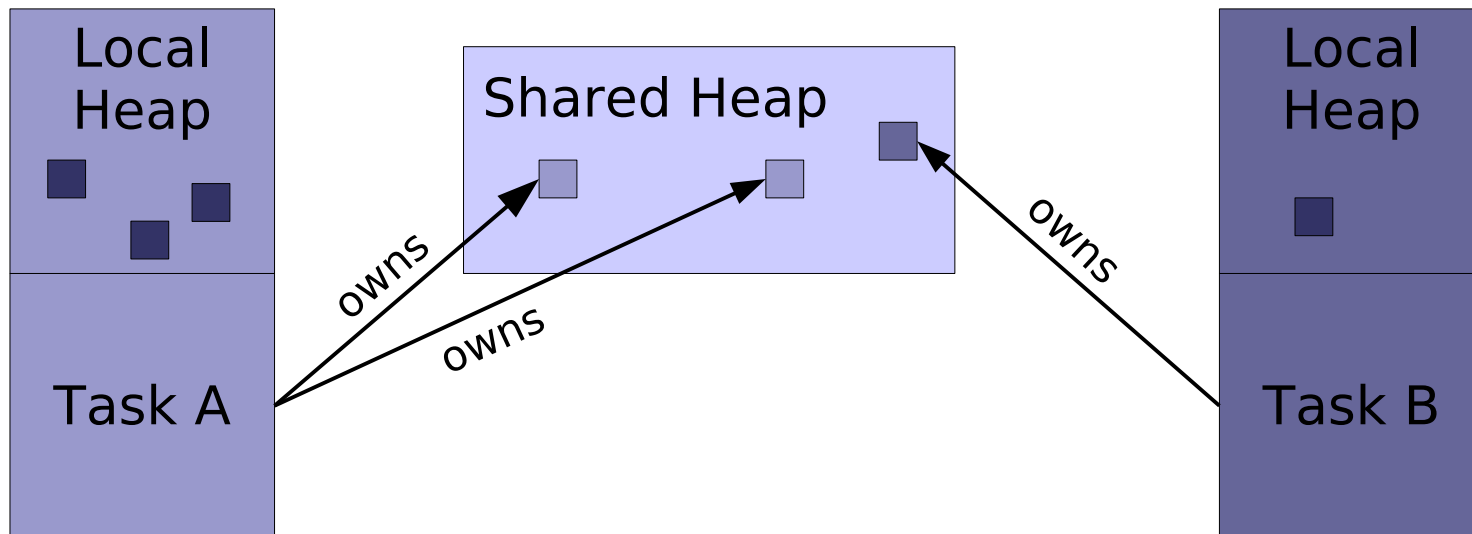


- Singularity
 - Research microkernel by MS Research
 - Written in a dialect of C# (Sing#)
 - Topic of a paper reading exercise
- All applications run in privileged mode.
 - No system call overhead - syscalls are normal function calls
- Enforce system safety at compile time.
 - Isolation completely realized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



- 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



- 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)



Purpose

Implementation

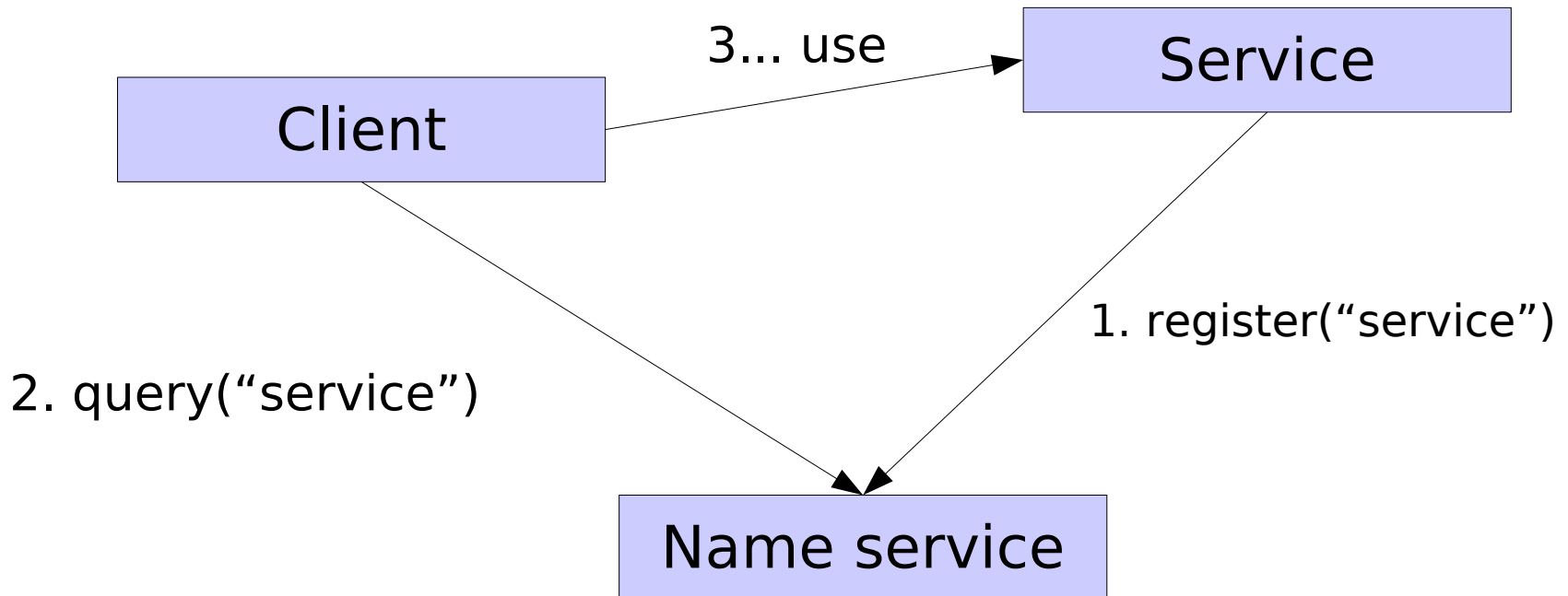
Tool/Language support

Security

How to find a service?

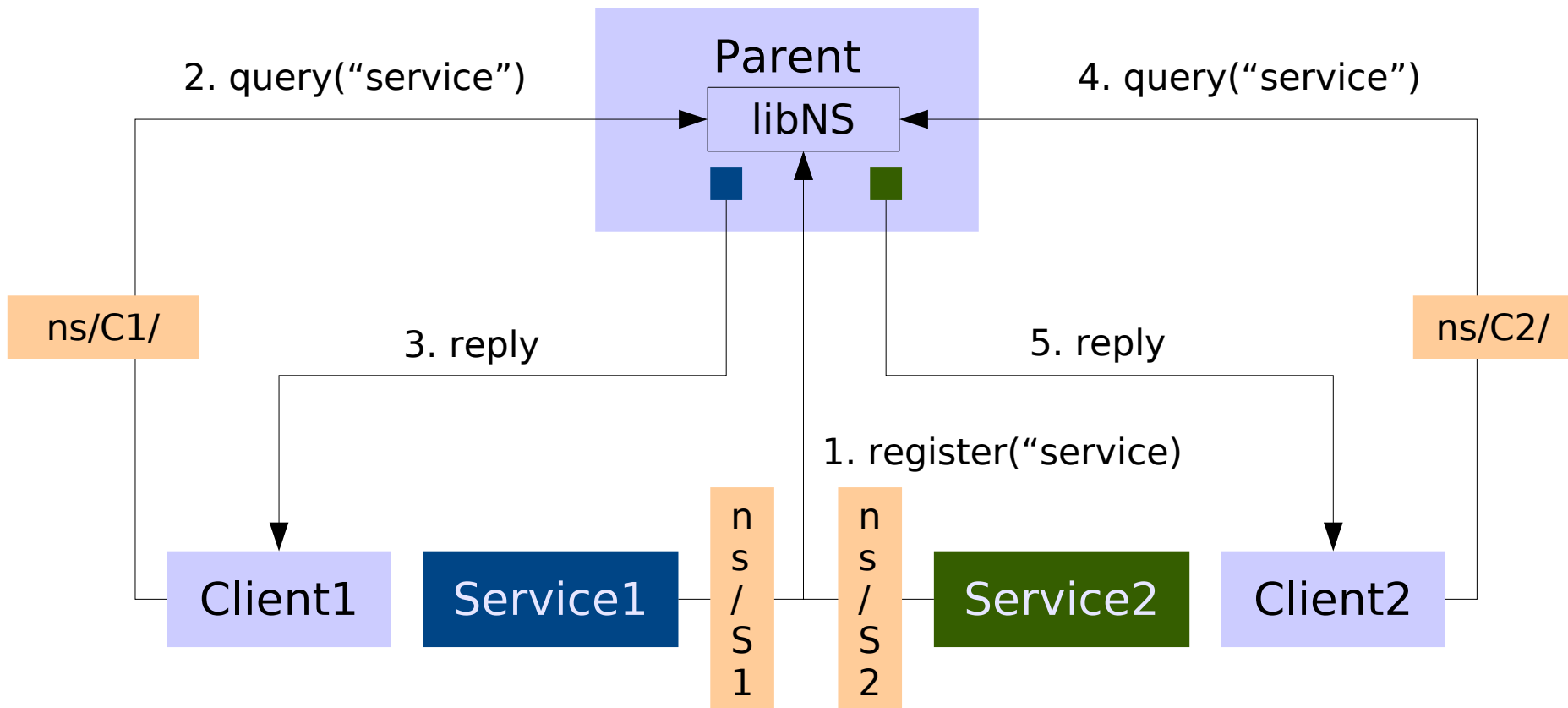
Shared memory

- 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.



- **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



- 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.



Purpose

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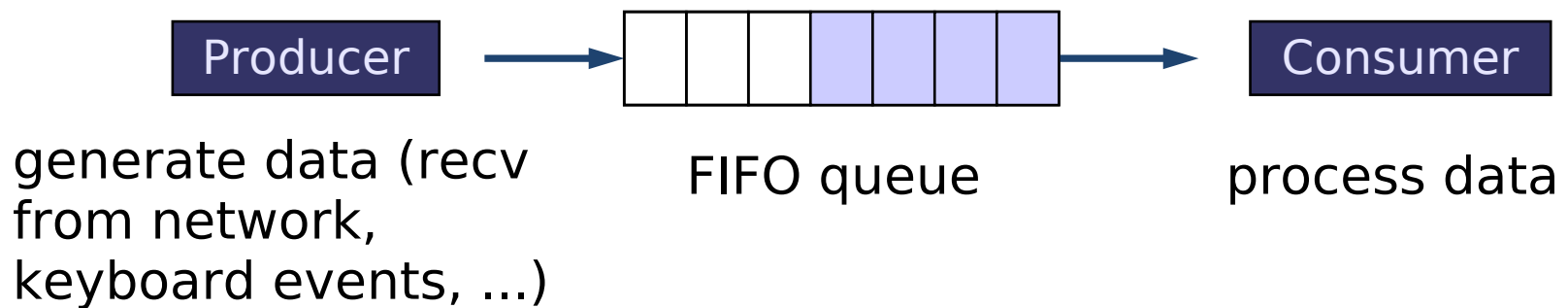
How to find a service?

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

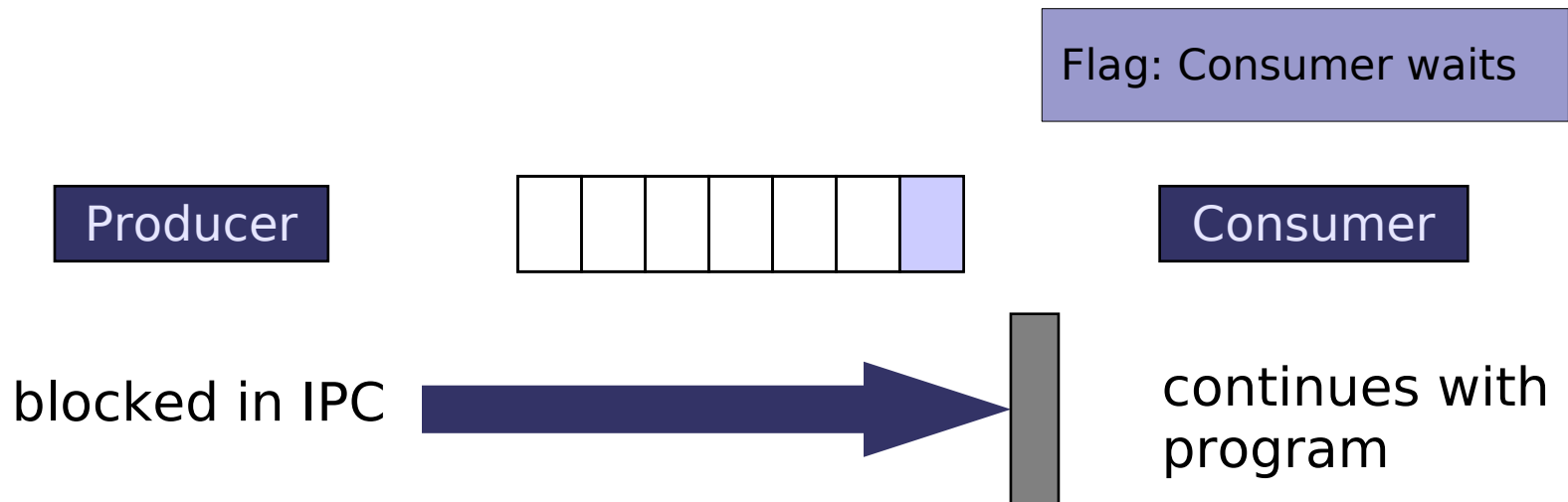
- Zero-copy communication
 - Producer writes data in place
 - Consumer reads data from the same physical location
- Kernel seldom involved
 - At setup time: establish memory mapping (flexpage IPC + resolution of pagefaults)
 - Synchronization only when necessary
- Ergo: Shared mem communication is fast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

- 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



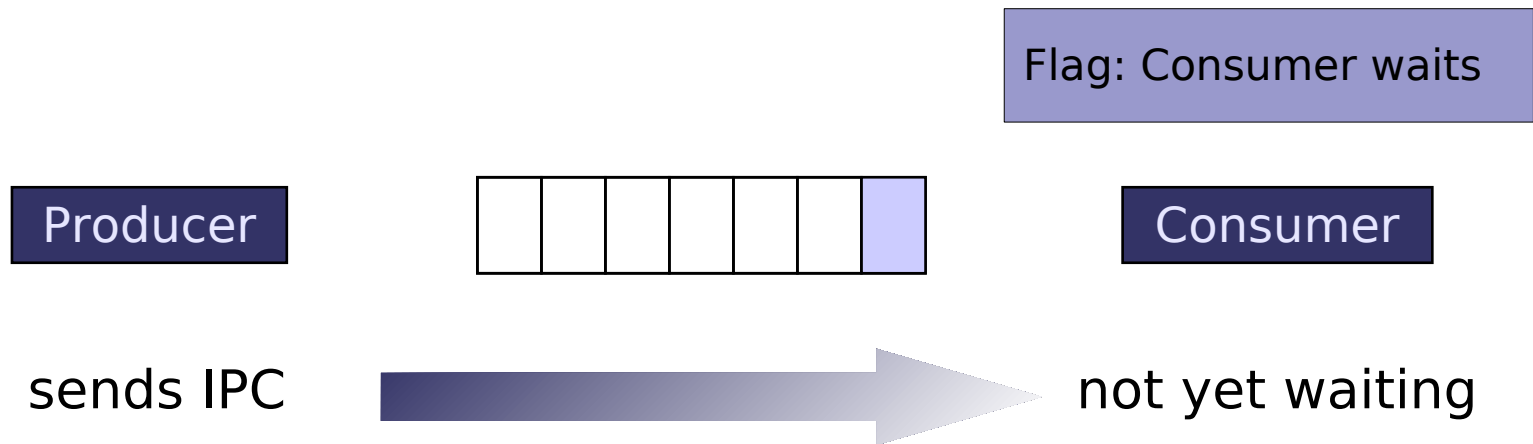
1st try: Consumer sets flag

- 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



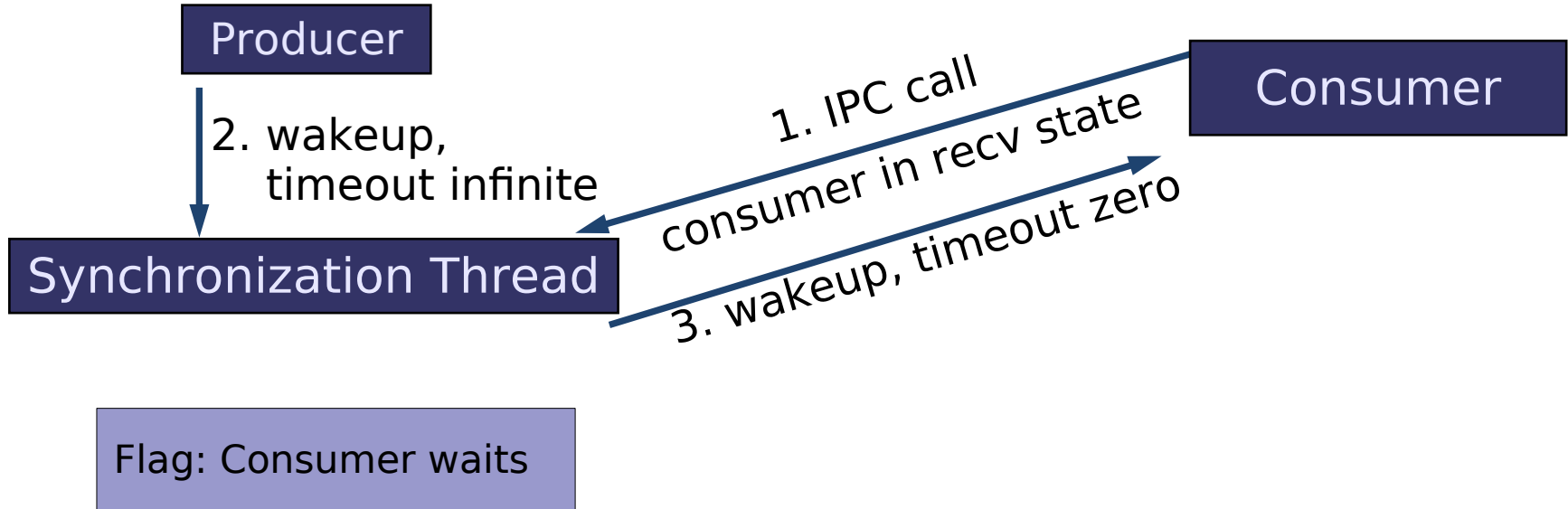
2nd try: Notify with zero Timeout

- 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

- Solution: set flag and enter wait state atomically
- (Delayed preemption)
- L4 IPC call is atomic



- L4 kernel manual:
<http://l4hq.org/docs/manuals/Ln-86-21.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”*

- Next lecture: Threads on November 7th
- Next exercise: Booting L4 on November 7th
- IPC exercise on December 19th