TECHNISCHE UNIVERSITÄT DRESDEN

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

Memory, IPC, and L4Re

Björn Döbel

What we talked about so far

- Microkernels
- Fiasco.OC
- Threads in Fiasco.OC

Lecture Outline

- Some more Fiasco.OC fundamentals
  - Inter-Process Communication
  - Memory Management
- L4Re Mechanisms to implement clients and servers

Communication

- Threads are the basic building blocks of Fiasco.OC/L4Re applications.
- Threads need to communicate to achieve their goals:
  - Data exchange
  - Synchronization
  - Sleep
  - Handle hardware/software interrupts
  - Grant resource access
- This is all done using the **Inter-Process Communication (IPC)** mechanisms provided by Fiasco.OC.
- Jochen Liedtke: *"IPC performance is the master."*

IPC: Issues

- How to implement it?
- How to integrate with languages / environments?
- How to manage IPC securely?
- How to make it fast?

IPC: Design Decisions

Asynchronous IPC

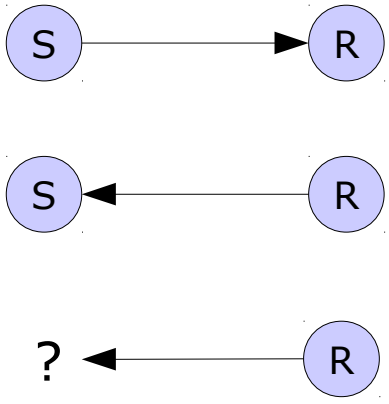
- Example: Mach
- Pro:
  - fire&forget messaging
- Cons:
  - 2 copies: into kernel and out of kernel
  - DoS attack possible if kernel does not manage IPC properly

Synchronous IPC

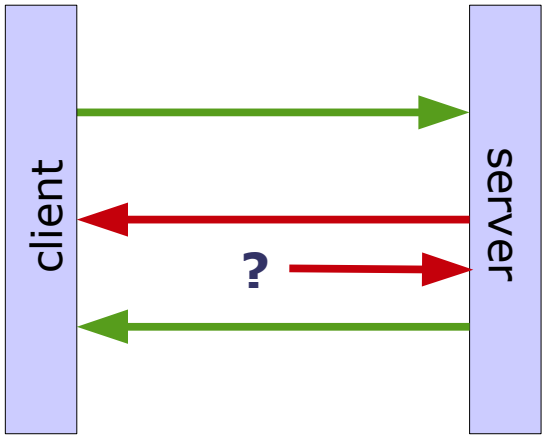
- Example: L4
- Pros
  - No double copy
  - No kernel memory involved
- Con
  - Partners need to synchronize

IPC: Flavors

Basics



Special cases for client/server IPC



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

IPC in Fiasco.OC

- IPC building block: kernel **IPC Gate** object
- Creation:

```
L4::Factory* factory = L4Re::Env::env()->factory();
l4_msgtag_t tag = factory->create_gate(
                    target_cap, thread_cap, label);
```

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- IPC building block: kernel **IPC Gate** object
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```
L4::Factory* factory = L4Re::Env::env()->factory();
l4_msgtag_t tag = factory->create_gate(
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```

The factory is a kernel object to create new kernel objects.

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```
L4::Factory* factory = L4Re::Env::env()->fa
l4_msgtag_t tag = factory->create_gate(
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```

L4Re::Env::env() gives a program access to its initial capability environment.

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L4::Factory* factory = L4Re::Env::env()->factory();
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```

A thread may be attached to multiple IPC gates. To identify through which gate a message arrived, every gate may get a dedicated “label” assigned.

IPC in Fiasco.OC

- IPC building block: kernel **IPC Gate** object
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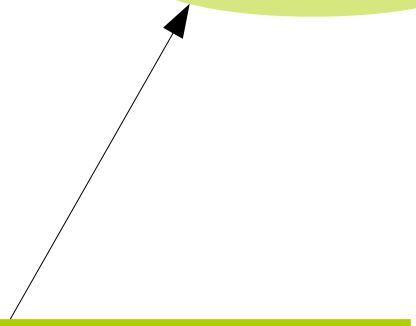


A free slot in the task's capability table. The newly created object is referenced by this slot. Usually allocated using:
`L4Re::Util::cap_alloc.alloc()`

IPC in Fiasco.OC

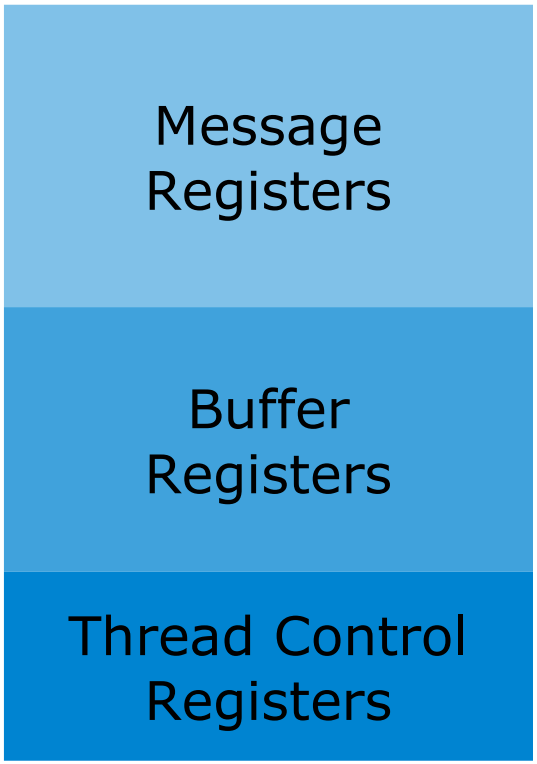
- IPC building block: kernel **IPC Gate** object
- Creation:

```
L4::Factory* factory = L4Re::Env::env()->factory();
l4_msgtag_t tag = factory->create_gate(
                    target_cap, thread_cap, label);
```

- Receiving a message:
  - Open wait using thread's UTCB
  - Unblocks upon message arrival → use label to distinguish IPC gates
- Sending a reply:
  - Normally, one would need a capability to send the reply to. But we only have the (one-way) IPC gate!
  - Fiasco.OC stores last caller's reply capability internally.
    - May be used until next wait() starts.

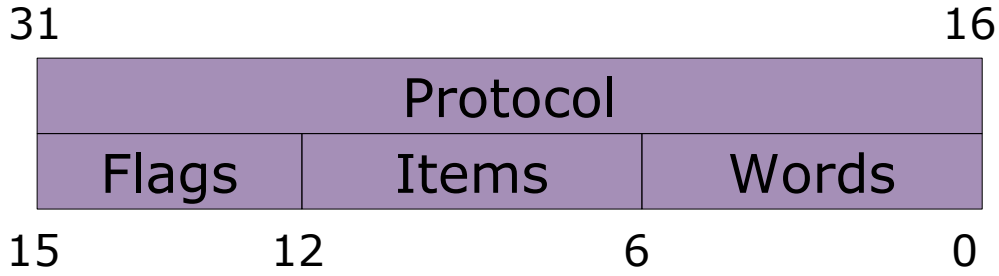
IPC: The UTCB

- **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: The Message Tag

- Special descriptor that defines which parts of the UTCB are valid upon an IPC call.



- Protocol: user-defined “message type”
- Words: number of valid items in message registers. Directly copied to receiver.
- Items: number of valid items in buffer registers. Handled specially by the kernel.

IPC: Special Features

- Timeouts
  - Maximum amount of time to wait for partner to become ready.
  - Most common: 0 and NEVER
  - Separate timeouts for send and receive phases
- Exceptions
  - Fiasco.OC can notify an exception handler thread of special events that happened to another thread
    - Memory management: page faults
    - Virtualization exceptions

Happily writing IPC code...

```
/* 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_error(l4_ipc_call(dest, l4_utcb(), tag, TIMEOUT_NEVER));
}
```

Happily … ?

- This is dull and error-prone work!
- It can be automated:
  - Take 1: Interface Definition Language (IDL)

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

  - IDL Compiler automatically generates IPC code.
    - Worked for older versions of L4(Env):
      Dice – **D**ROPS **I**DL **C**ompil**e**r
  - Currently out of service. :(

Integrating IPC with C++

- L4Re (and Genode!) use C++ stream operators to make IPC fancier.
  - Compiler takes care of serializing basic data types into the right place.
- Stream library can abstract from the underlying kernel
  - reuse the same IPC code on different kernels
  - heavily used in Genode
- Users work with special IPC Stream objects.
- Good news: This can even be combined with an IDL compiler.

L4Re: IPC Streams – Client

```
int Foo::op1(l4_cap_idx_t dest, int arg1,
             char *arg2, unsigned arg2_size)
    {
        int result = -1;
        L4_ipc_iostream i(l4_utcb()); // create stream
        i << Foo::Op1                 // args → buffer
          << arg1
          << Buffer(arg2, arg2_size);

        // perform call
        int err = l4_error(i.call(dest);)
        if (!err)
           i >> result;
        return result;
    }
```

L4Re: IPC Streams – 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 ..
  }}
```

L4Re: IPC Framework

- L4Re provides IPC framework
  - Implementation (& docs): l4/pkg/cxx/lib/ipc/include
  - C++ streams → ipc_stream
    - Marshalling/unmarshalling of basic data types (C++ POD, C strings)
  - C++ server framework → ipc_server
- Usage example: l4/pkg/examples/clntsrv

L4Re: Server Infrastructure

- C++ classes to implement servers
  - Basic message reception
    - Optional advanced error handling etc.
  - Handling of server objects
    - Varying types
    - Varying amount of objects

L4Re: Init scripts & connections

- Implements a basic server loop

L4::Server

```
while (1) {
    m = recv_message();
    ret = dispatch(m.tag(), ios);
    reply(m, ret);
}
```

- Users need to provide a `dispatch()` function.
  - If curious, see `L4::Ipc_svr::Direct_dispatch`
- Plus: Loop hooks
  - Allows you to specify callbacks for
    - IPC error
    - Timeout
    - Prepare to wait
  - You should get away with `L4::Default_look_hooks`

Server objects

L4::Server_object

- Servers may provide
  - Different services
  - To different clients
  - Through different server objects
- A server object is basically a wrapper for a capability: `L4::Server_object::obj_cap()`
- Server object implementations may vary
  - Need a dedicated `dispatch()` function per object
- But how does the server decide at runtime which function to call?

Object registry

- Server objects are stored in per-server object registry

L4::Basic_registry

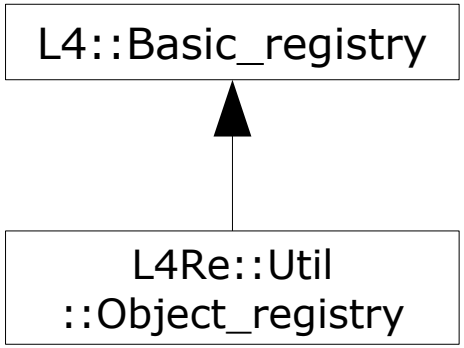
- Registry provides a function to find an object by an ID

```
L4::Basic_registry::Value
   L4::Basic_registry::find(l4_umword_t id);
```

- ID is the label of the IPC gate through which a message arrived.
- Basic_registry is **basic**:
  - No ID management
  - ID is simply interpreted as a pointer to a local object

Advanced object management

- Advanced servers want to bind objects to
  - IPC gates or
  - Names specified in the Lua init script



- Use object pointer as label for IPC gate

```
L4::Cap<void> register_obj(L4::Server_object *o,
                           char const *service);

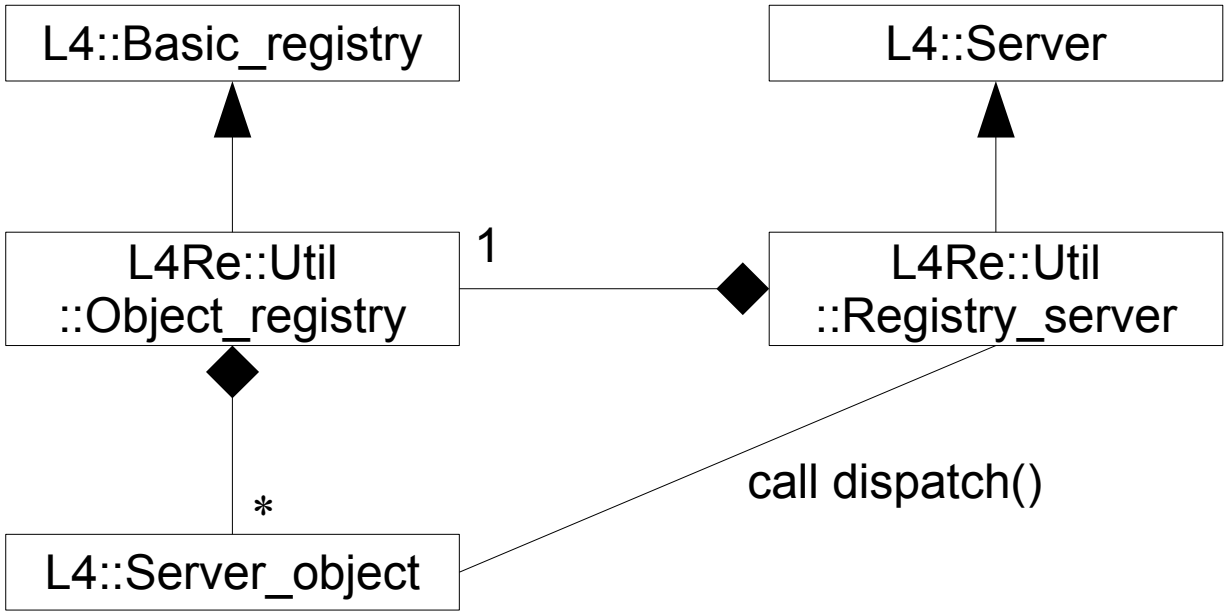
L4::Cap<void> register_obj(L4::Server_object *o);

bool unregister_obj(L4::Server_obj *o);
```

Using Object_registry in a server

- There's a utility class representing a server with an object registry:

  `L4Re::Util::Registry_server`



Server Implementation for Beginners

- Declare a server:

```
static L4Re::Util::Registry_server<> server;
```

- Implement a session factory object:

```
class MySessionServer
    : public L4::Server_object
{ .. };
```

- Implement a dispatch function:

```
int MySessionServer::dispatch(l4_umword_t o,
            L4::Ipc_iostream& ios)
{ .. };
```

Connecting Client & Server

- L4Re setups are usually started using an init script → Lua programming language.
- So far, we put a single binary as direct parameter to moe:

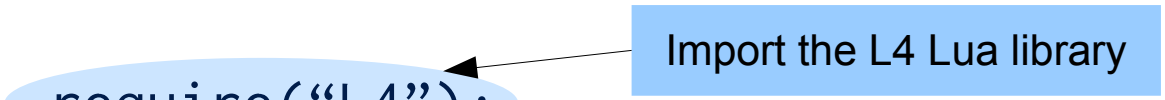
```
roottask moe --init=rom/hello
```

→ instead of --init, we can pass a Lua script:

```
roottask moe rom/hello.lua
..
module hello.lua
```

Initialization: Lua

- Simple script to start hello:




```
require("L4");
L4.default_loader:start( {}, "rom/hello" );
```

Initialization: Lua

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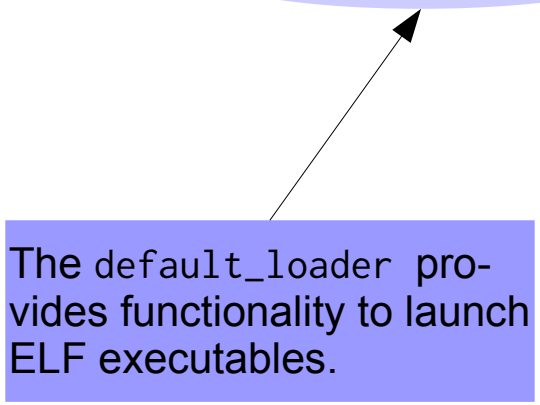

Initialization: Lua

- Simple script to start hello:

```
require("L4");
L4.default_loader:start( {}, "rom/hello" );
```

The start() function takes 2 parameters:

1. An environment for the application. (More later.)
2. The file name of the binary to launch.

L4/Lua: Connecting Services

- Lua interpreter establishes communi
  and passes them through the enviro

new_channel() creates an IPC gate. No thread is bound to it yet.

```
local ld = L4.default_loader;
local the_server = ld:new_channel();

ld:start( { caps = { calc_server = the_server:svr() },
            log  = { "server", "blue" } },
          "rom/server" );

ld:start( { caps = { calc_server = the_server },
            log = { "client", "green" } },
          "rom/client" );
```

L4/Lua: Connecting Services

caps = {} defines additional capabilities that are passed to the application on startup. The syntax is <name> = <object>, where name is later used to query this capability at runtime and object is a reference to an object.

For IPC channels, 'object' is the sender side of the channel, while 'object:svr()' refers to the server/ receiver side.

```
ld:start( { caps = { calc_server = the_server:svr() },
            log = { "server", "blue" } },
          "rom/server" );

ld:start( { caps = { calc_server = the_server },
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L4/Lua: Connecting Services

- Lua interpreter establishes communication channels and passes th

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local ld = L4.
local the_ser

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            log = { "server", "blue" } },
          "rom/server" );

ld:start( { caps = { calc_server = the_server },
            log = { "client", "green" } },
          "rom/client" );
```

log = { <tag>, <color> }
configures this application's log output. All log messages will be sent to the serial line by default. Every line for the application will start with "<tag> | " and will be colored in the respective VT100 terminal color.

Requesting an external object

- All objects that are placed in a program's capability space can at runtime be requested using

```
L4::Cap<Foo> cap =
    L4Re::Env::env()->get_cap<Foo>("name");

if (cap.is_valid())
    /* use cap */
```

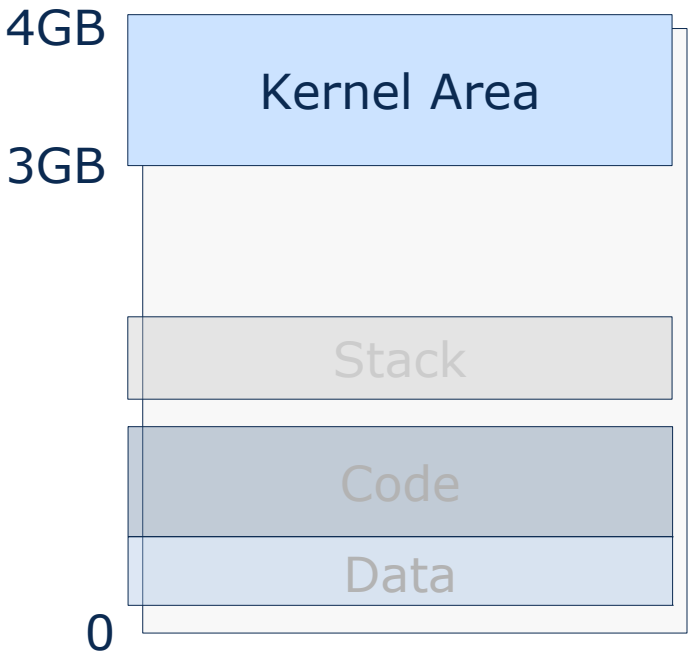
That's a lot of information!

- There are examples to try out in l4/pkg/examples!
  - Might not be checked out yet, so go to l4/pkg and do
    ```
    $> svn up examples
    ```
  - Example code is rather small and demonstrates only one feature at a time.

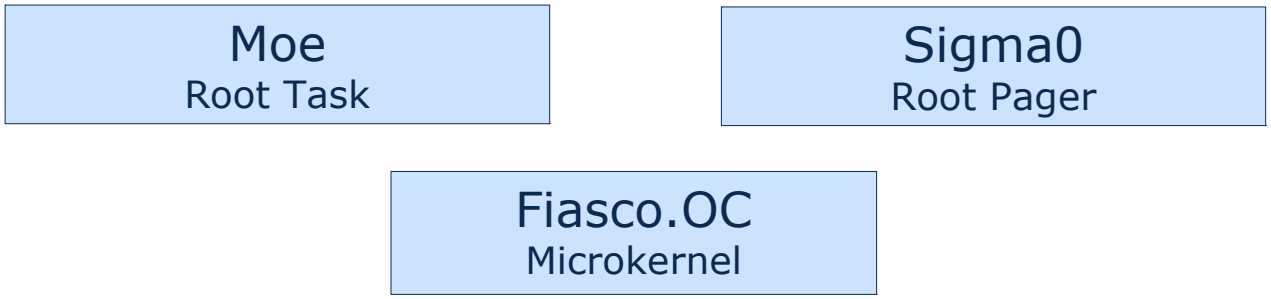
Booting Fiasco.OC

- **BIOS** initializes platform and then executes boot sector.
- **Boot loader** (e.g., GRUB) loads kernel and multiboot modules.
  - We skip this step in QEMU.
- **Bootstrap**
  - interprets multiboot binaries
  - sets up the kernel info page
  - Launches Fiasco.OC kernel
- **Fiasco.OC** initializes and then starts
  - **Sigma0** (by definition, L4's basic resource manager)
  - **Moe** (the root task)

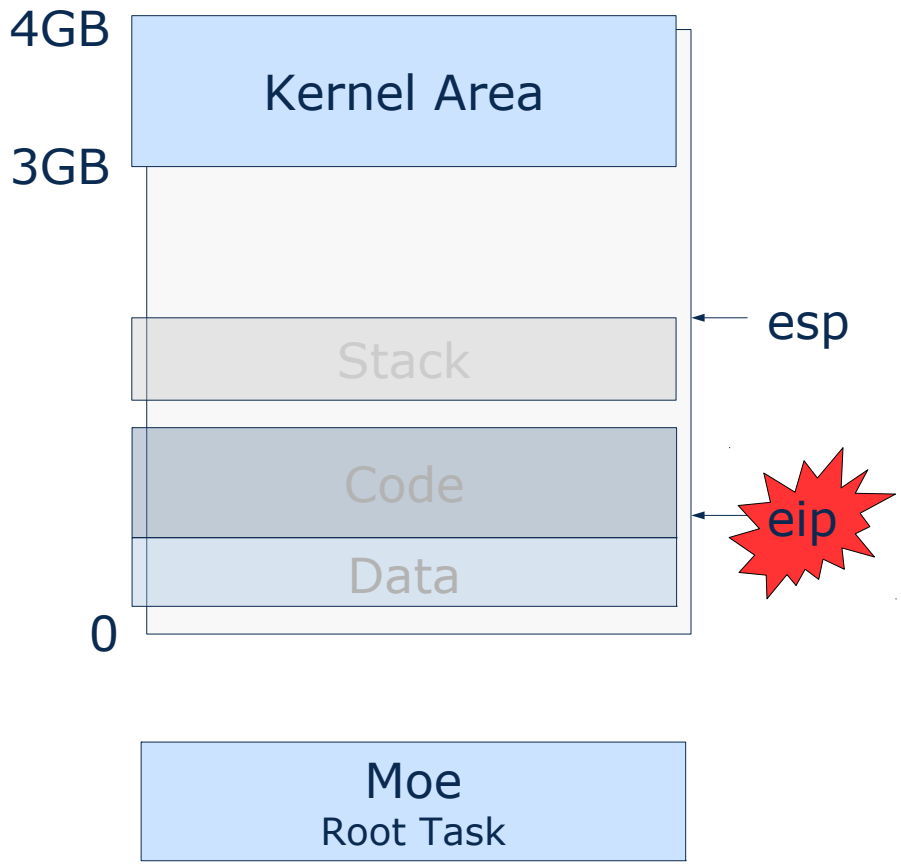
Moe starts a new task



- Thread needs code / data / stack to execute.
- Loader retrieves code and data from the program binary.
- Stack is allocated at runtime through the application's memory allocator.



Moe starts a new task

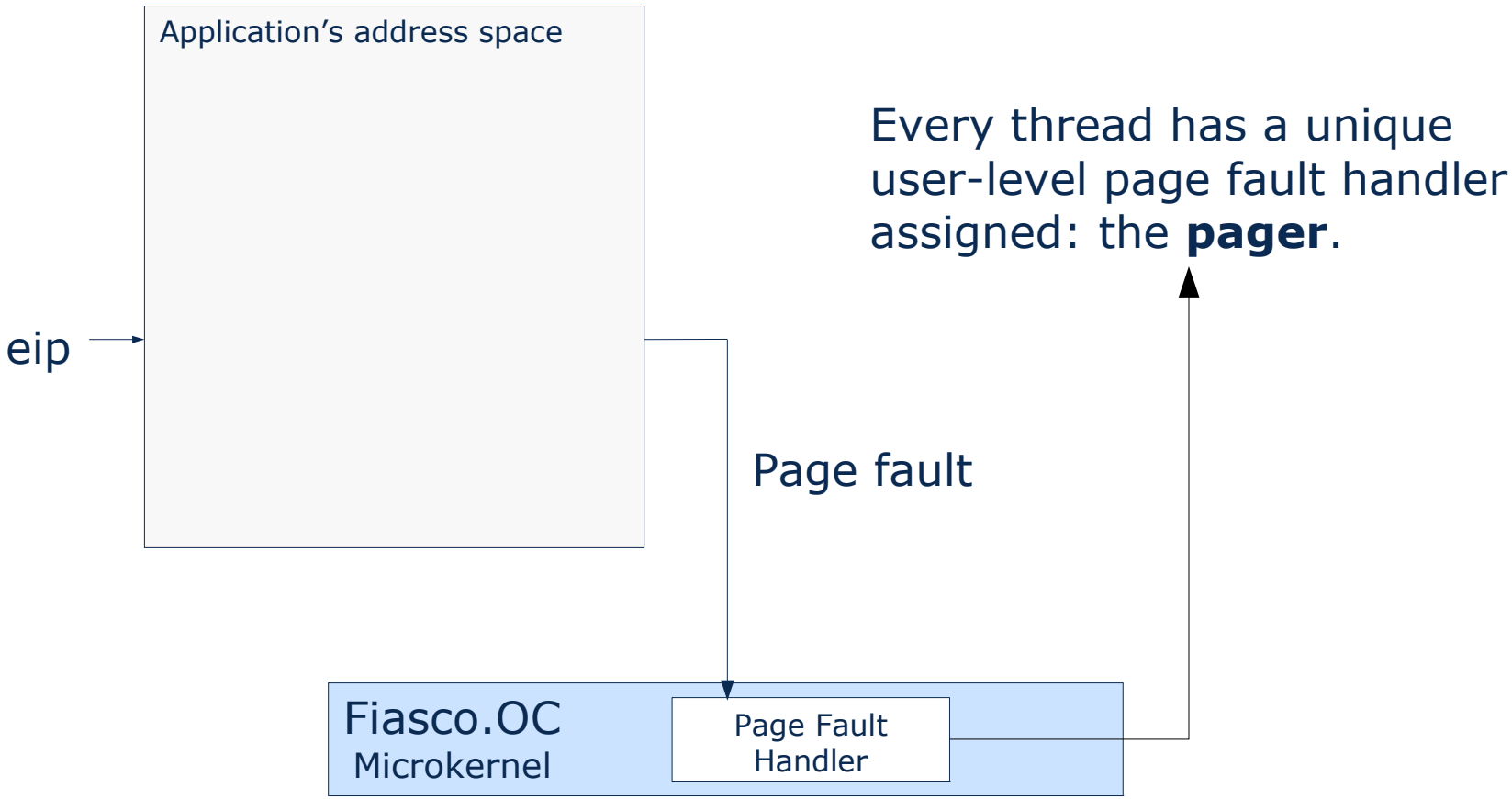


- ELF loader determines binary entry point → EIP
- ELF loader sets up an initial stack (containing argv & env) → ESP
- Loader creates task with initial thread set to EIP / ESP

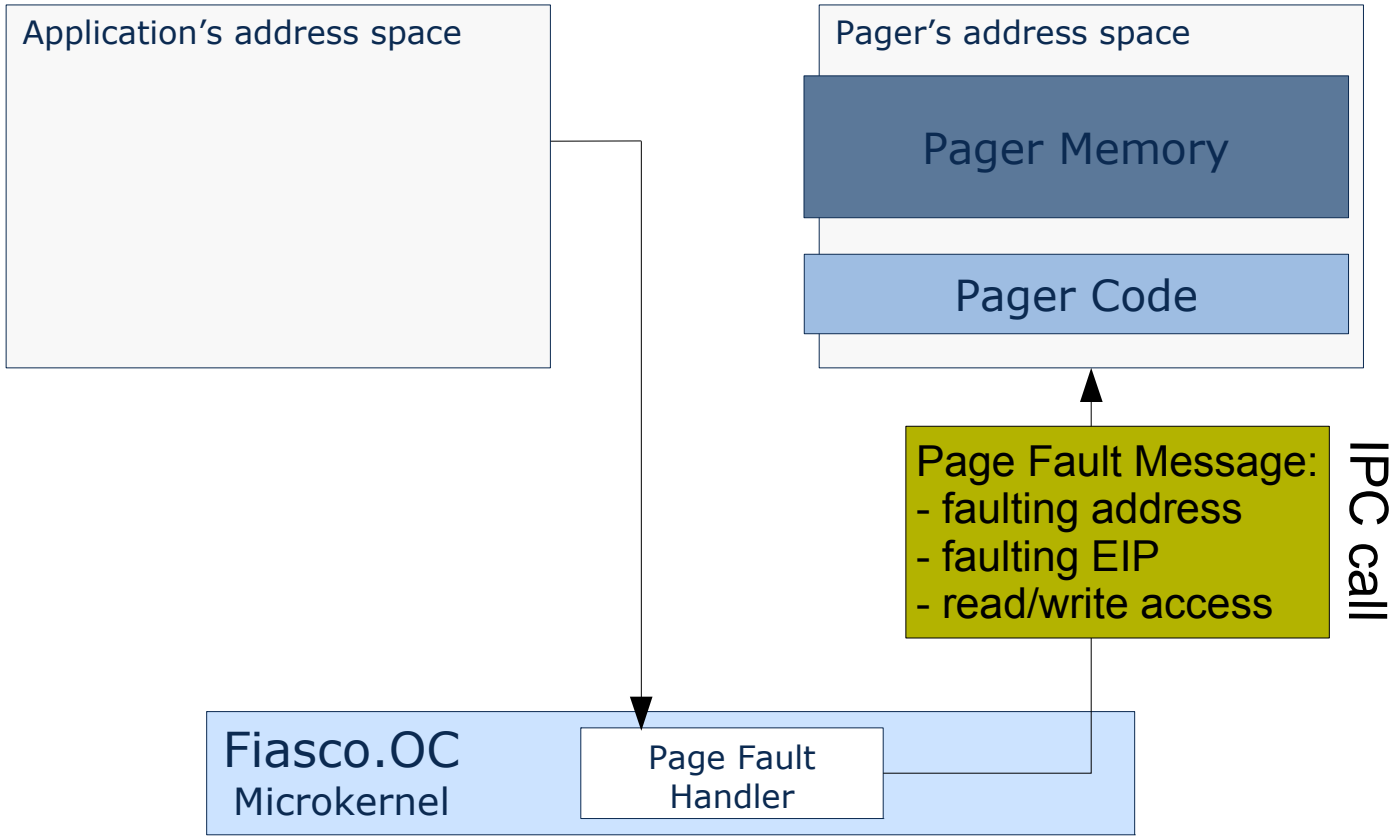
Initial thread raises a page fault

- Initial thread starts
  - → accesses first instruction
  - → HW finds no valid page table entry
  - → page fault!
- Page faults are a CPU exception (#14)
  - → delivered in kernel mode
  - → kernel needs to have set up an IDT entry
  - → IDT entry points to a handler function (page fault handler)
- Page fault handler needs to make a decision on how the HW page table needs to be modified
  - → decision is a policy
    - → should be kept out of the kernel!
  - → PT modifications are privileged operations
    - → needs to be handled in kernel!

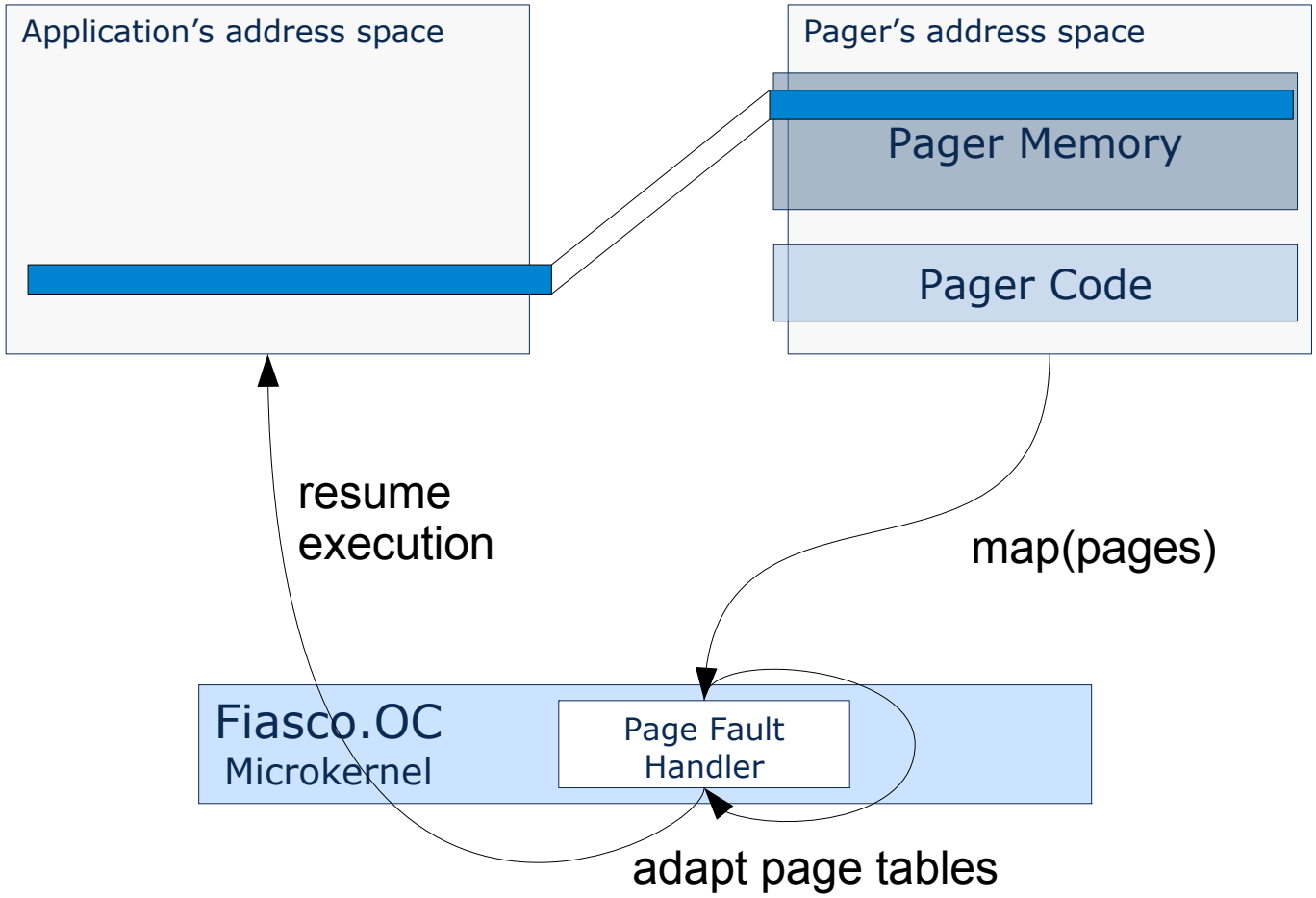
Fiasco.OC: Page Fault Handling



Fiasco.OC: Pager



Fiasco.OC: Memory mapping



Fiasco.OC: Mapping

- Page fault reflection and mapping are implemented using IPC.
  - Pager blocking waits for page fault messages.
  - Range to map from pager to client is described in special data structure: **flexpage.**

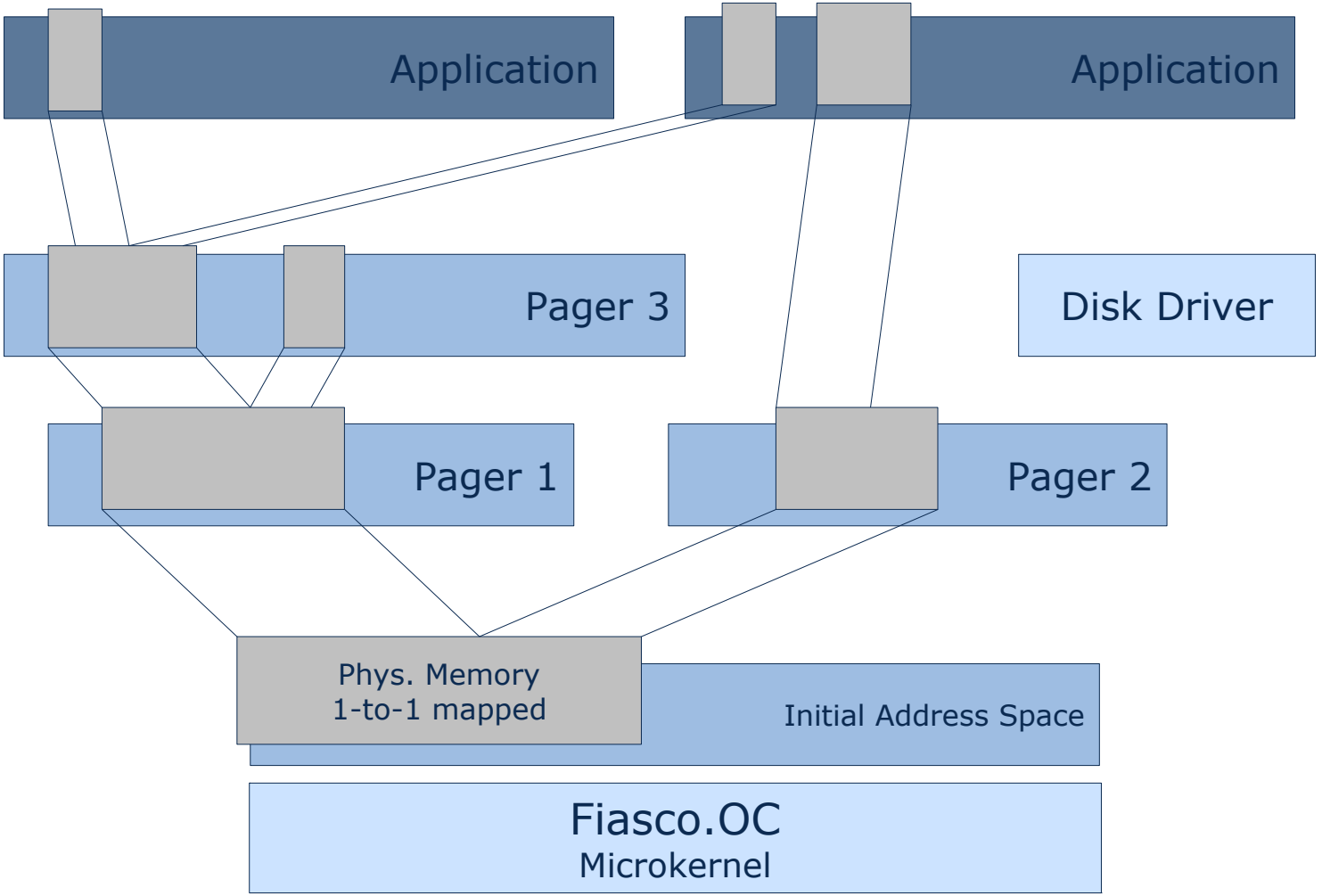
page address$_{(20)}$	size$_{(6)}$	~$_{(2)}$	rights$_{(4)}$

  - The thread's UTCB contains an area that is intended to hold flexpages → buffer registers.

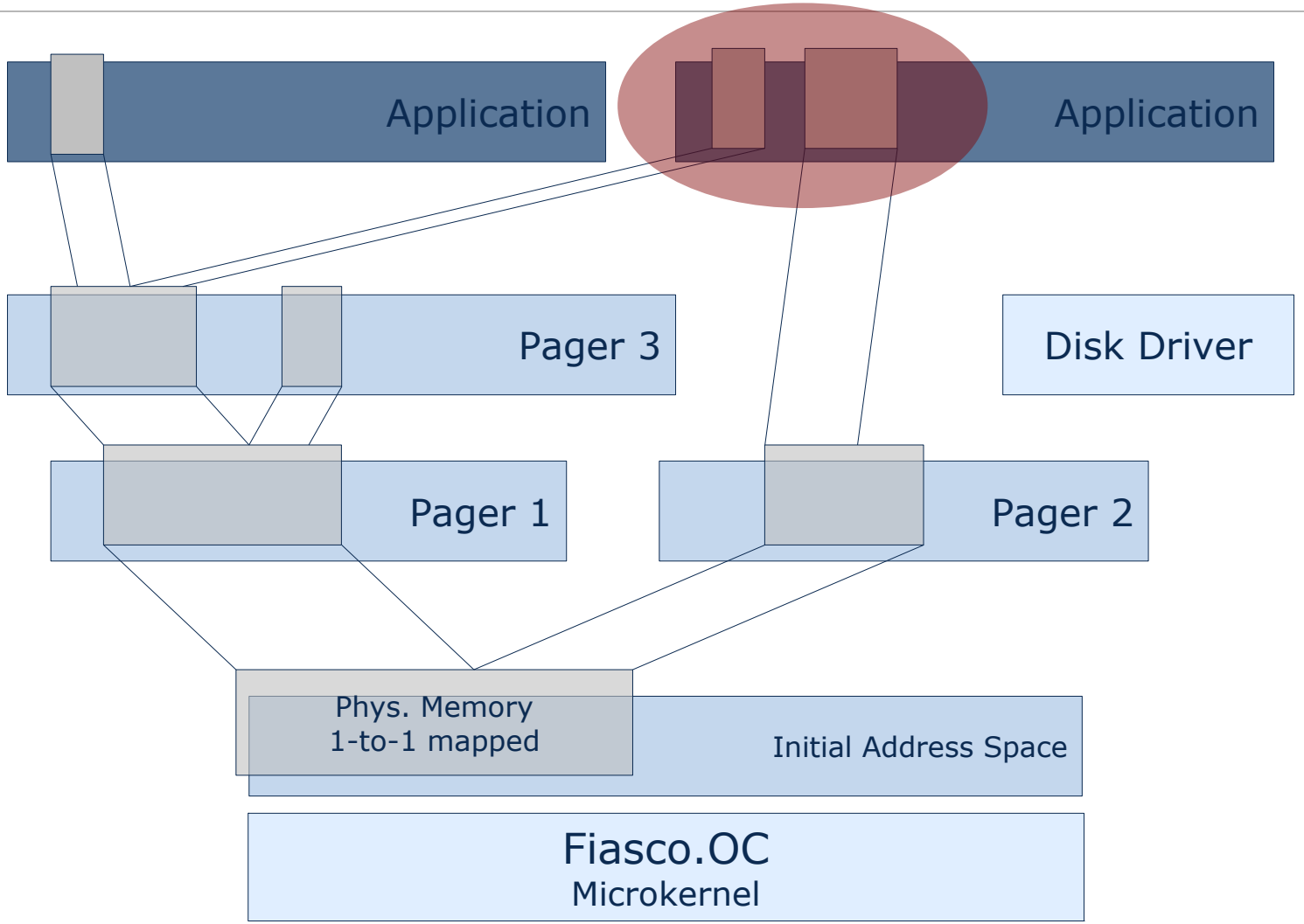
User-Level Pagers

- Chicken vs. egg: who resolves page faults for sigma0, the initial pager?
  - Fiasco.OC initially maps all memory to sigma0, so that it never raises page faults.
- User-level pagers allow implementing complex management policies
  - But basic services might only want simple management.
- Solution: Pagers can be stacked into pager hierarchies.

Pager Hierarchies



Pager Hierarchies: A Problem



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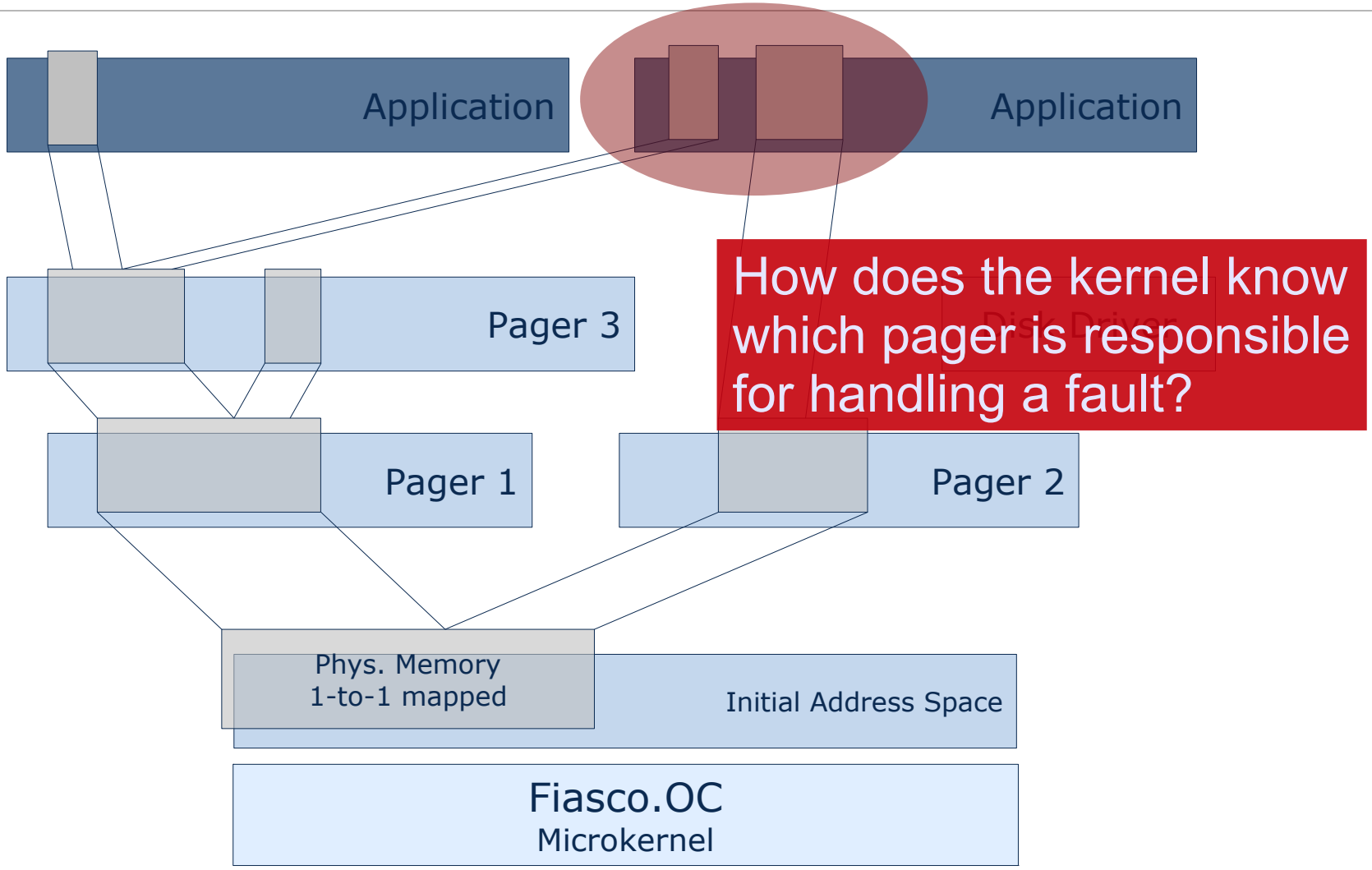

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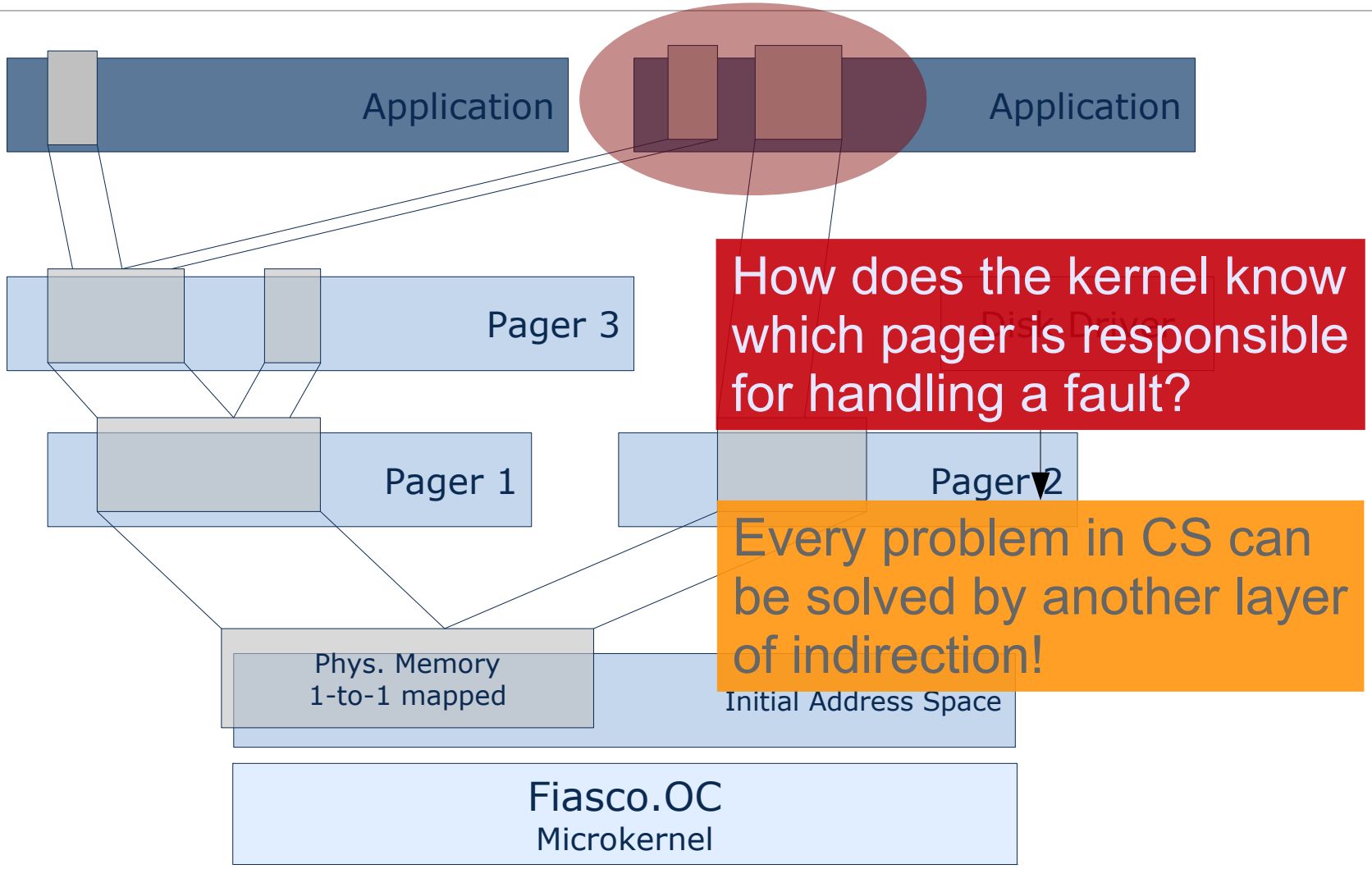

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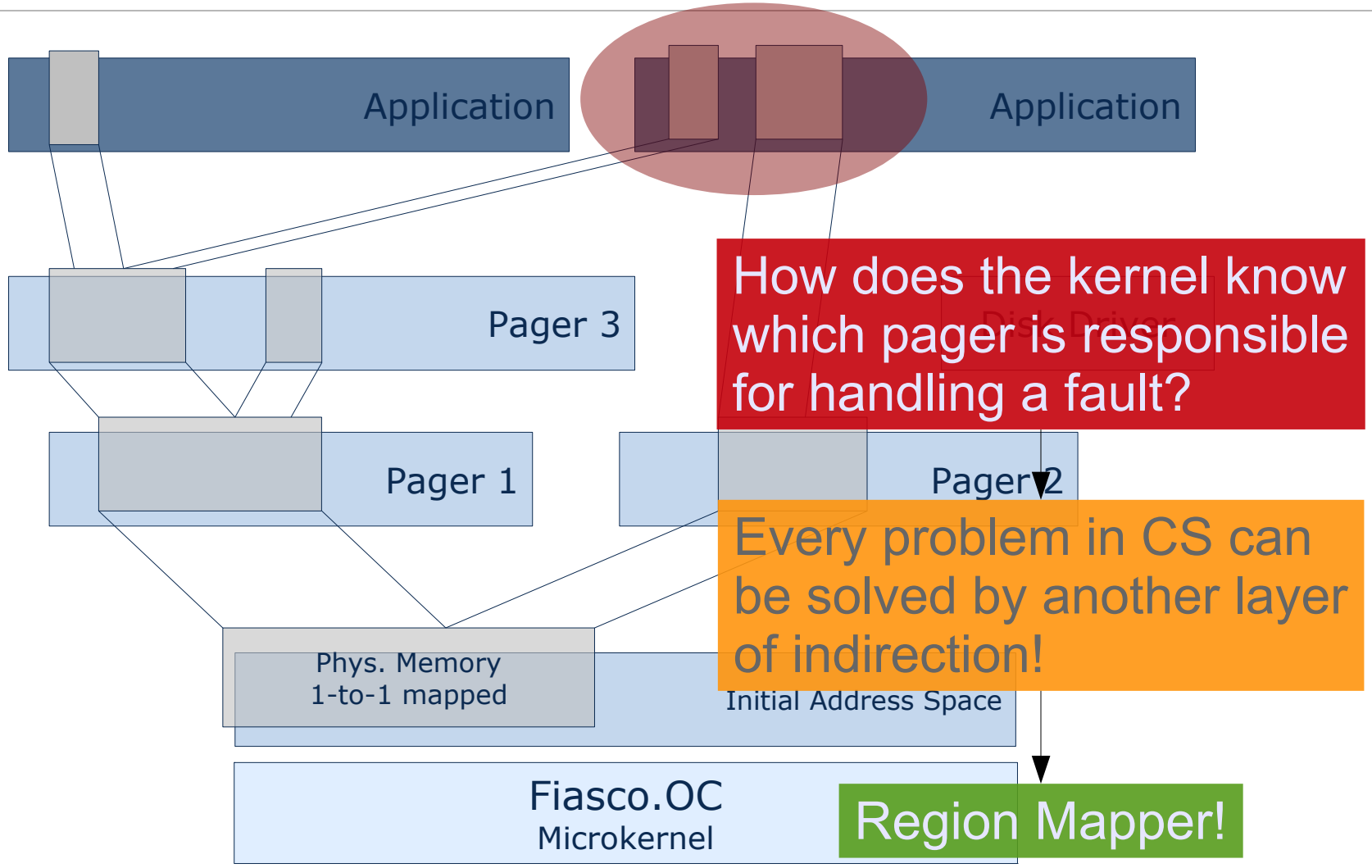
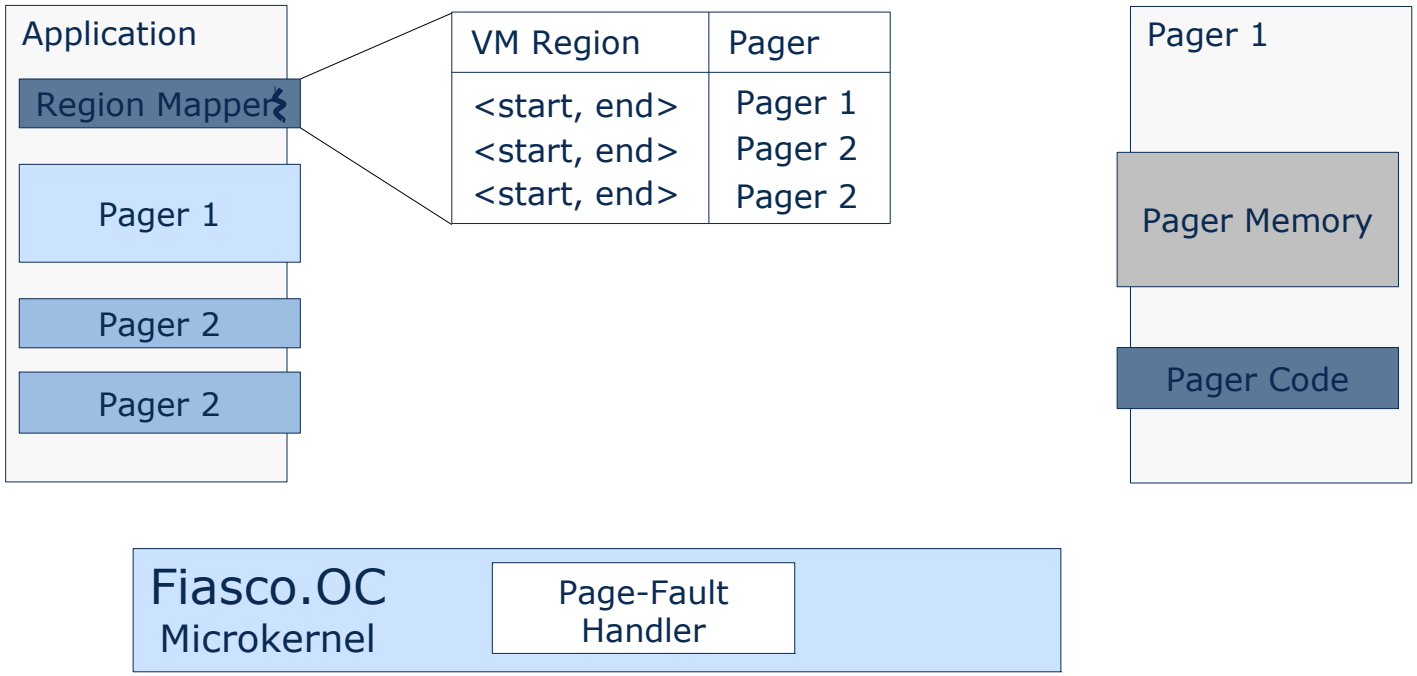


Region Mapper

- Every task has a single pager thread, the **region mapper (RM)**.
  - RM is the first thread within an L4Re task.
  - RM maintains a region map:



Region Mapper and Page Faults

- All threads of a task have the RM assigned as their pager.
- Fiasco.OC redirects all page faults to the RM.
- RM then uses synchronous IPC calls to obtain “real” memory mappings from the external pager responsible for a region.
- This requires a last building block: a generic abstraction for mapping memory.

→ **Dataspaces**

Dataspaces

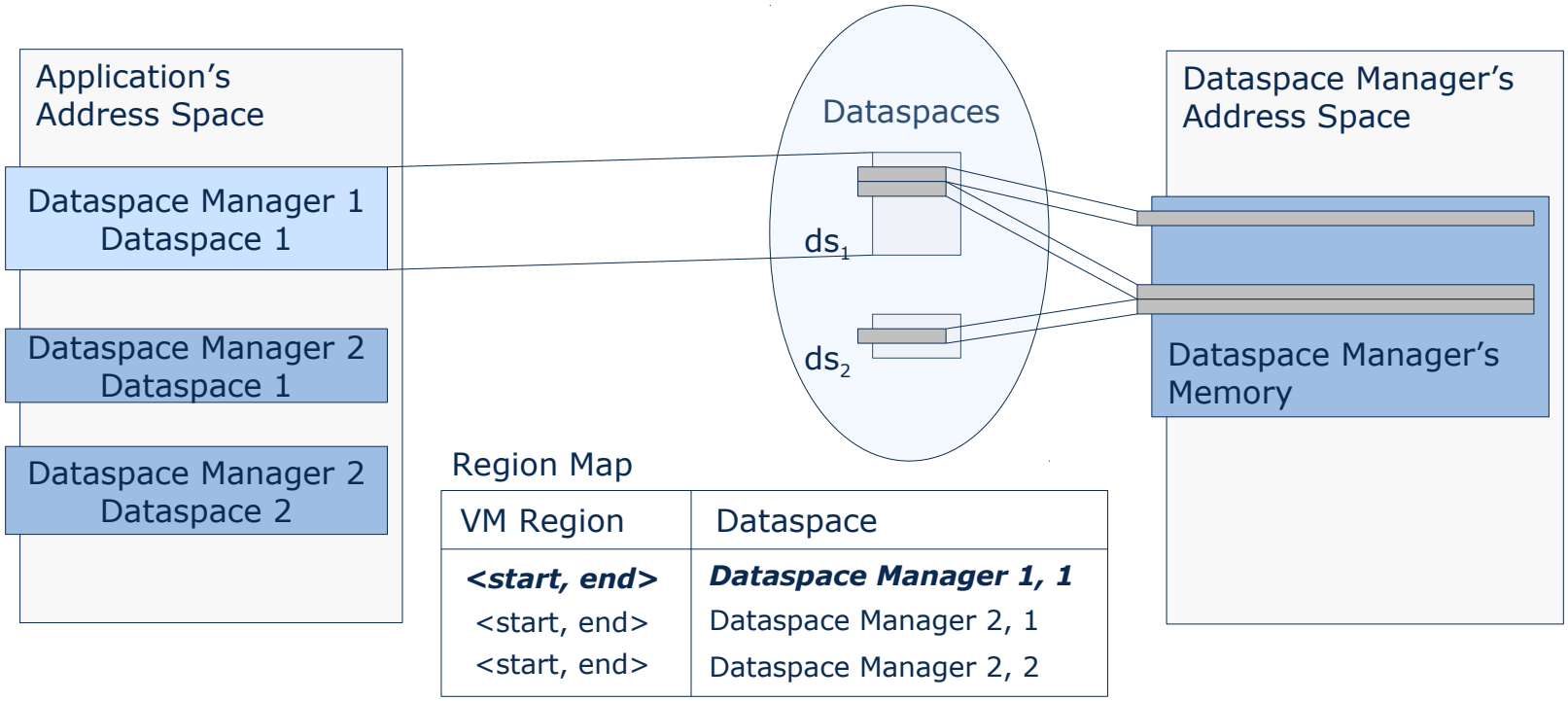
- Address spaces may consist of memory from different sources
  - Binary: code/data sections
  - File system: memory-mapped files
  - Anonymous memory (stacks)
  - Network packets
  - Device MMIO regions

- The RM does not care about the details. It only manages regions consisting of pages.
  → generic memory object: dataspace
  → detailed implementation in dedicated memory manager

L4Re Dataspace Management

- Application obtains a **capability** to a **dataspace**
- Application asks its RM to **attach** this dataspace to virtual memory.
  - RM finds free block in virt. AS that fits the DS.
  - RM returns the address of this block.
- The application now uses the dataspace by simply accessing memory.
- The RM makes sure that all page faults are handled by obtaining mappings from the **dataspace manager**.

Putting things together



Region Map

VM Region	Dataspace
<start, end>	***Dataspace Manager 1, 1***
<start, end>	Dataspace Manager 2, 1
<start, end>	Dataspace Manager 2, 2

Assignment

- Implement an encryption server based on L4Re
  - For an example, see l4/pkg/examples/clntsrv
  - 2 functions: encrypt and decrypt
    - Encryption: client sends plain text and receives encrypted version.
    - Decryption: client sends encrypted text and receives plain text.
  - If you fancy learning about dataspaces:
    - initialize session by letting the client pass a dataspace to the server
    - The dataspace can then be used to exchange plain and encrypted texts

Further Reading

- N. Feske: *"A case study on the cost and benefit of dynamic RPC marshalling for low-level system components"*
  http://os.inf.tu-dresden.de/papers_ps/feske07-dynrpc.pdf
  Using C++ streams for IPC marshalling

- M. Aron: "The SawMill Framework for Virtual Memory Diversity"
  http://cgi.cse.unsw.edu.au/~kevine/pubs/acsac01.pdf
  Generic memory management using dataspaces

- G. Hunt: "Singularity – Rethinking the Software Stack"
  http://research.microsoft.com/apps/pubs/?id=69431
  Some very cool ideas on using safe languages for implementing operating systems.