TECHNISCHE UNIVERSITÄT DRESDEN

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

Microkernel-based Operating Systems —Introduction—

Jan Bierbaum
Carsten Weinhold

Dresden, October 14th 2025

Lecture Goals

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- Provide deeper understanding of OS mechanisms

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- Promote OS research at TU Dresden

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- Illustrate alternative design concepts
- Promote OS research at TU Dresden
- Make you all enthusiastic about OS development in general and microkernels in particular

Administrativia

- Slides: https://tud.de/inf/os → ☰ → Studies → Lectures → MOS

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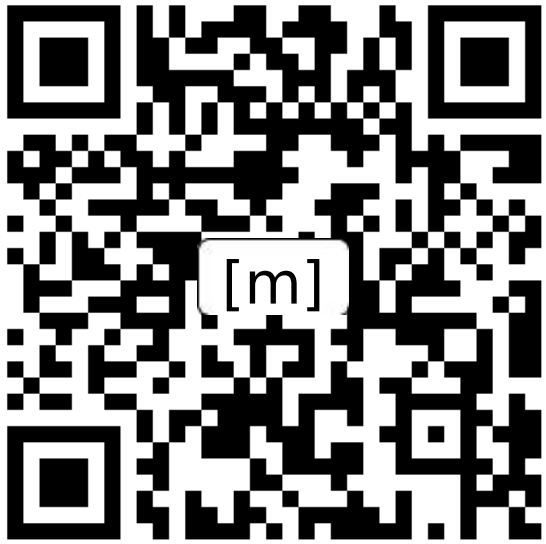

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- (Mostly) hybrid via BBB
- All content relevant for exams

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- Exercises *may* take place online/hybrid
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- Practical exercises
  - Implement aspect of a MOS in the computer pool
  - First one on *Nov 4th*
- Paper reading exercises
  - Read a paper **beforehand**
  - Prepare questions/observations
  - Actively participate in the discussion
  - First one *next week (Oct 21st)*

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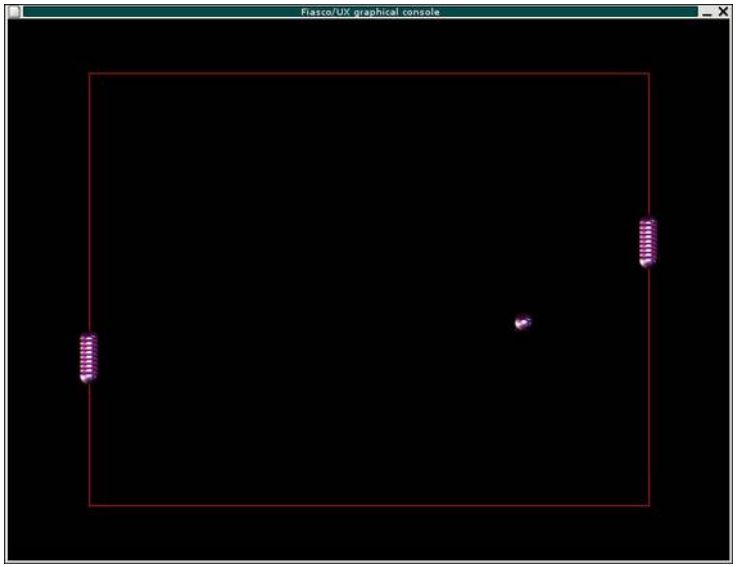

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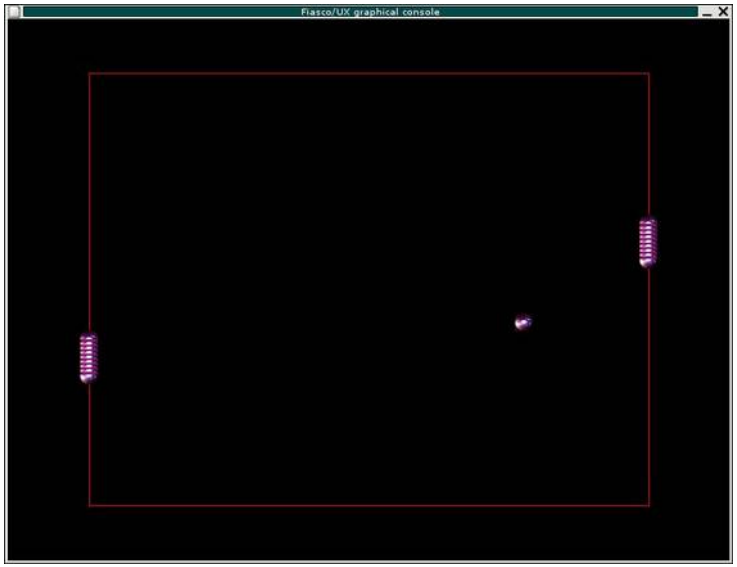
- Build several components of an MOS
- Mainly programming on your own *(optional)*
- Coordination via dedicated mailing list → website
- First meeting *today* after the lecture



Monoliths vs. Microkernels

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  - Hardware (CPU, memory, storage, network, …)
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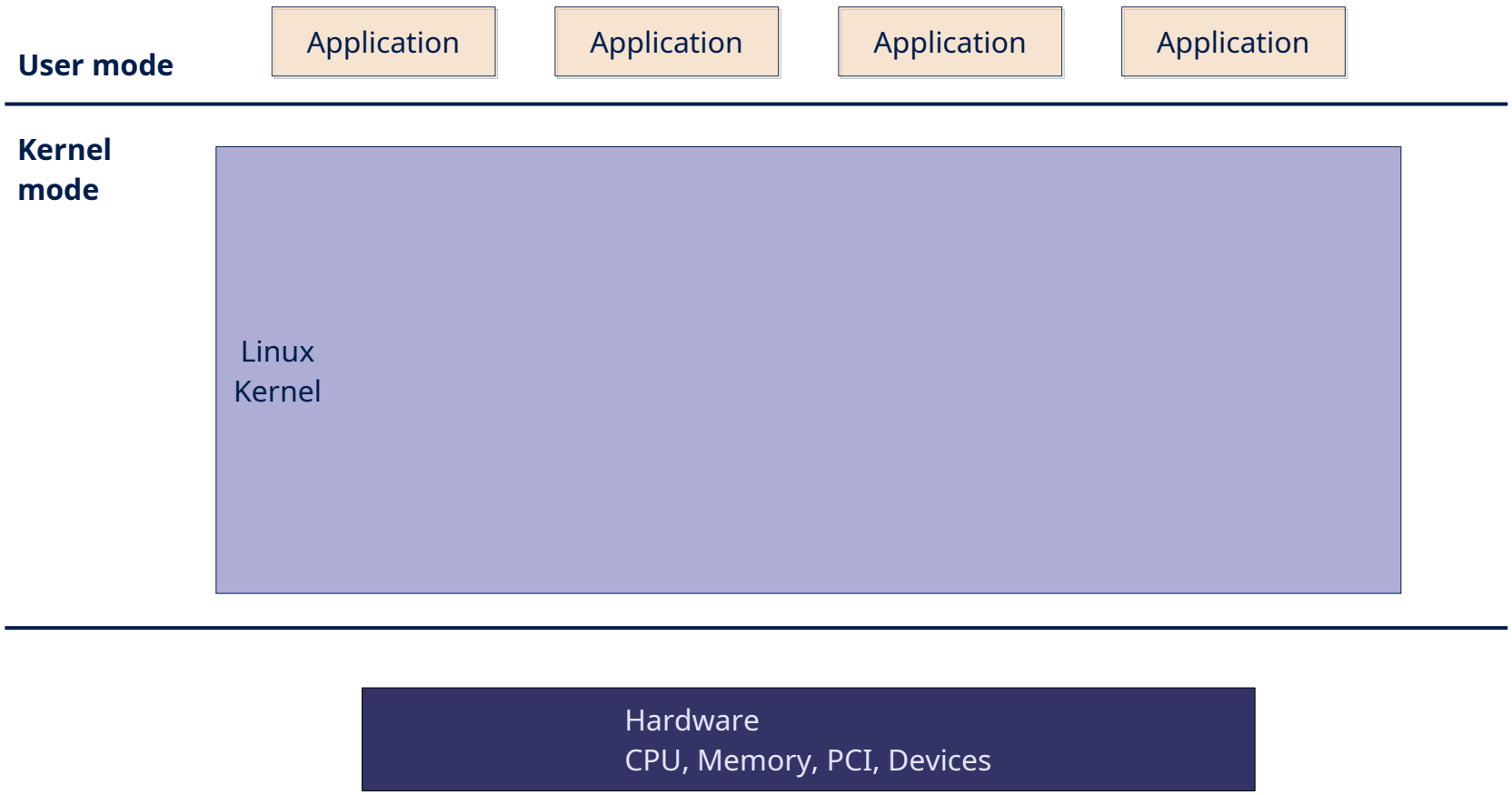
  - x86: ring 0 vs. ring 3
  - Device drivers
- Provide separation and means for collaboration
  - Isolate users / processes from each other
  - Allow cooperation if needed (e.g., sending messages between processes)

Monolithic Kernels: Linux



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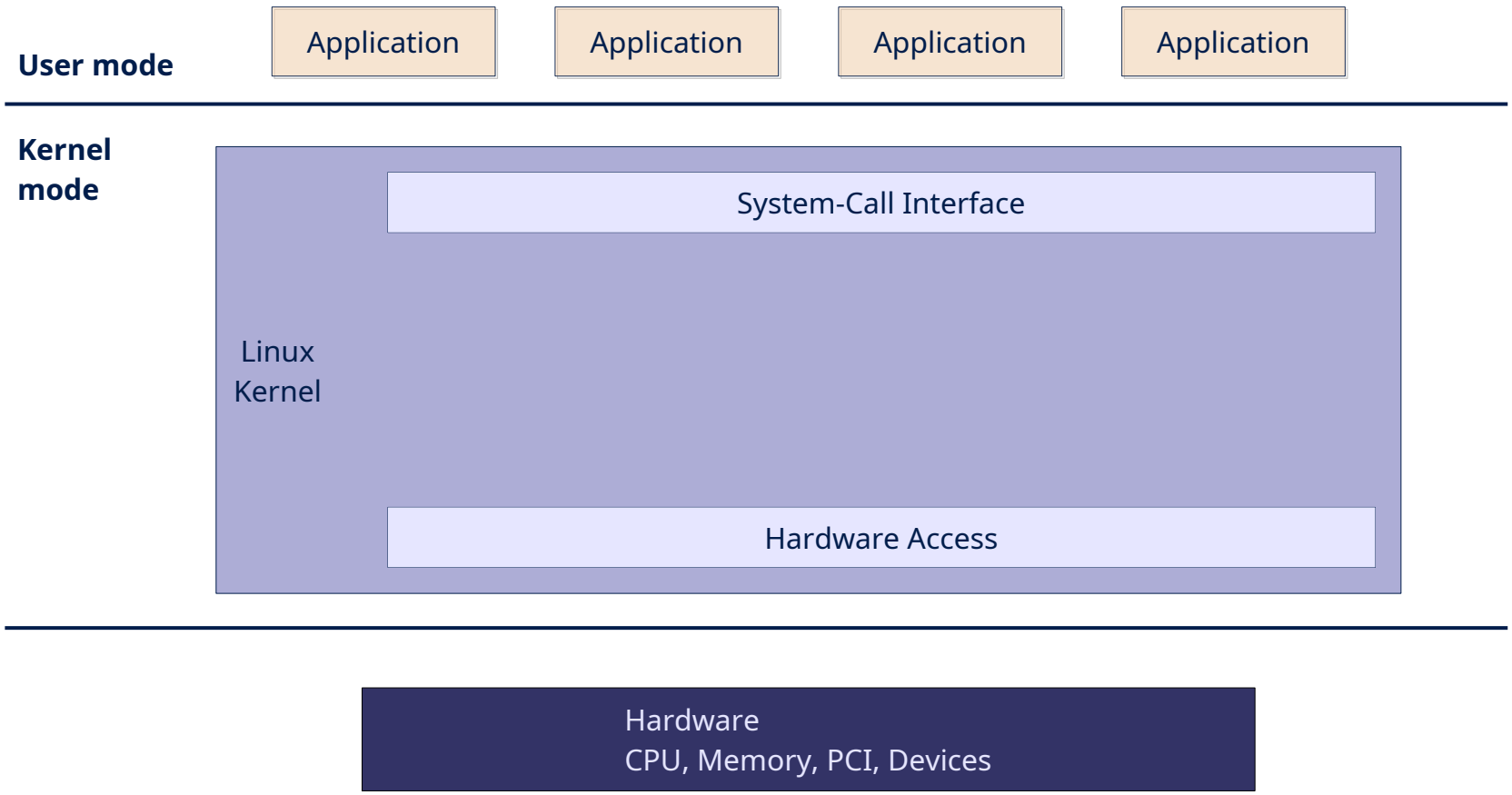

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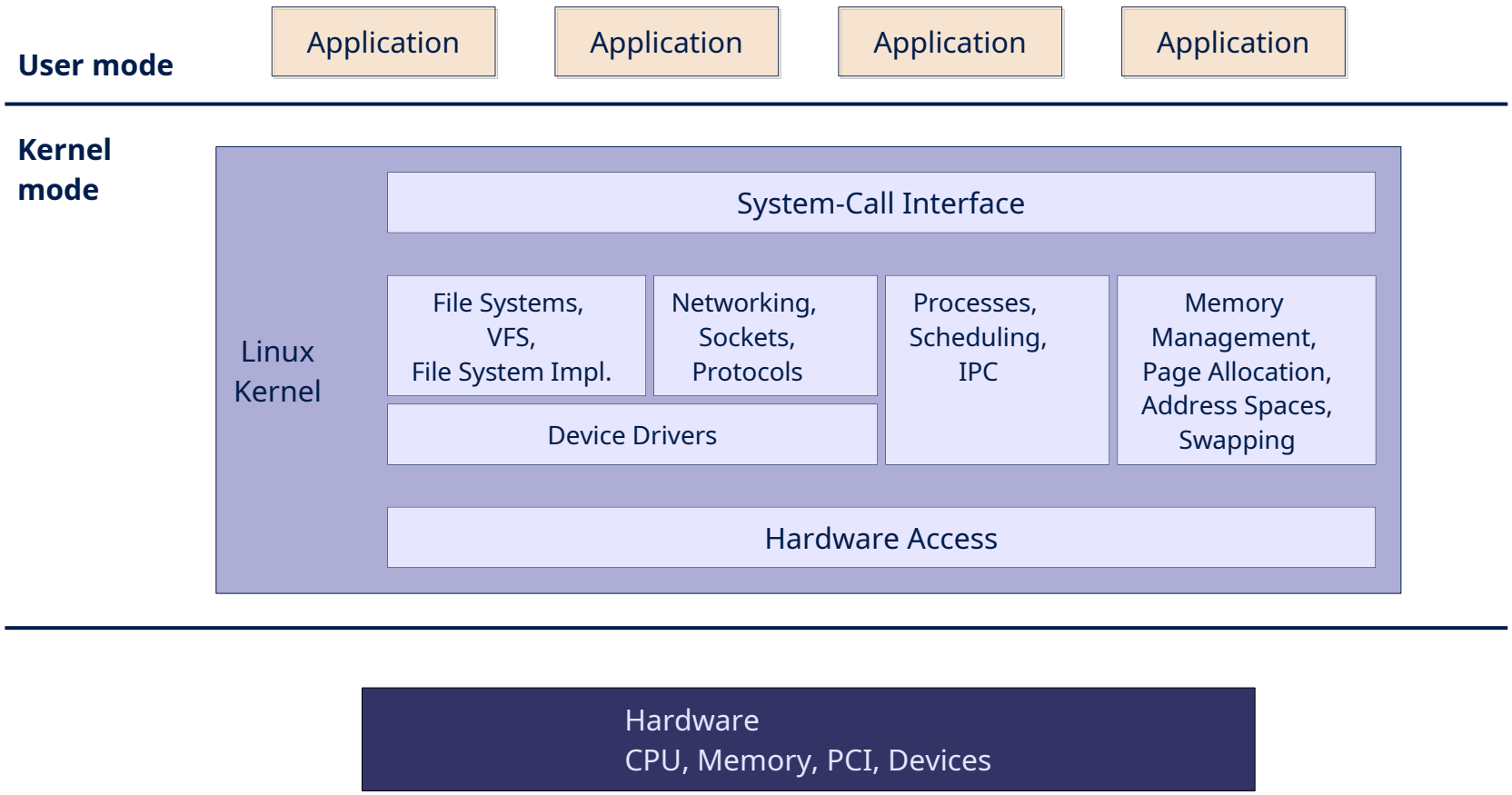

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  - 75% of today's OS kernels are drivers
- Software-level issues
  - Complexity is hard to manage
  - Custom OS for hardware with scarce resources?

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  - Less error prone (less code → fewer errors)
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- System services in user-level *servers*
  - Flexible and extensible
- Protection between individual components
  - More resilient: crashing component does not (necessarily…) crash the whole system
  - More secure: inter-component protection

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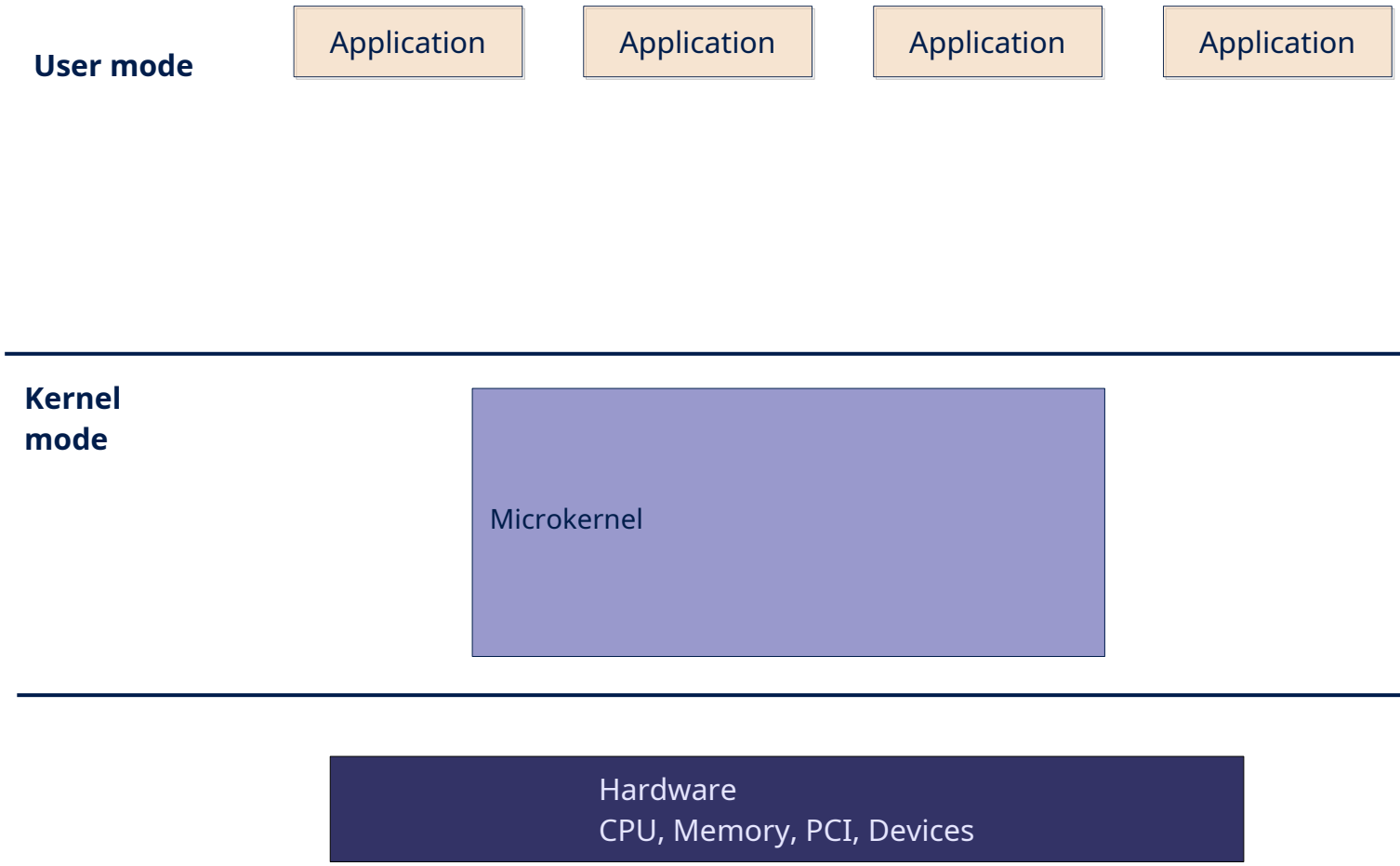

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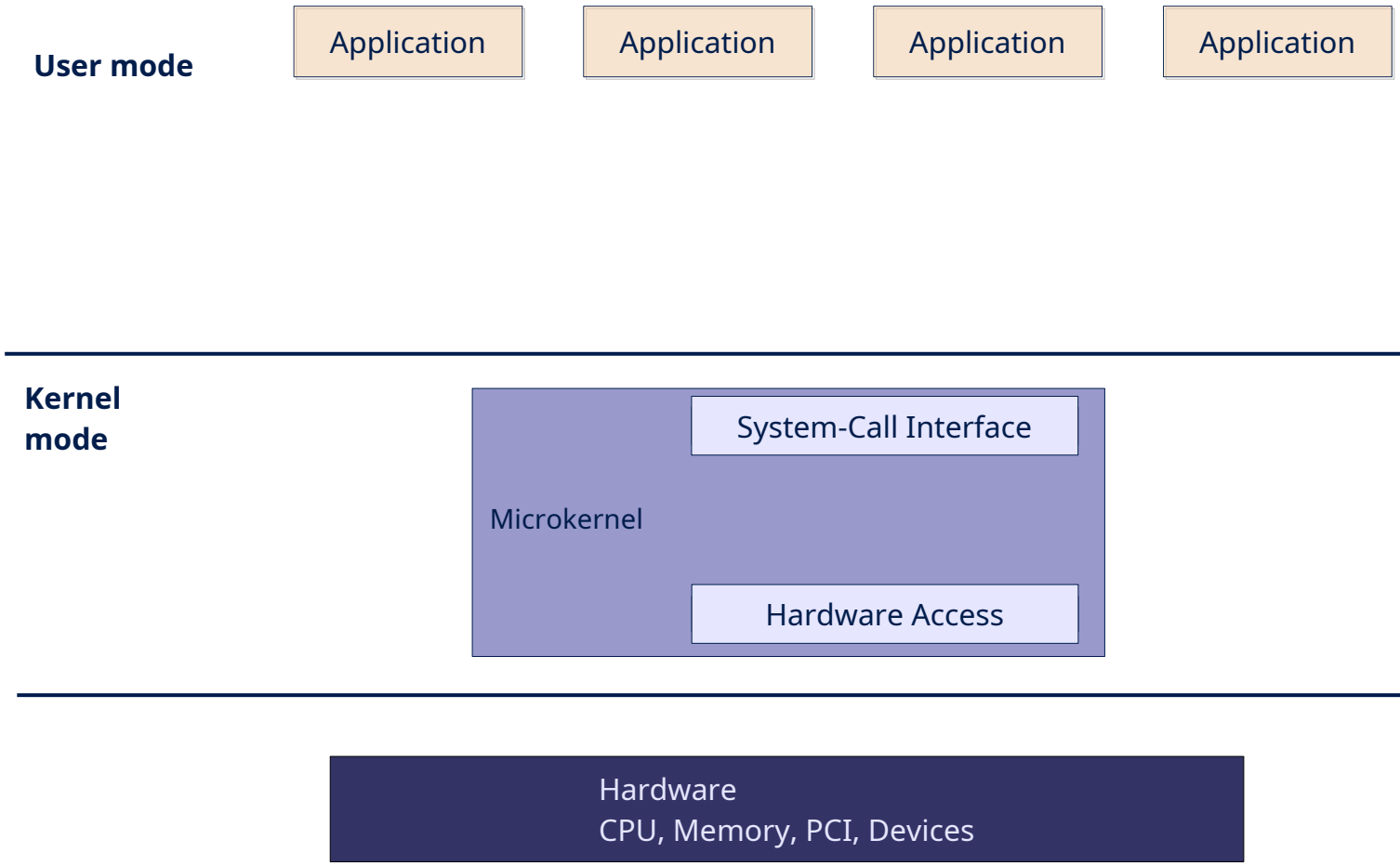

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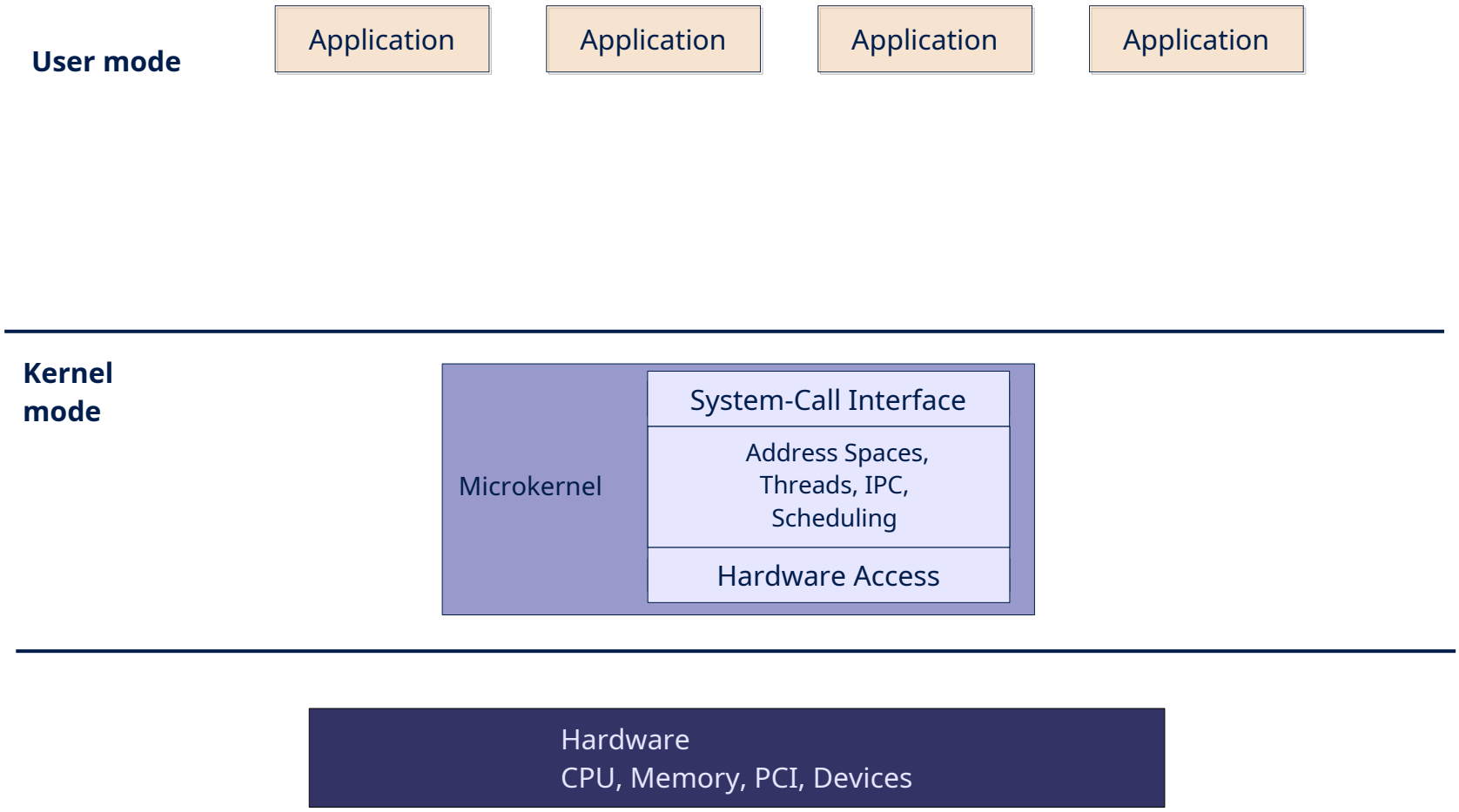

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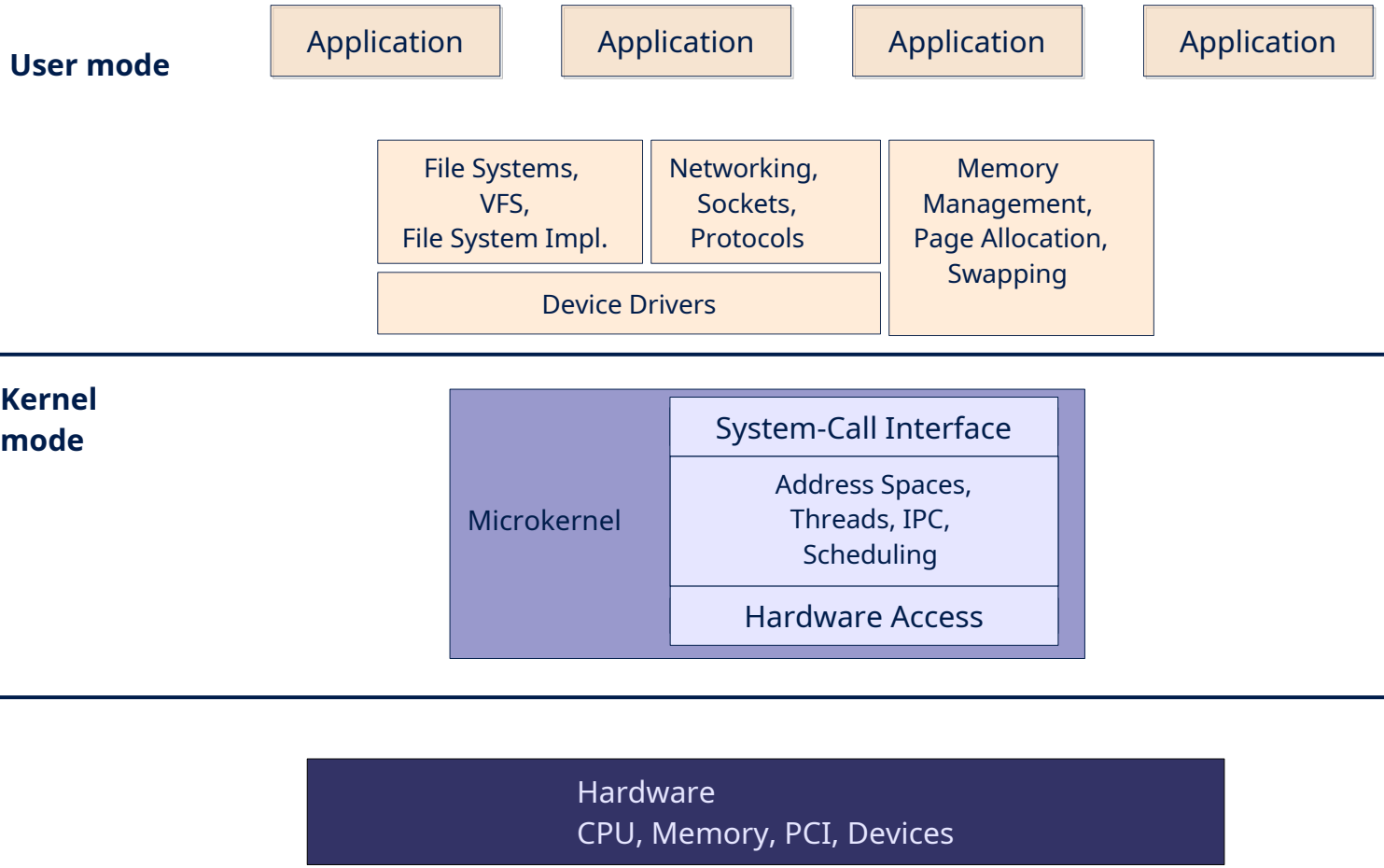

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- OS personalities
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  - Servers may be configured to suit the target system (small embedded systems, desktop PCs, SMP systems, ...)
  - Remove unnecessary servers
- Enforce reasonable system design
  - Well-defined interfaces between components
  - Access to components only via these interfaces
  - Improved maintainability

Mach: A 1st-generation Microkernel

- Developed at CMU, 1985 – 1994
  - Rick Rashid (former head of MS Research)
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Mach: Overview

- Simple, extensible *communication kernel*
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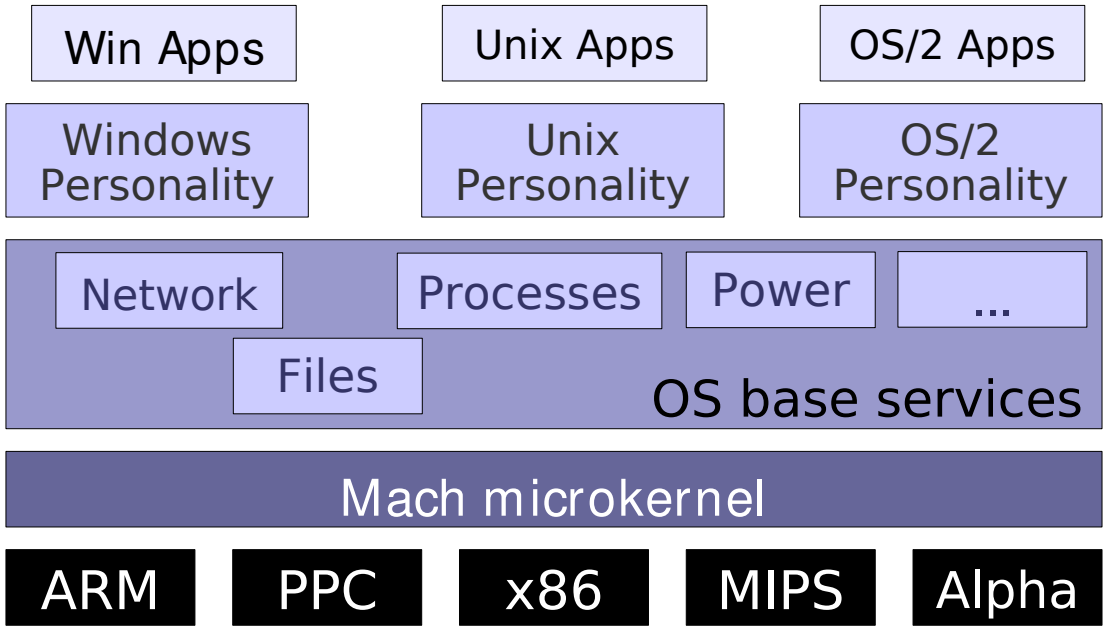
- Shortcomings
  - Performance
  - Drivers in the kernel

Case Study: IBM Workplace OS

- Main goals:
  - Multiple OS personalities
  - Support for multiple HW architectures



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- Conclusion: Microkernel worked, but system atop the microkernel did not

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- Customisability
  - Tailored memory management / scheduling / ... algorithms
  - Adaptable to embedded / real-time / secure / ... systems

Challenges

- We need fast and efficient kernels
  - Covered in the “Microkernel Construction” lecture in the summer term

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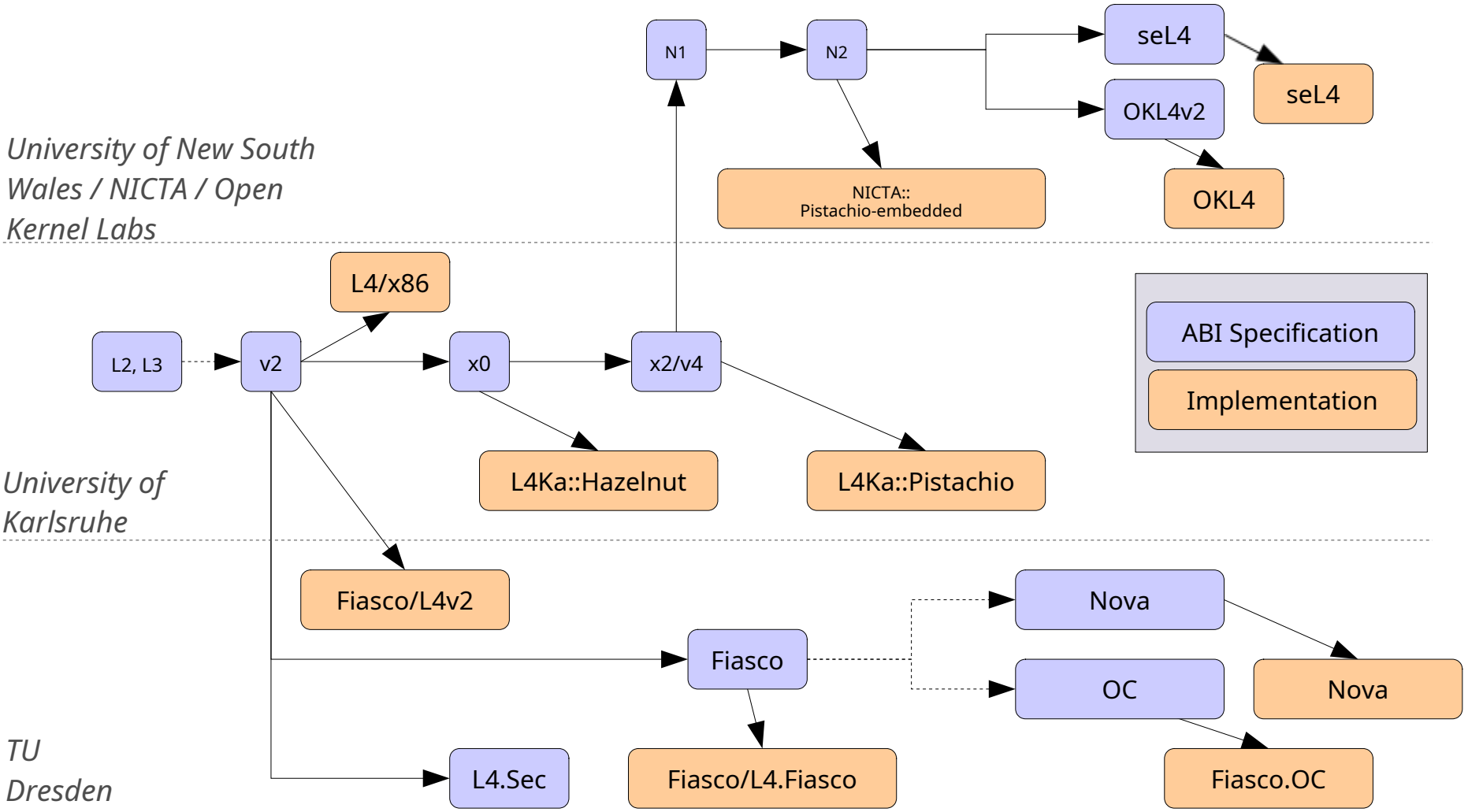
- We need fast and efficient OS services
  - Memory and resource management
  - Synchronisation
  - Device Drivers
  - File systems
  - Communication interfaces

  → Subject of this lecture

Who's Out There?

- Minix @ FU Amsterdam (Andrew Tanenbaum)
- Singularity @ MS Research
- EROS/CoyotOS @ Johns Hopkins University
- The L4 Microkernel Family
  - Originally developed by Jochen Liedtke at IBM and GMD
  - 2nd-generation microkernel
  - Several kernel ABI versions

The L4 Family Tree



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  - Abstractions
    - Threads
    - Address spaces (tasks)
  - Mechanisms
    - Communication
    - Resource mapping
    - (Scheduling)

Taking a closer look at L4

Case study: **L4/Fiasco.OC**

- “Everything is an object”

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  - Task Address space
  - Thread Activities, scheduling
  - IPC Gate Communication, resource mapping
  - IRQ Communication
  - Factory Create other objects, enforce quotas
- One system call: **`invoke_object()`**
  - Parameters passed in UTCB
  - Types of parameters depend on type of object

L4/Fiasco.OC: Kernel Objects

- Kernel-provided objects
  - Threads
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- Kernel-provided objects
  - Threads
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  - …
- Generic communication object: IPC gate
  - Send message from sender to receiver
  - Allows to implement *new objects* in *user-level* applications

L4/Fiasco.OC: User-Level Objects

- Build everything above kernel using user-level objects that provide a service
  - Networking stack
  - File system
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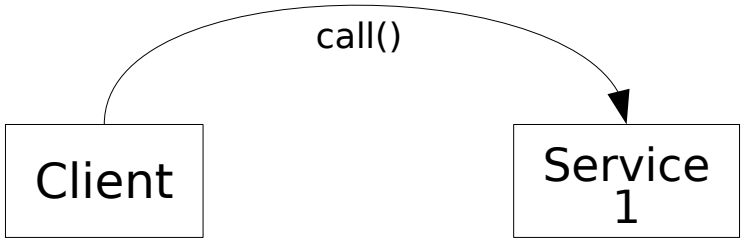

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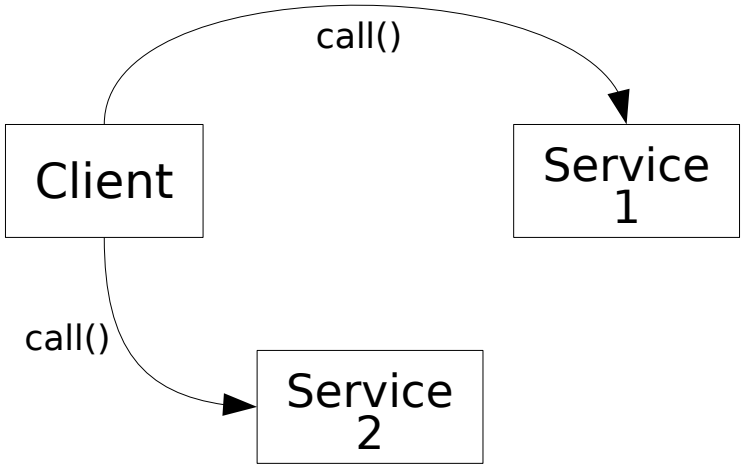

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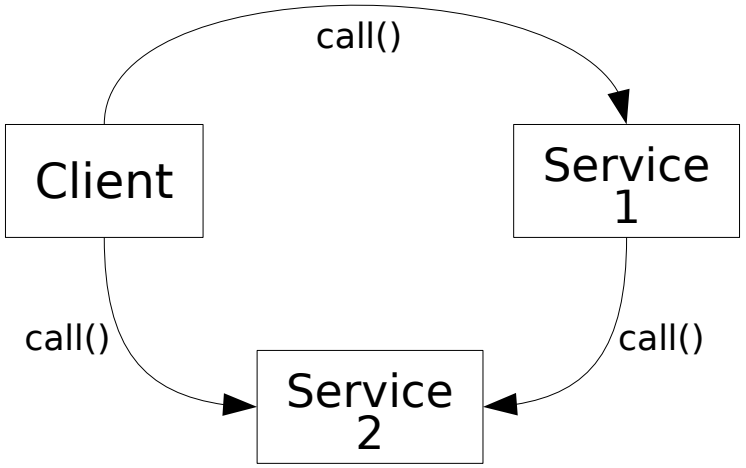

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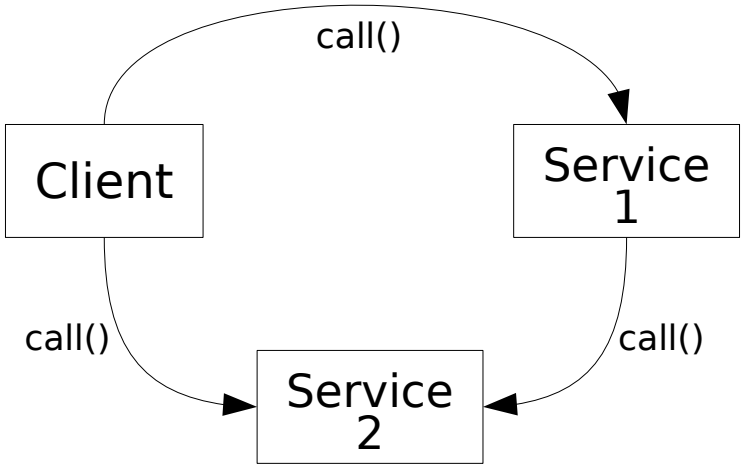

- Kernel provides
  - Object creation/management
  - Object interaction: Inter-Process Communication (IPC)

L4/Fiasco.OC: How to Use an Object?

- To call an object, we need an address:
  - Telephone number
  - Postal address
  - IP address
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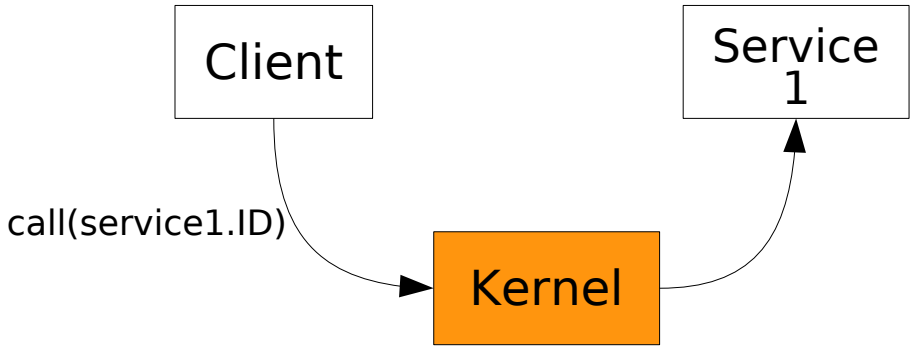

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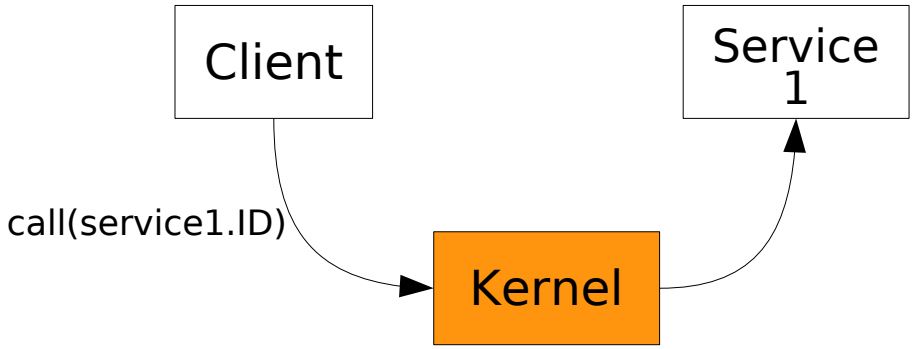

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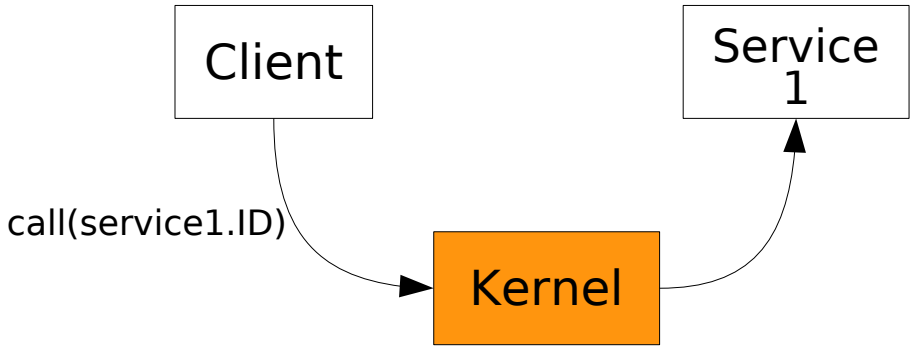

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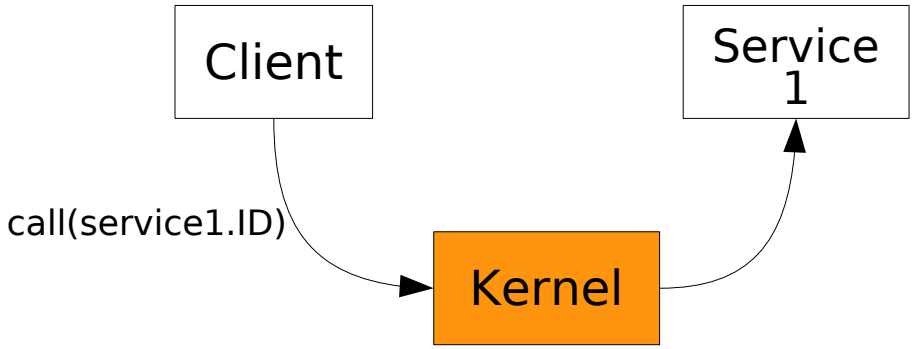

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- ID is wrong? Kernel returns ENOTEXIST
- But not so fast! This scheme is insecure:
  - Client could simply "guess" IDs brute-force
  - (Non-)Existence can be used as a covert channel

L4/Fiasco.OC: Capabilities

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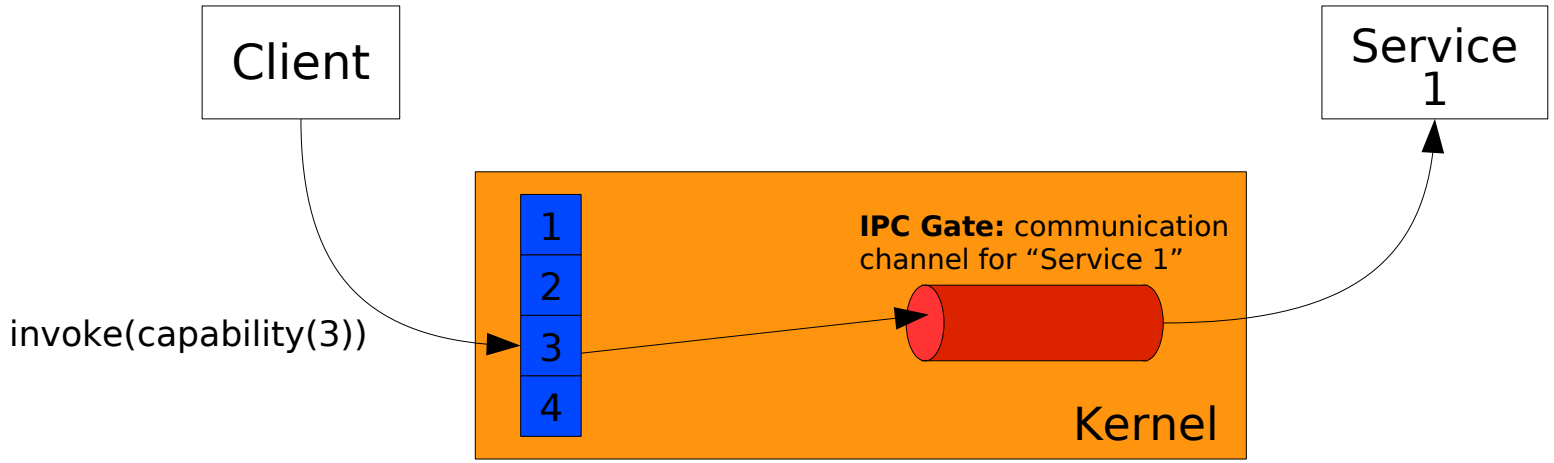
  - inconvenient (programmer needs to know about partitioning in advance)
- Solution in Fiasco.OC
  - Task-local *capability space* as indirection
  - *Object capability* required to invoke object
  - Per-task name space
    - Maps names to object capabilities
    - Configured by task's creator

L4/Fiasco.OC: Object Capabilities

- Capability:
  - Reference to an object
  - Protected by the kernel
    - Kernel knows all capability–object mappings
    - Managed as a per-process capability table
    - User processes only use indices into this table



L4/Fiasco.OC: Communication

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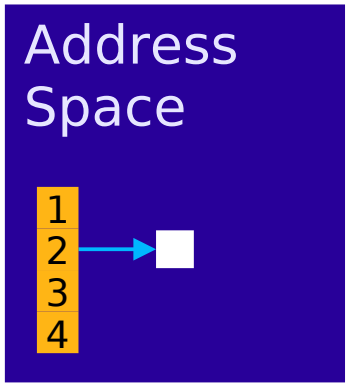
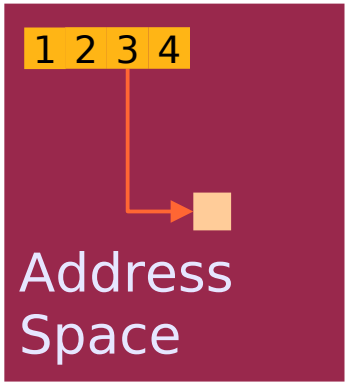
  - Kernel copies message to receiver thread's UTCB
  - Both continue, knowing that message has been transferred/received

Capabilities = Local Names





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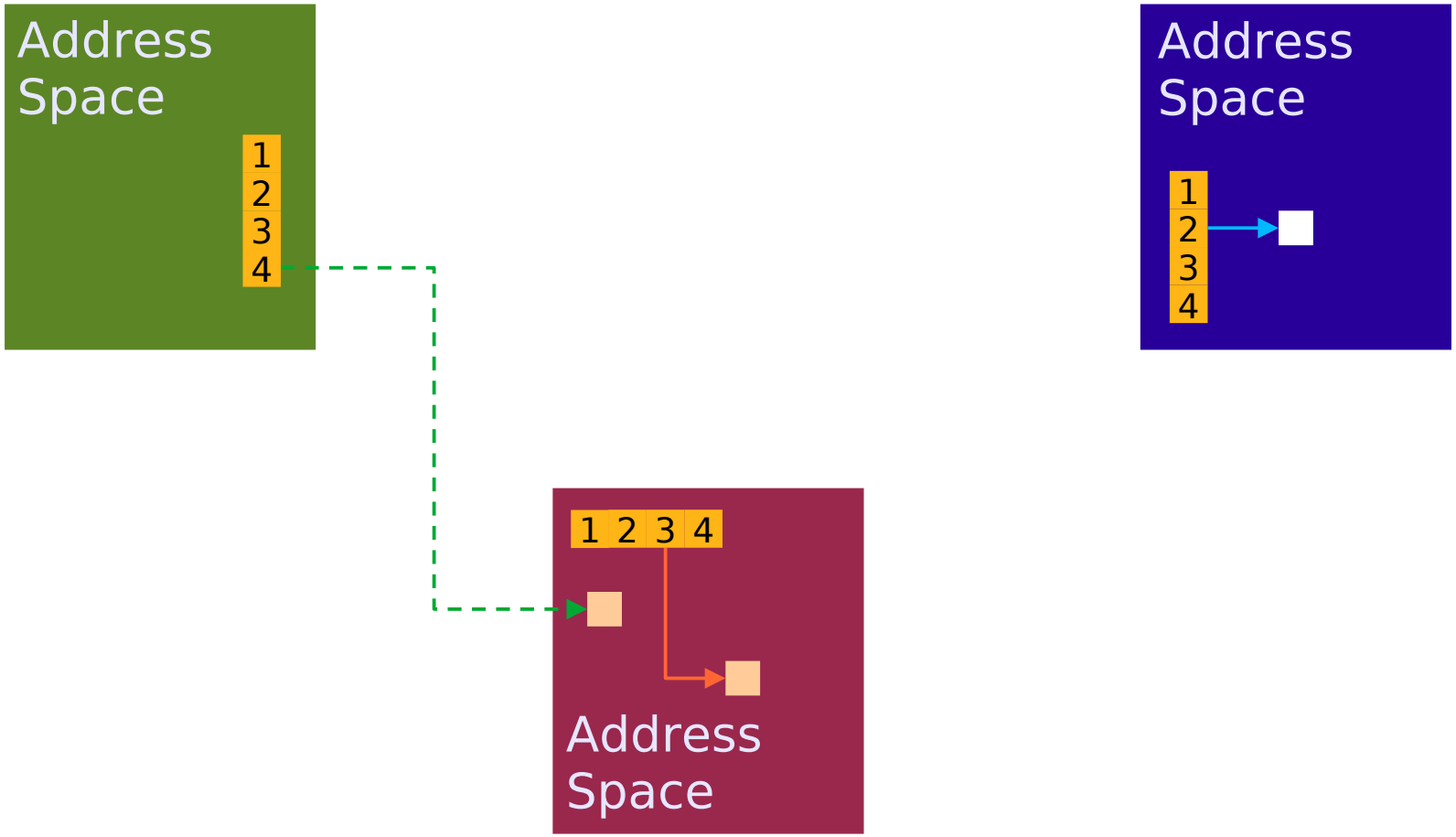

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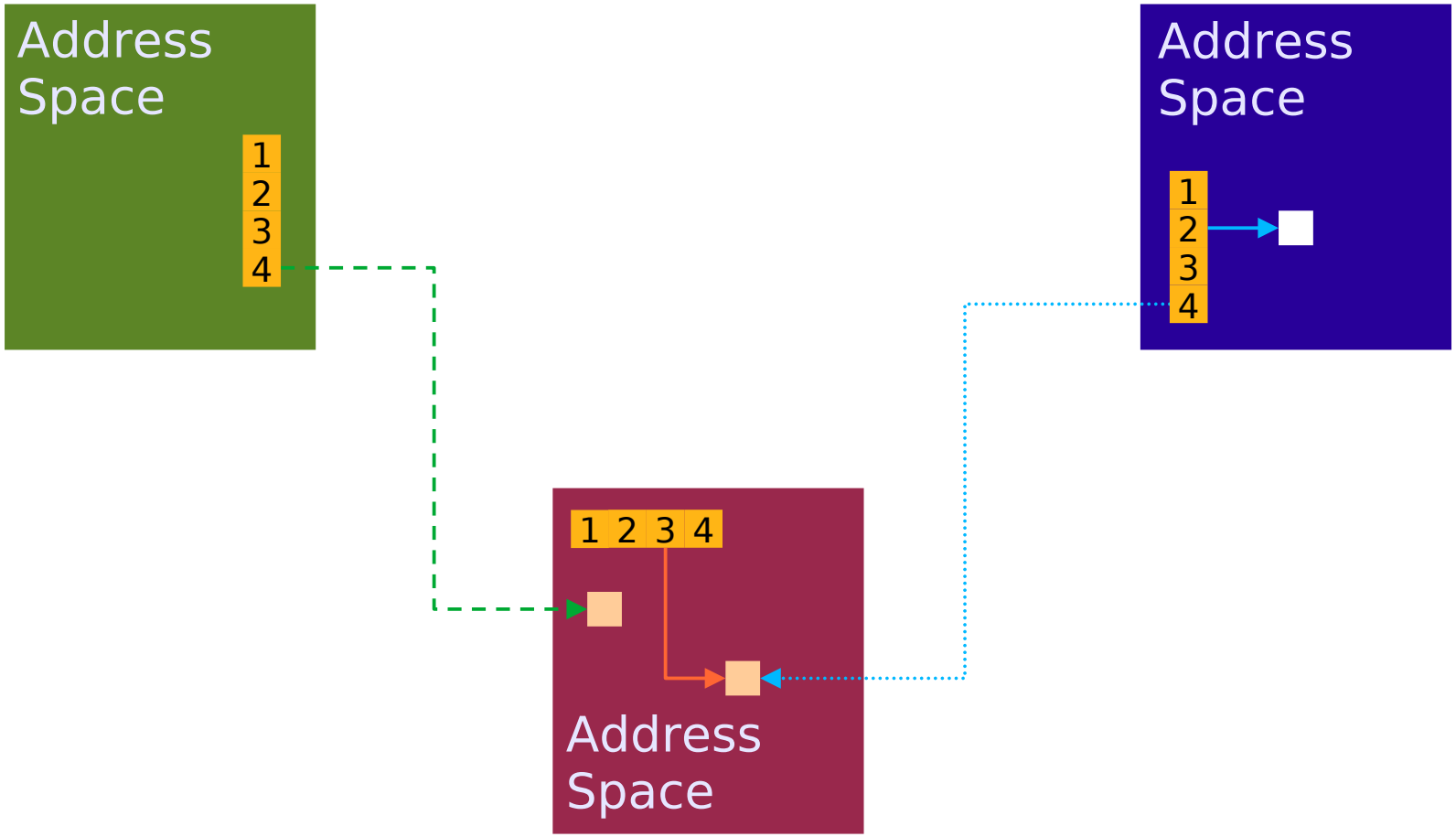

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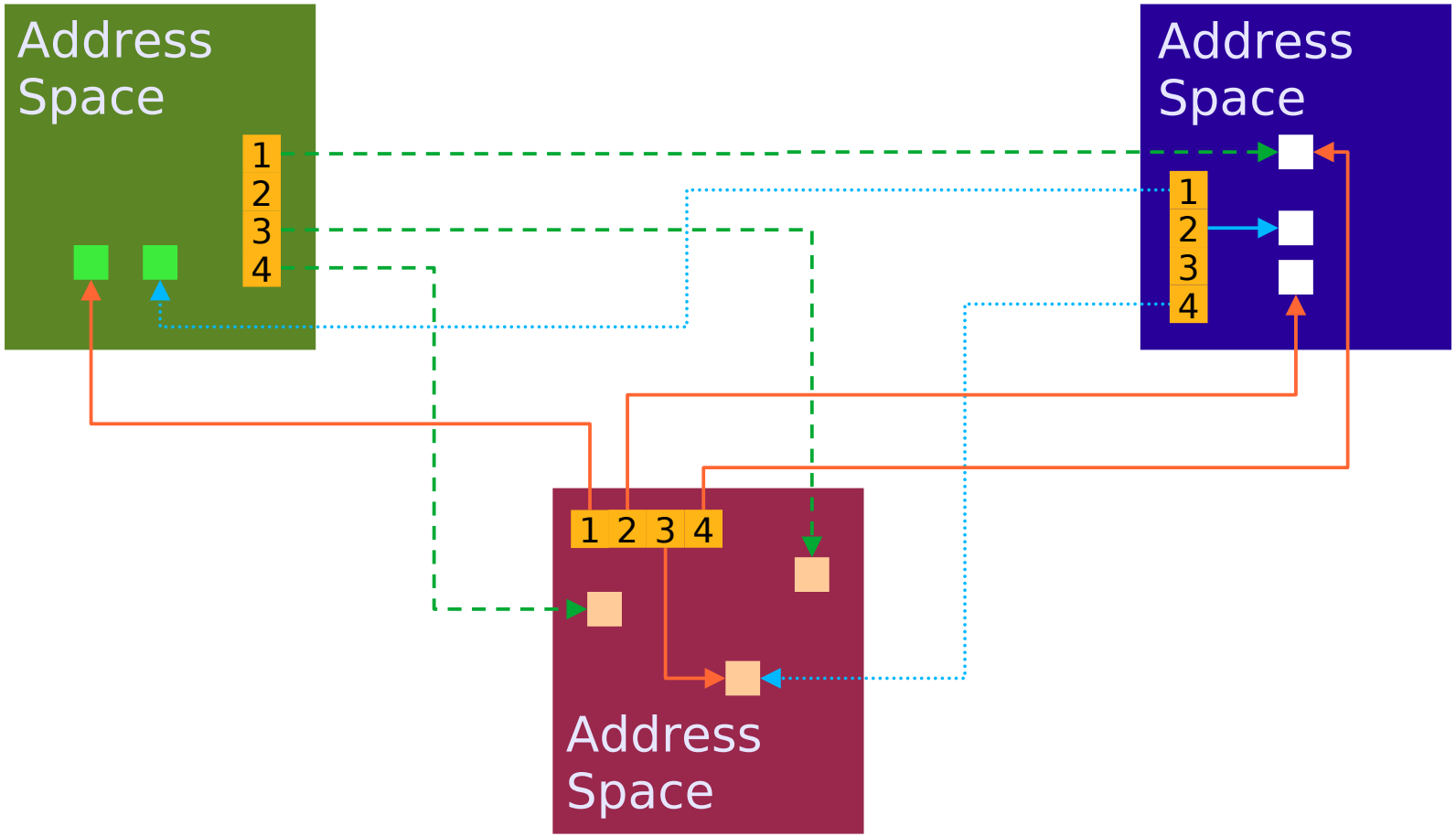
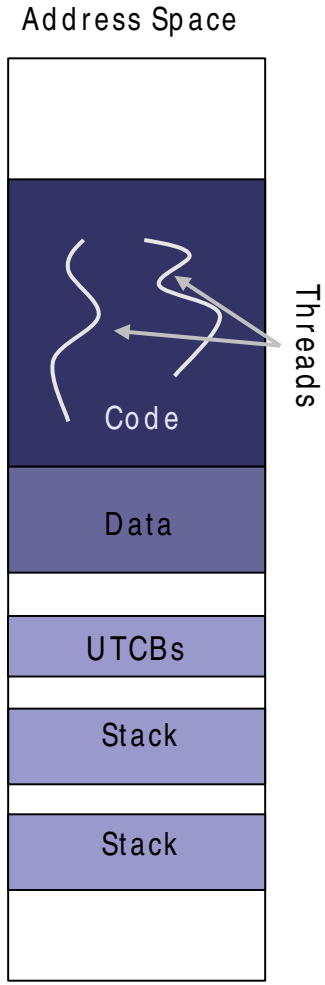


More L4 concepts

L4/Fiasco.OC: Threads

- Thread
  - Unit of execution
  - Implemented as kernel object



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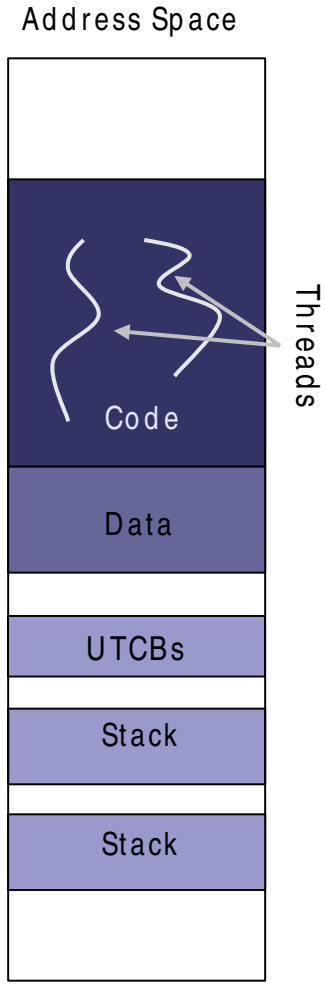

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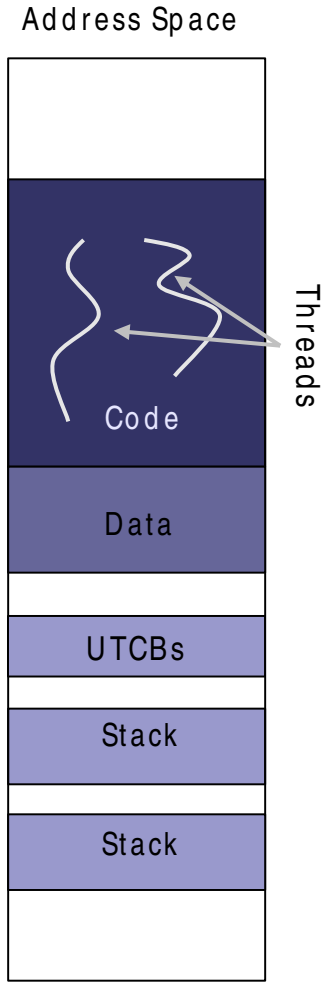
- User-level applications need to
  - allocate stack memory
  - provide memory for application binary
  - find entry point
  - …



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Kernel

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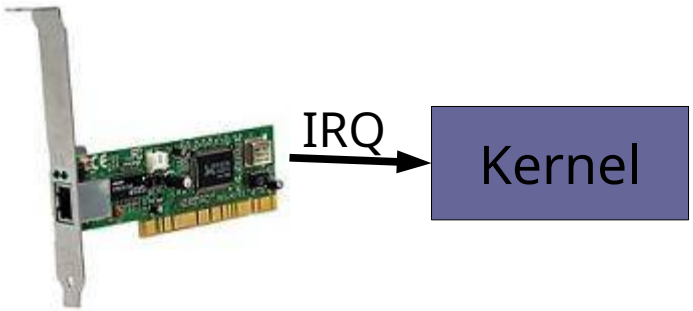

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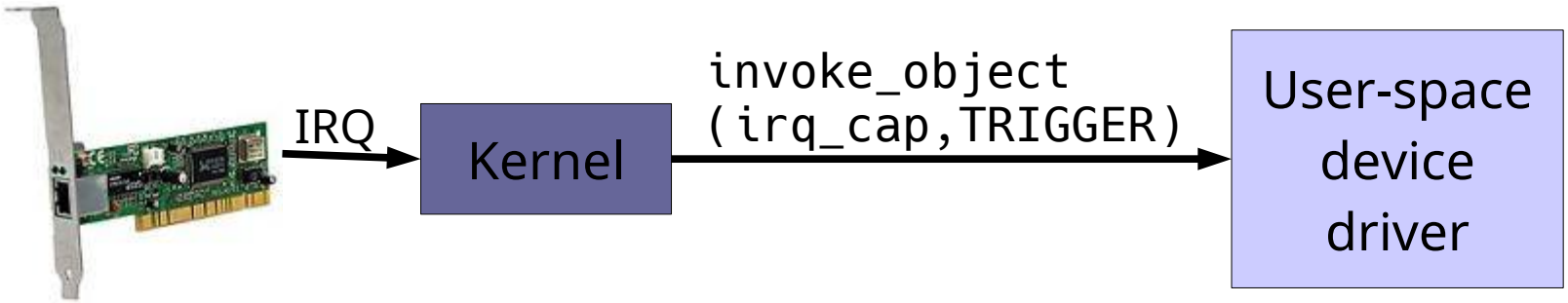
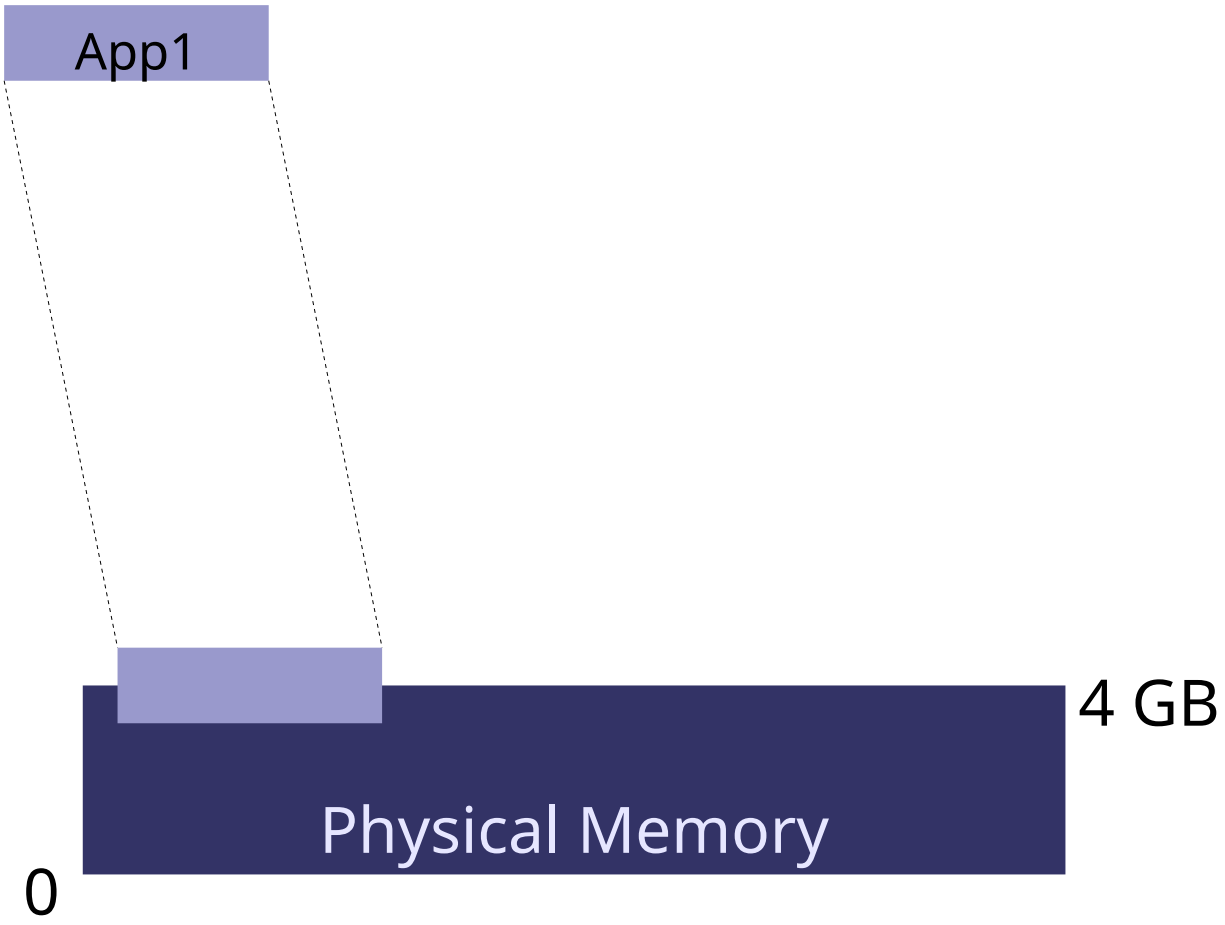


Challenge: Memory partitioning



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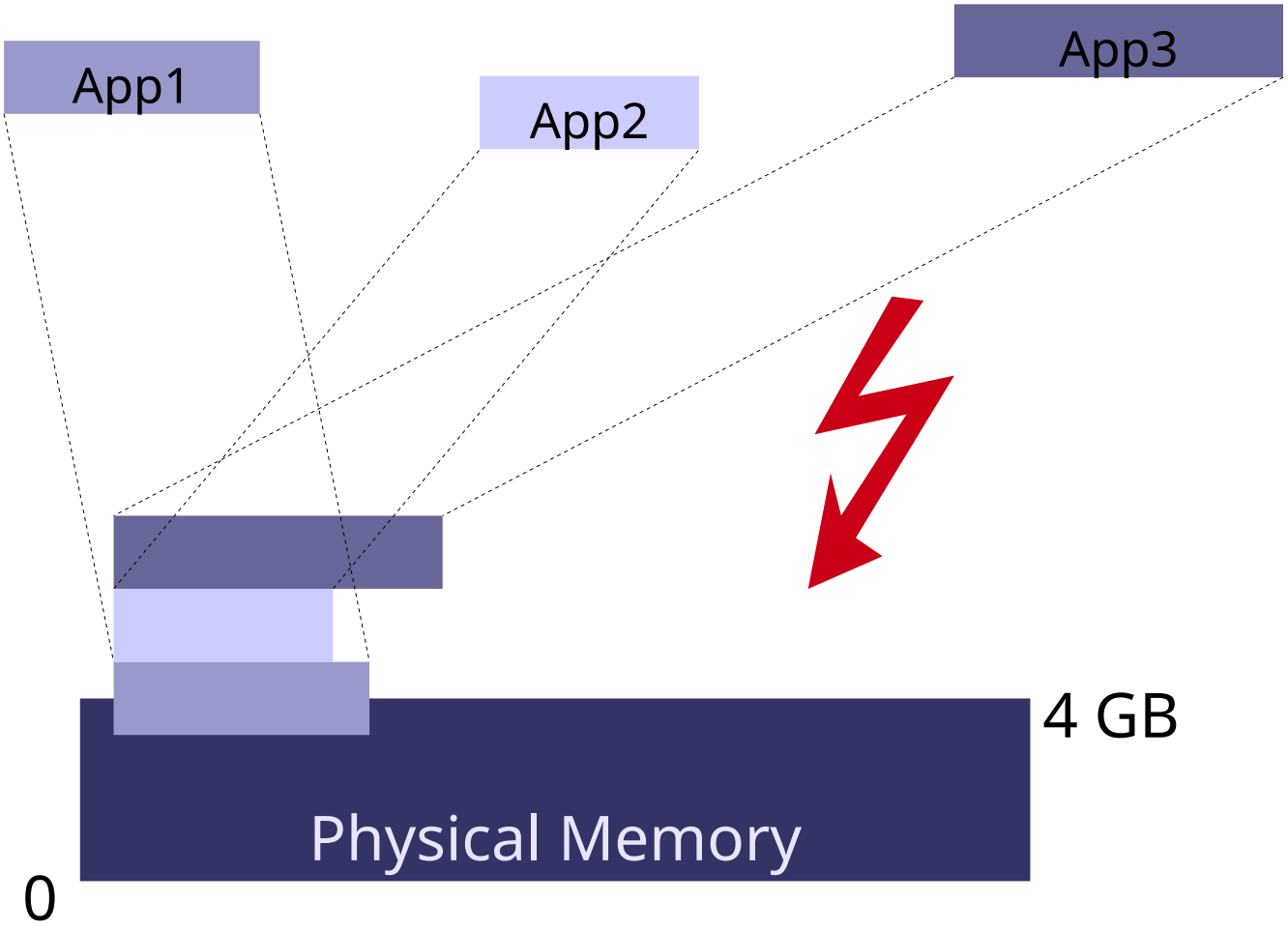
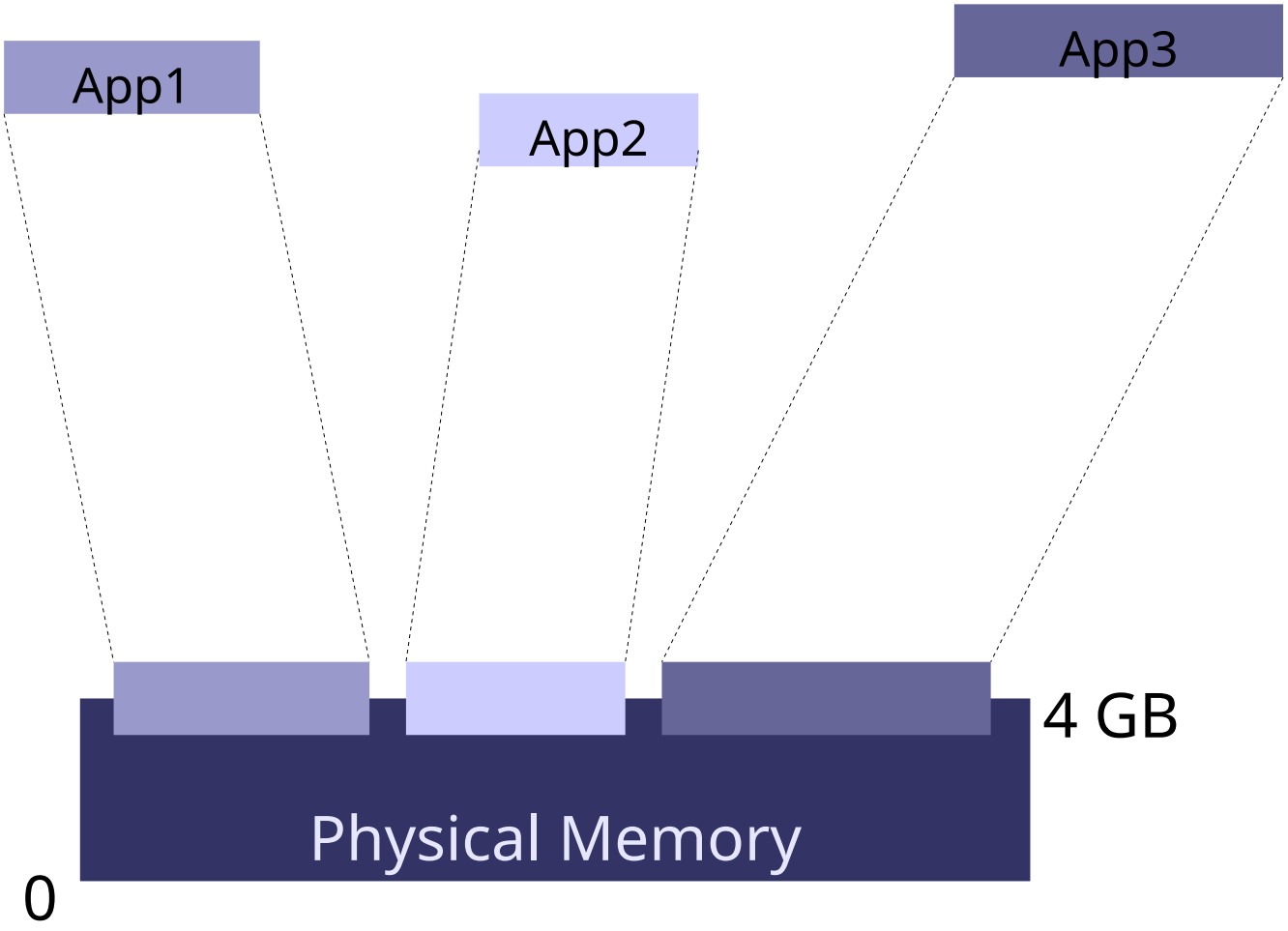
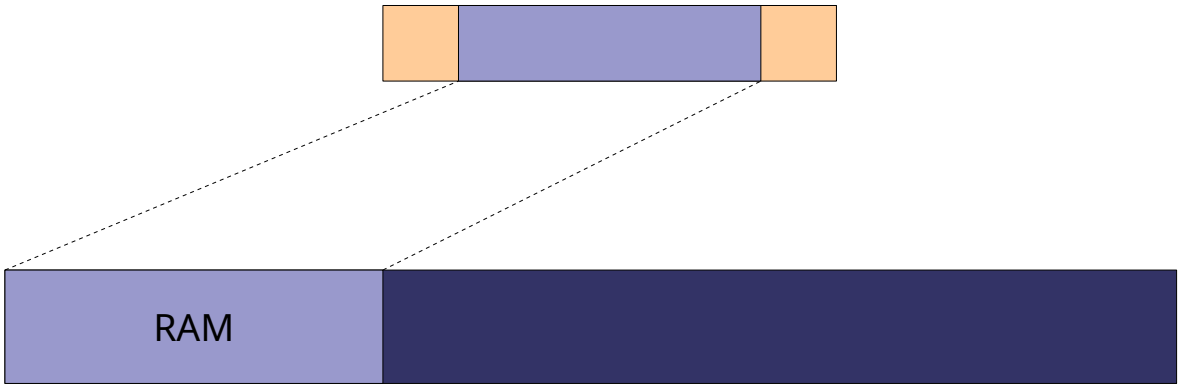


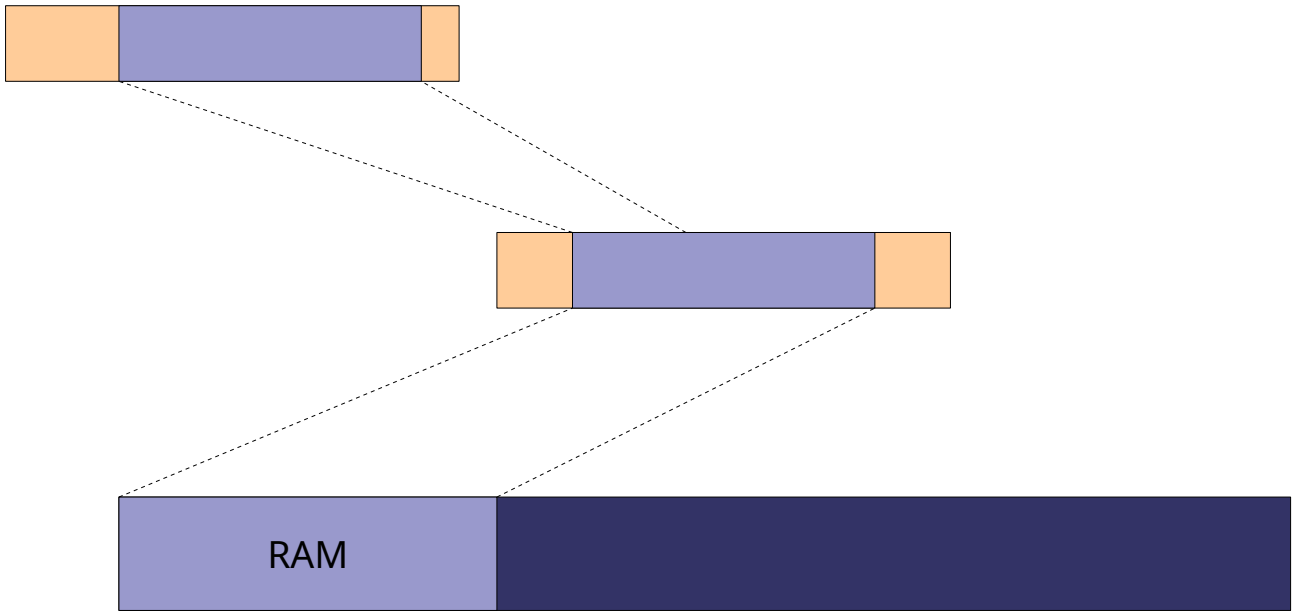
Solution: Virtual Memory





Physical Address Space

L4: Recursive Address Spaces



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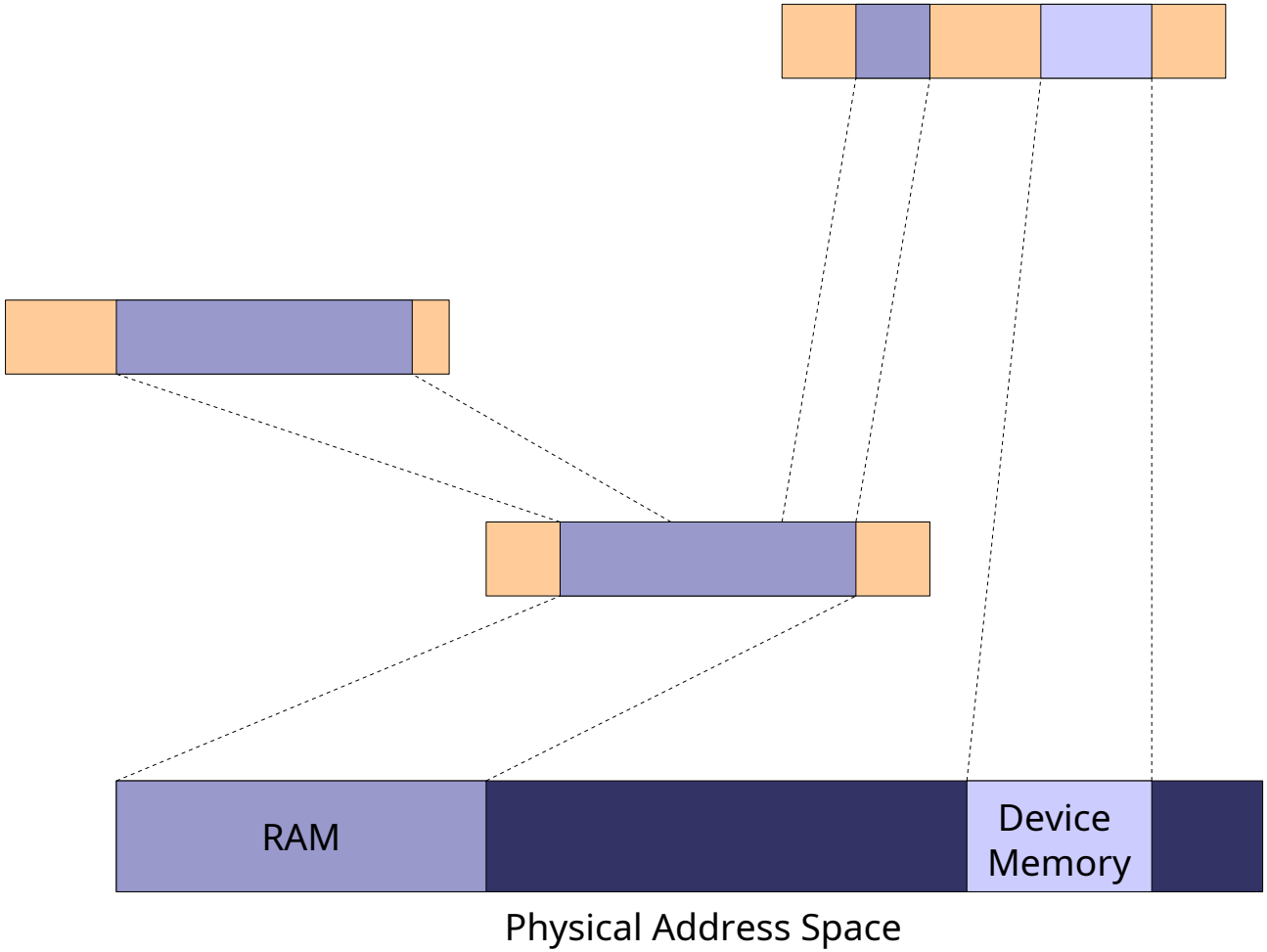

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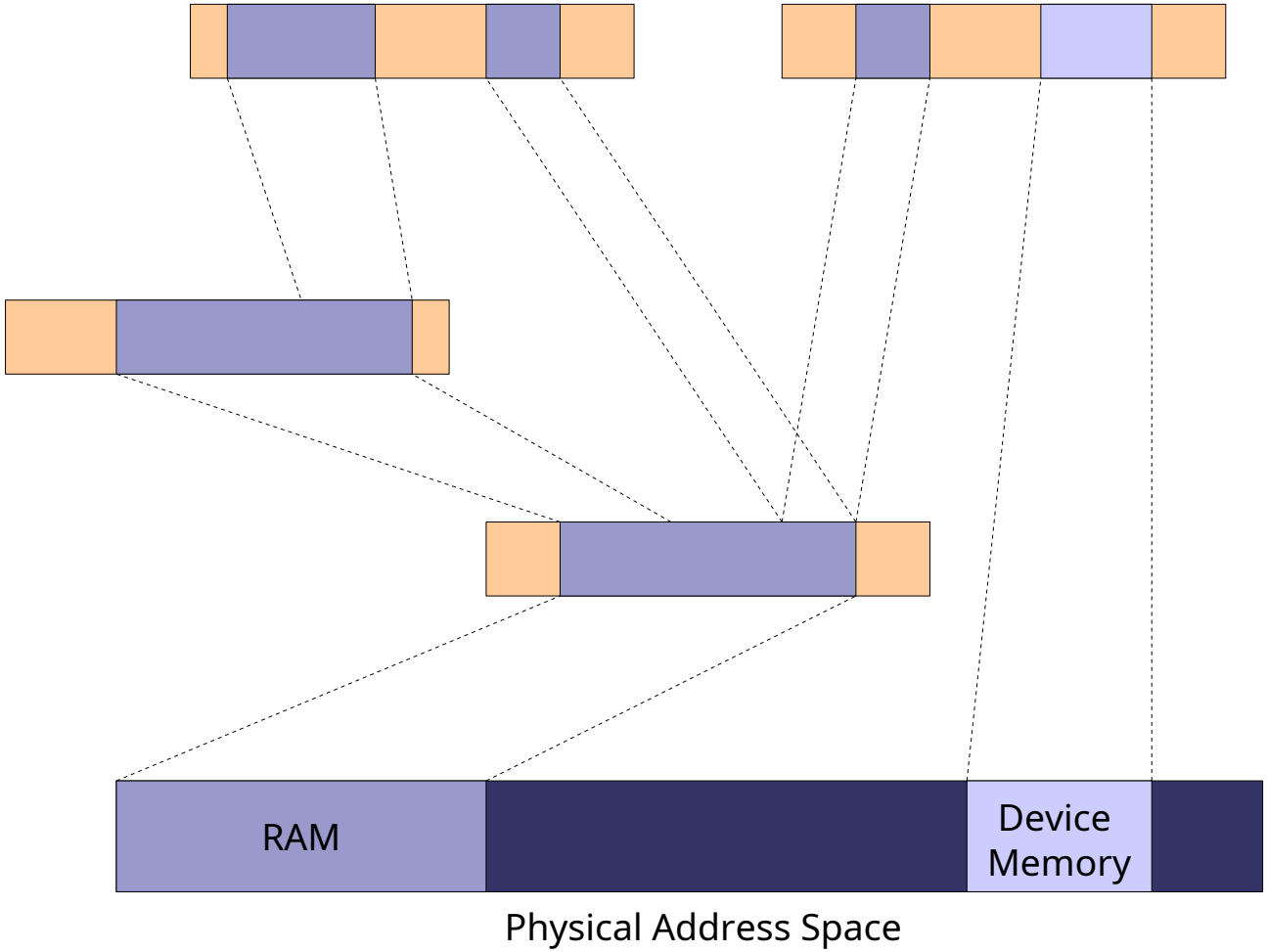

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- Mapping / not mapping of capabilities used to implement access control
- Abstraction for mapping: *flexpage*
  - Location and size of resource
  - Receiver's rights (read-only, mappable)
  - Type (memory, I/O, communication capability)

L4/Fiasco.OC: Object Types (Recap)

- Summary of object types
  - Task
  - Thread
  - IPC Gate
  - IRQ
  - Factory

- Each task gets initial set of capabilities for some of these objects at startup

What can we build with this?

Kernel vs. Operating System

- Fiasco.OC is not a full operating system!
  - No device drivers (except UART + timer)
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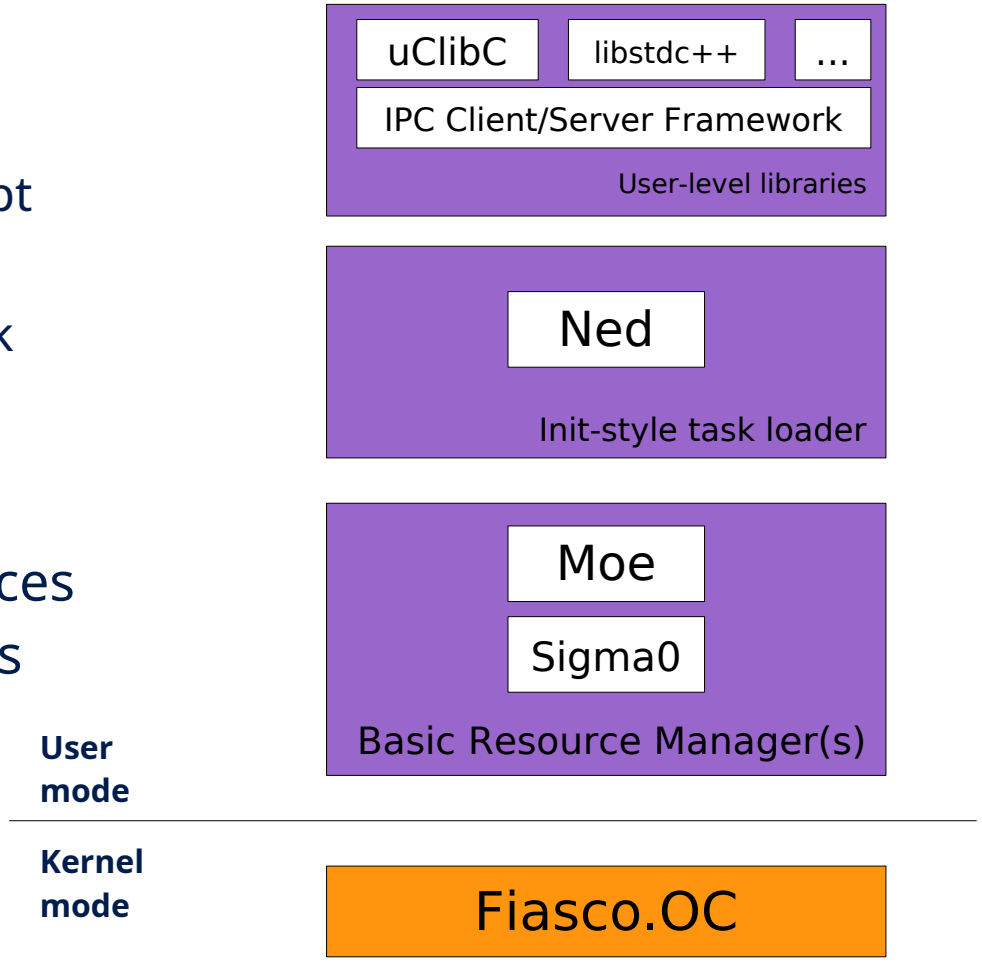

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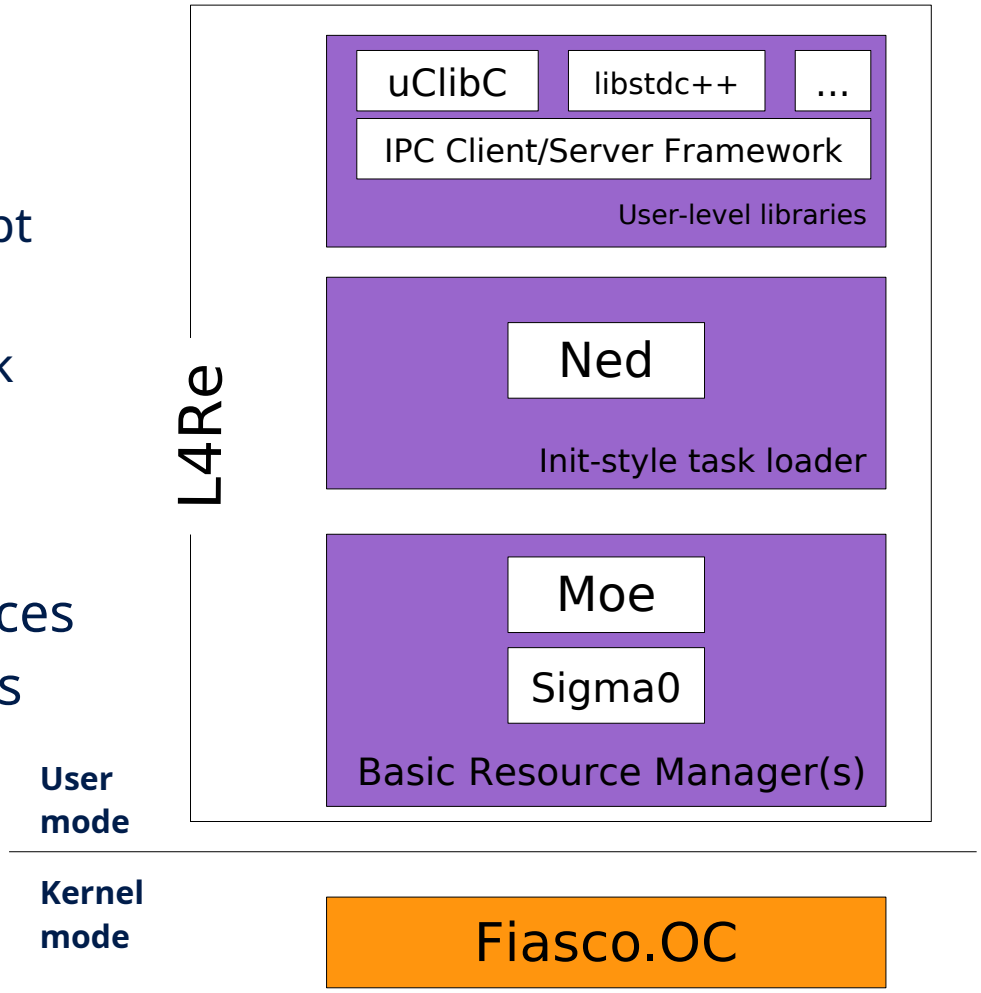
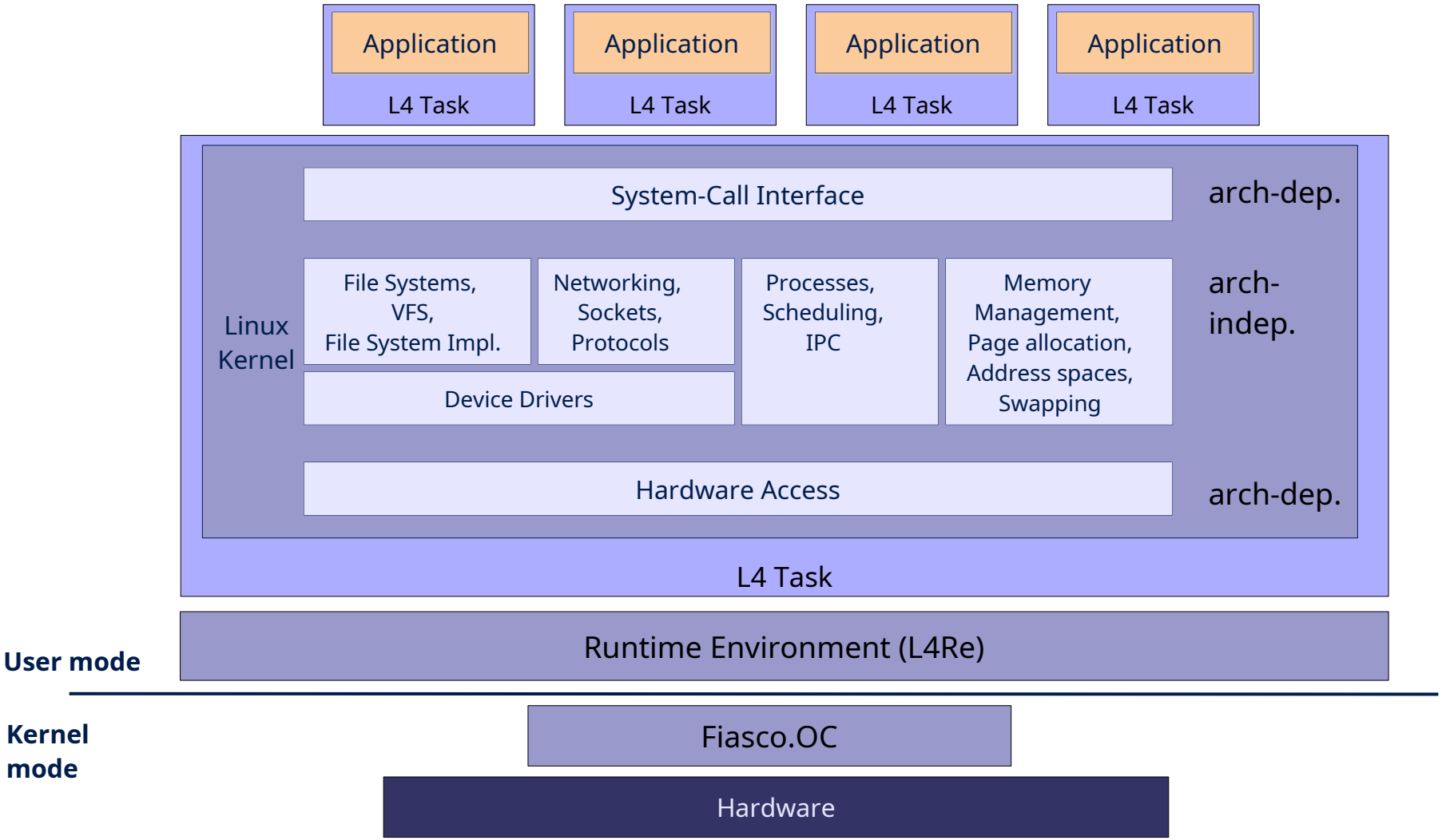
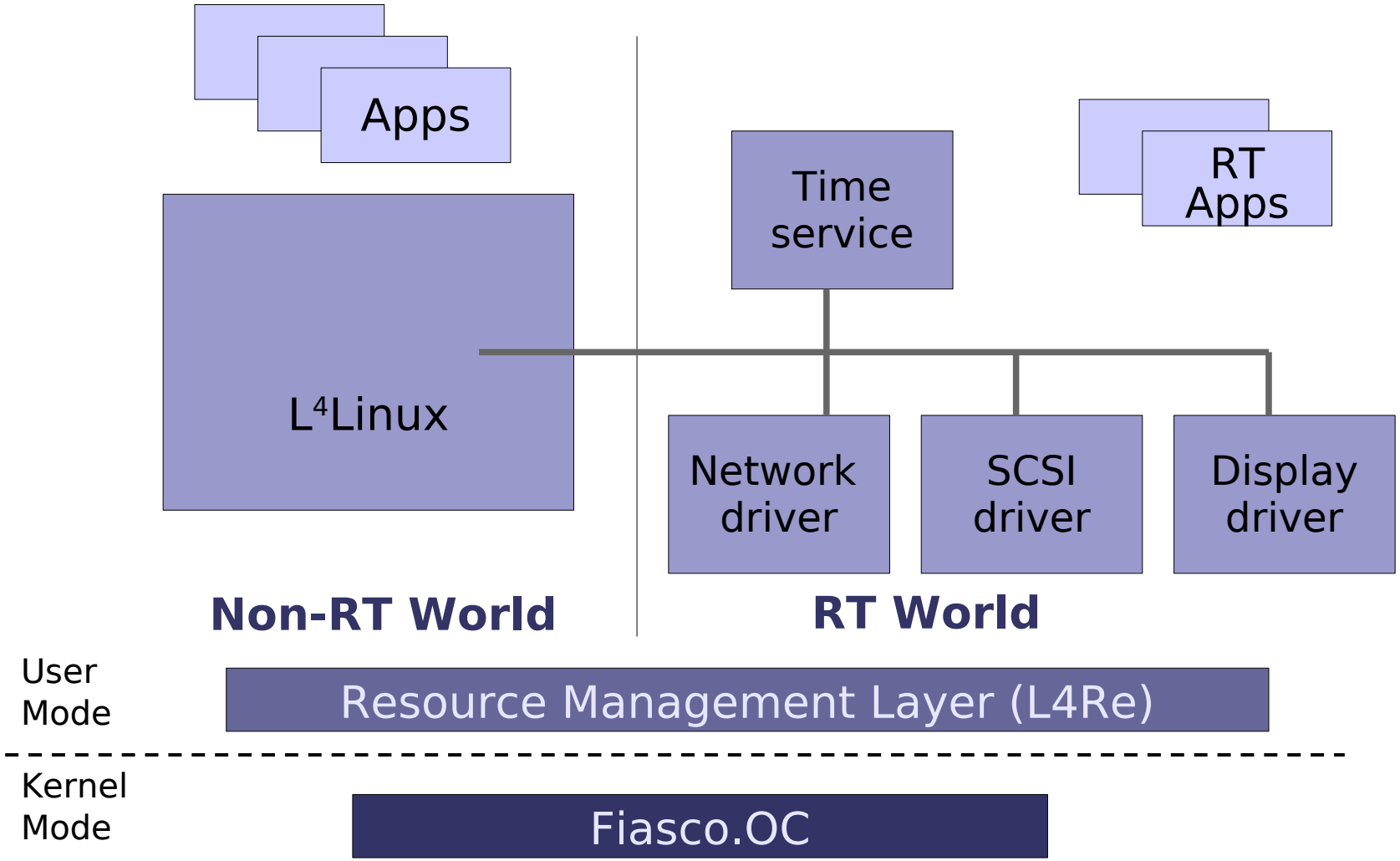
→ L4Re = L4 Runtime Environment



L4Linux: Linux on L4

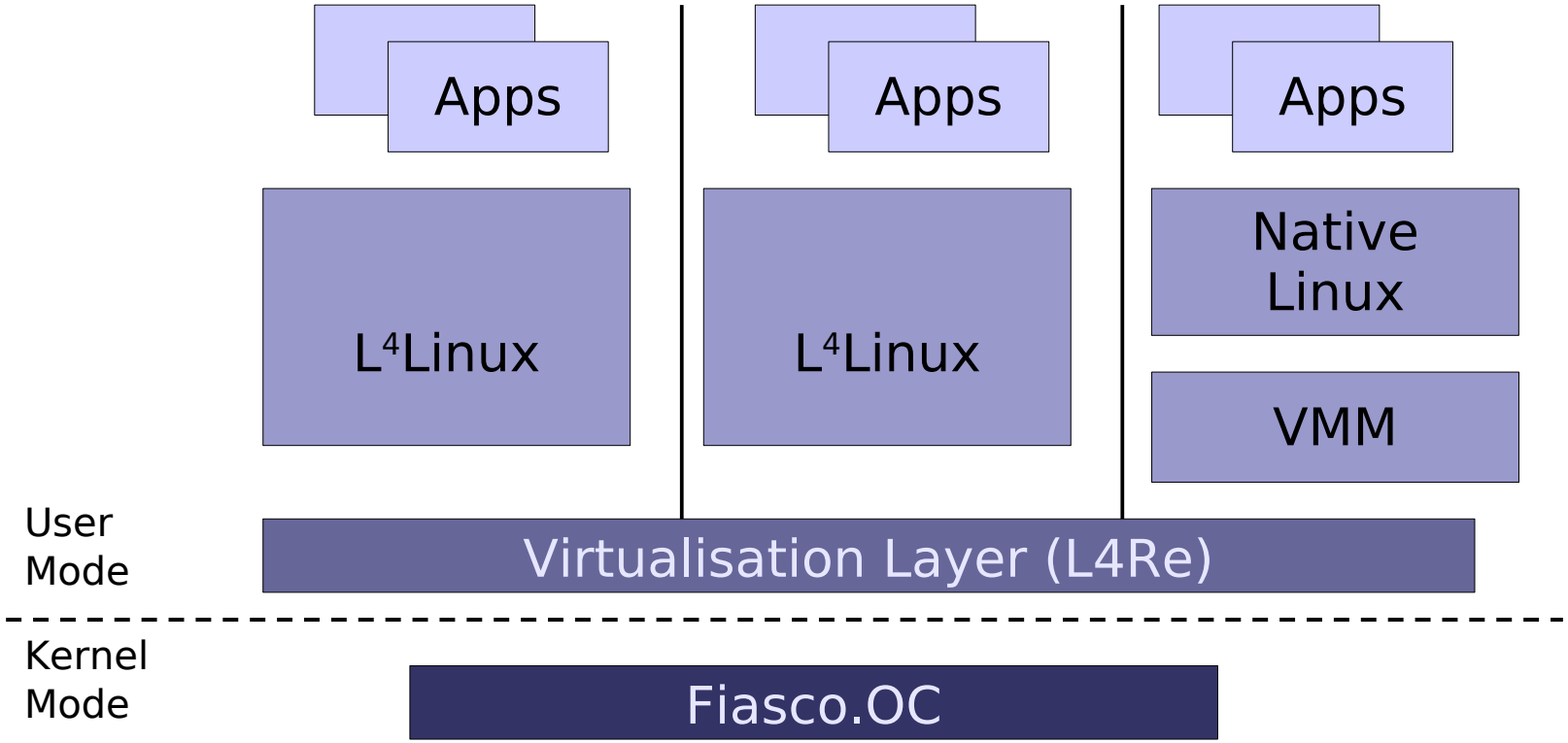


Drops: **D**resden **R**eal-Time **Op**erating **S**ystem



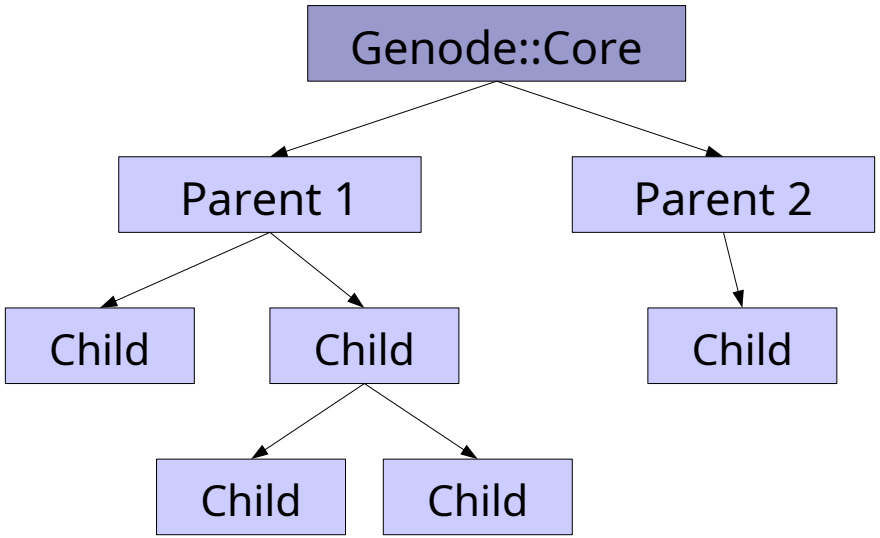
Virtual Machines

- Isolate not only processes, but also complete operating systems (compartments)
- “Server consolidation”



Genode OS Framework

- Genode = C++-based OS framework developed here in Dresden
- Goal: hierarchical system that
  - supports resource partitioning
  - layers security policies on top of each other



What’s to come?

Lecture Outline

- **Basic mechanisms and concepts**
  - Memory management
  - Tasks, Threads, Synchronisation
  - Communication

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- **Basic mechanisms and concepts**
  - Memory management
  - Tasks, Threads, Synchronisation
  - Communication
- **Building real systems**
  - What are resources and how to manage them?
  - How to build a secure system?
  - How to build a real-time system?
  - How to re-use existing code (Linux, standard system libraries, device drivers, ...)?
  - How to improve robustness and safety?

(Preliminary) Schedule

Date	14:50 @ APB E008	16:40 @ APB E009 / E065
Oct 14	Intro	*Lab: Intro*
Oct 21	IPC	Paper
Oct 28	Threads & Synchronization	—
Nov 4	Memory Management	Practical
Nov 11	Device Drivers	Practical
Nov 18	Real-Time	*Lab*
Nov 25	Resource Management	*Lab*
Dec 2	Virtualisation	Paper
Dec 9	Legacy Reuse	Paper
Dec 16	—	—
Jan 6	Secure Systems	*Lab*
Jan 13	Heterogenous Systems	Practical
Jan 20	—	—
Jan 27	Trusted Computing	Paper
Feb 3	Dependable Systems	—