Microkernels and Client-Server Architectures

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I'm not interested in making devices look like user-level. They aren't, they shouldn't, and microkernels are just stupid.

Linus Torwalds

Motivation

- Early operating systems had very little structure.
- A strictly layered approach was promoted by [Dijkstra 1968].
- Later OS (more or less) followed that approach (e.g., Unix).

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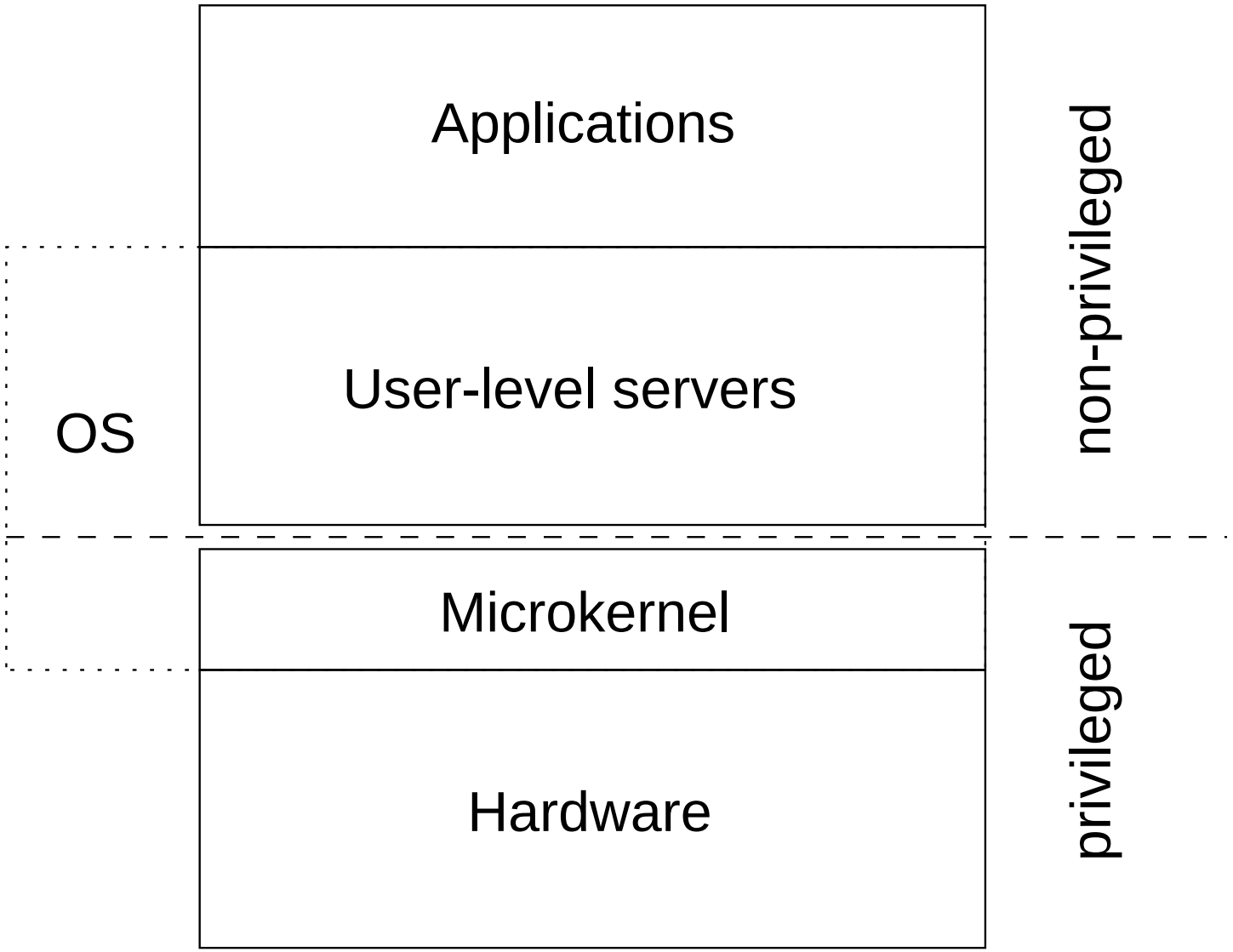
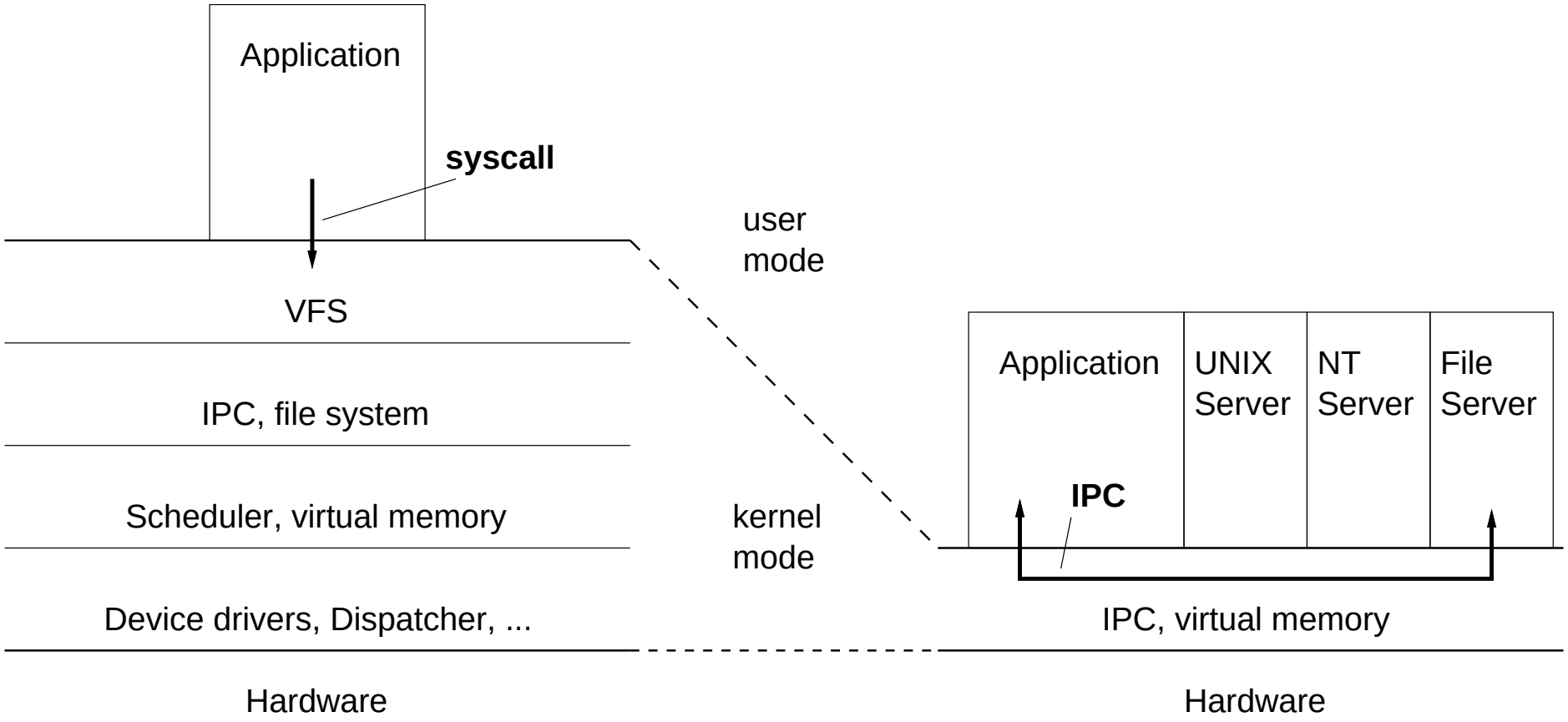
PROBLEMS WITH LAYERED APPROACH

- Widening range of services and applications
  $\Rightarrow$ OS bigger, more complex, slower, more error prone.
- Need to support same OS on different hardware.
- Like to support various OS environments.
- Distribution
  $\Rightarrow$ impossible to provide all services from same (local) kernel.

IDEA: BREAK UP THE OS



MONOLITHIC VS. CLIENT-SERVER OS STRUCTURE



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- Are hardware independent/portable,
- Provide “OS environment”/”OS personality” (maybe several),
- May be invoked:
  - ➜ from **application** (via message-passing IPC)
  - ➜ from **kernel** (upcalls);

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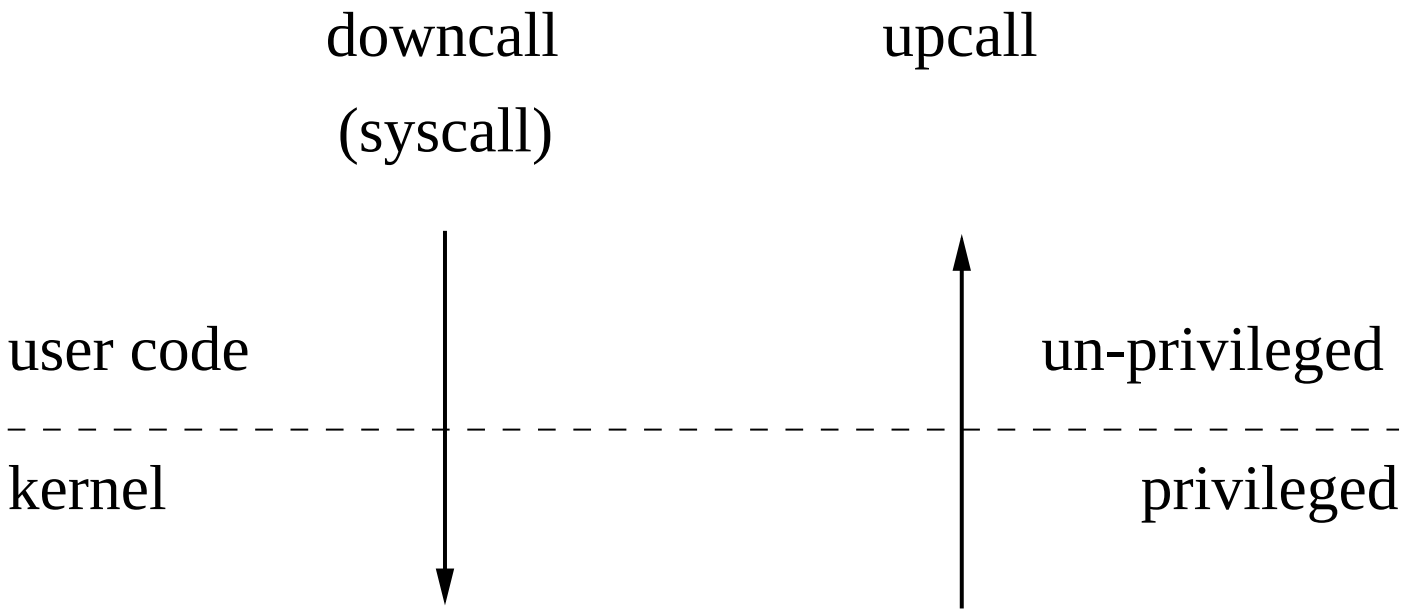
  - ➜ from **kernel** (upcalls);
- **Servers** implement *policies* [BH70].

Downcall vs. upcall



unprivileged code enters kernel mode

implemented via trap

privileged code enters user mode

implemented via IPC

Early example: Hydra

- Separation of mechanism from policy
  ➜ e.g. protection vs. security
- No hierarchical layering of kernel.
- Protection, even within OS.
  ➜ Uses (segregated) *capabilities*.
- Objects, encapsuation, units of protection.
- Unique object *name*, no ownership.
- Object persistence based on reference counting [WCC+74].

HYDRA ...

- can be considered the first *object-oriented* OS;
- has been called the first *microkernel* OS;
- has had enormous influence on later operating systems research;
- was never widely used even at CMU because of
  - ➜ poor performance,
  - ➜ lack of a complete environment.

Popular Example: Mach

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- *Portability:* almost all code H/W independent.
- *Real-time capability*.
- *Multiprocessor and distribution* support.
- *Security*.

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Coined term *microkernel*.

BASIC FEATURES OF MACH μ-KERNEL

- Task and thread management;
- interprocess communication (asynchronous message-passing);
- memory object management;
- system call redirection;
- device support;
- multicomputer support.

MACH TASKS AND THREADS

- Task consists of one or more threads.
- Task provides *address space* and other environment.
- Thread is active entity (basic unit of CPU utilisation) .
- Threads have own stacks, are kernel scheduled.
- Threads may run in parallel on multiprocessor.
- “Privileged user-state program” may be used to control scheduling.
- Task created from “blueprint” with empty or inherited address space.
- Activated by creating a thread in it.

MACH IPC: PORTS

- Addressing based on ports:
  - ➜ port is a mailbox, allocated/destroyed via a system call;
  - ➜ has a fixed-size message queue associated with it;
  - ➜ is protected by (segregated) capabilities;
  - ➜ has exactly *one receiver*, but possibly *many senders*;
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- Kernel detects ports without senders or receiver.
- Processes may have many ports (UNIX server has 2000!)
- Ports can be grouped into *port sets*.
  - ➜ Allows listening to many ports (like `select()`)

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  - ➜ Allows listening to many ports (like `select()`)
- Send blocks if queue is full
  - ➜ except with send-once cap (used for server replies)

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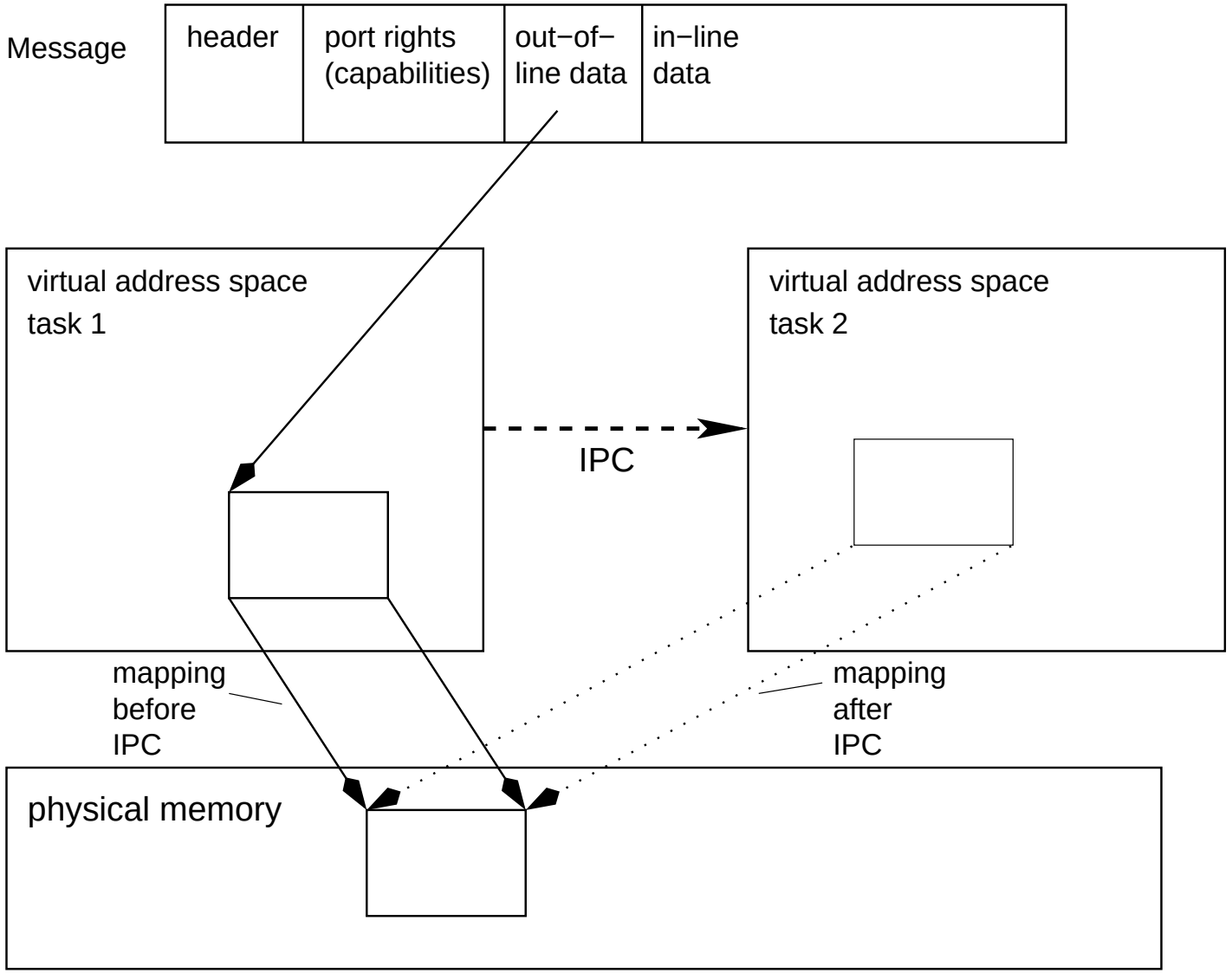
  - ⋆ possibly other capabilities;
  - ⋆ “in-line” (by-value) data;
  - ⋆ “out-of-line” (by reference) data, using copy-on-write,
    - ➜ may contain whole address spaces;

MACH IPC


Message
header
port rights (capabilities)
out−of− line data
in−line data
virtual address space task 1
virtual address space task 2
IPC
mapping before IPC
mapping after IPC
physical memory

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  - ✶ 3 page states:
    - ➜ unallocated,
    - ➜ allocated & unreferenced,
    - ➜ allocated & initialised

COPY-ON-WRITE IN MACH

- When data is copied (“blueprint” or passed by-reference):
  - ➜ source and destination share single copy,
  - ➜ both virtual pages are mapped to the same frame.
- Marked as read-only.
- When one copy is modified, a fault occurs.
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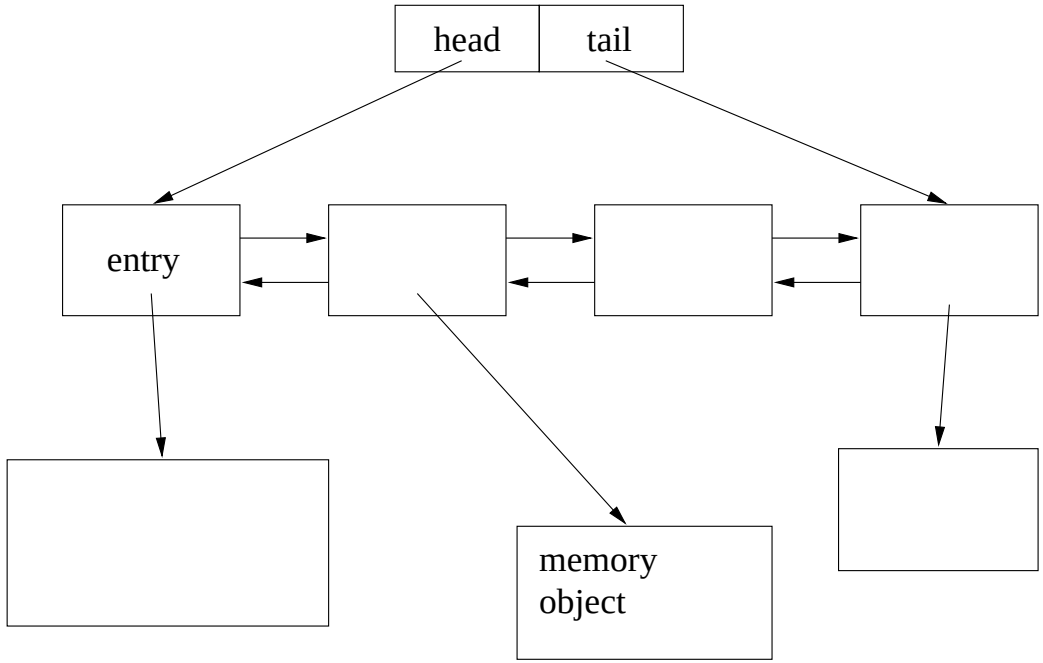
- Drawbacks:
  - ➜ expensive for small amounts of data (page table manipulations)
  - ➜ data must be properly aligned

MACH ADDRESS MAPS

- Address spaces represented as *address maps*:



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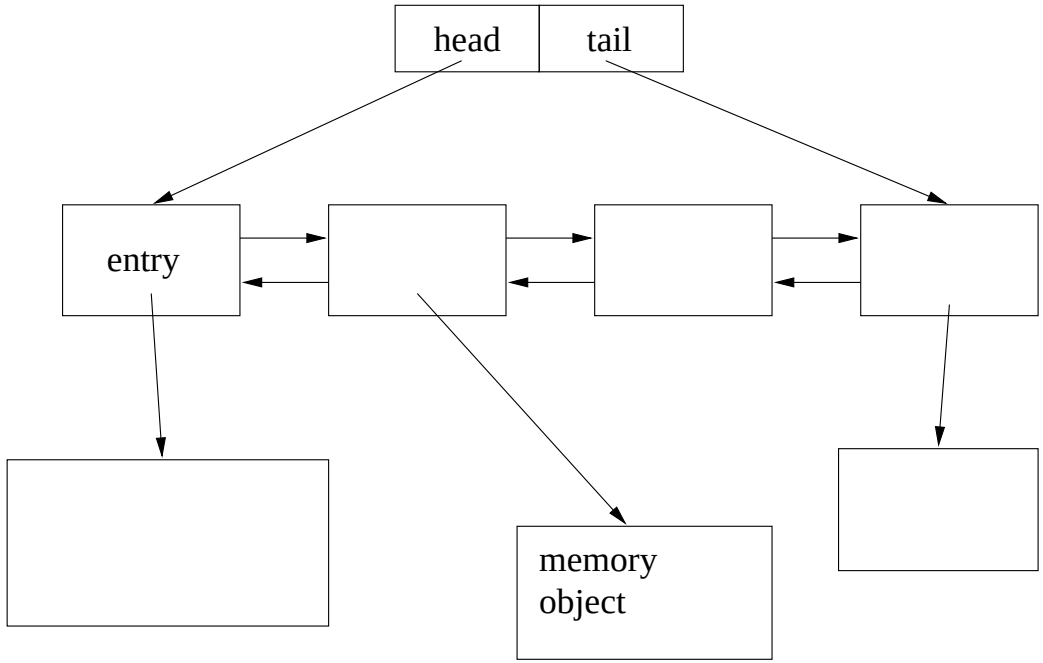


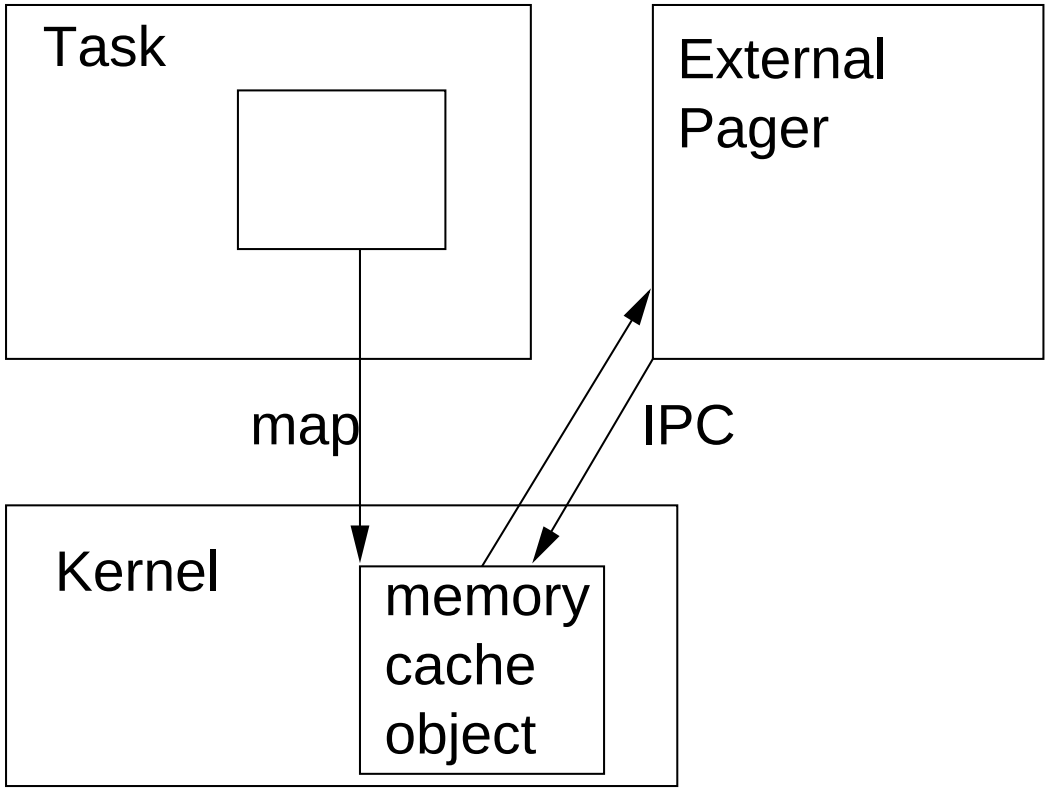
- Any part of AS can be mapped to (part of) a memory object
- Compact representation of *sparse* address spaces
  - ➜ Compare to multi-level page tables?

MEMORY OBJECTS

- Kernel doesn't support file system
- Memory objects are an abstraction of secondary storage:
  - ✶ can be mapped into virtual memory
  - ✶ are cached by the kernel in physical memory
  - ✶ pager invoked if uncached page is touched
    - ➜ used by file system server to provide data
- Support data sharing
  - ➜ by mapping objects into several address spaces
- Memory is only cache for memory objects

USER-LEVEL PAGE FAULT HANDLERS

- All actual I/O performed by *pager*; can be
  - ➜ default pager (provided by kernel), or
  - ➜ *external* pager, running at user-level.



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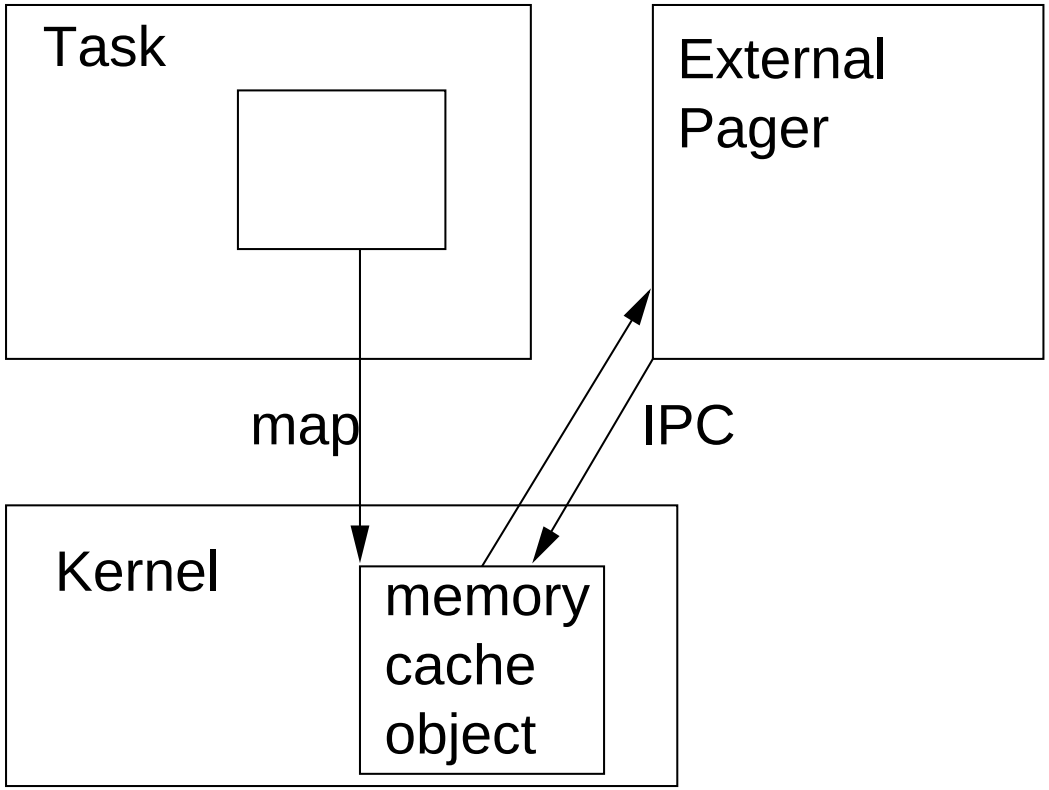


- Intrinsic page fault cost: 2 IPCs

HANDLING PAGE FAULTS

① Check protection & locate memory object

➜ uses address map

② Check cache, invoke pager if cache miss

➜ uses a hashed page table

③ Check copy-on-write

➜ perform physical copy if write fault

④ Enter new mapping into H/W page tables.

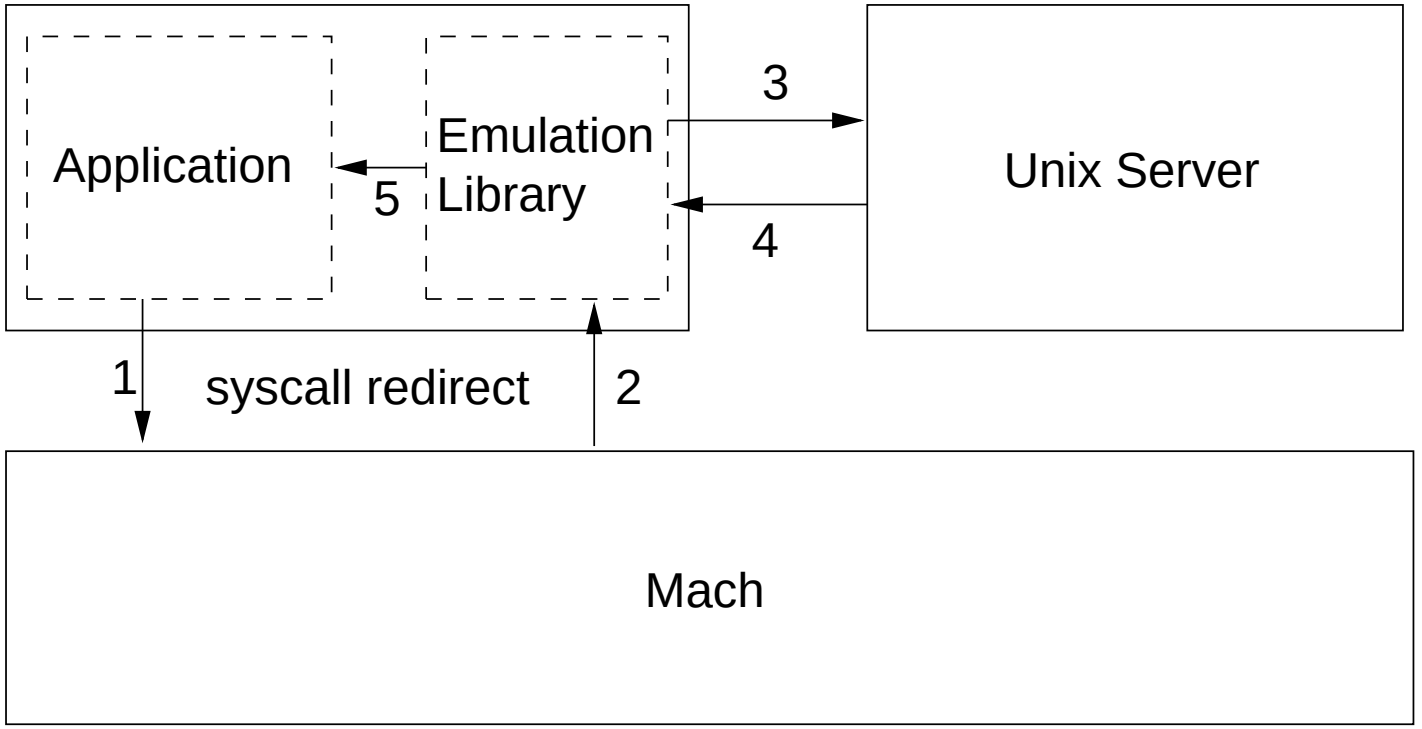
REMOTE COMMUNICATION

- Client A sends message to server B on remote node.
  ① A sends message to local *proxy port* for B's receive port
  ② User-level *network message server* receives from proxy port
  ③ NMS converts proxy port into (global) *network port*.
  ④ NMS sends message to NMS on B's node

  ➜ may need conversion (byte order...)

  ⑤ Remote NMS converts network port into local port (B's).
  ⑥ Remote NMS sends message to that port.

MACH UNIX EMULATION



- emulation library in user address space handles IPC
- invoked by system call redirection (*trampoline mechanism*)
  ➜ supports binary compatibility

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- Performance???
  ➜ tendency to move features into kernel
- Served as basis for OSF/1, MacOS X...
- Further information on Mach: [YTR+87, CDK94, Sin97]

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- Basic ideas similar to Mach
- Servers can be:
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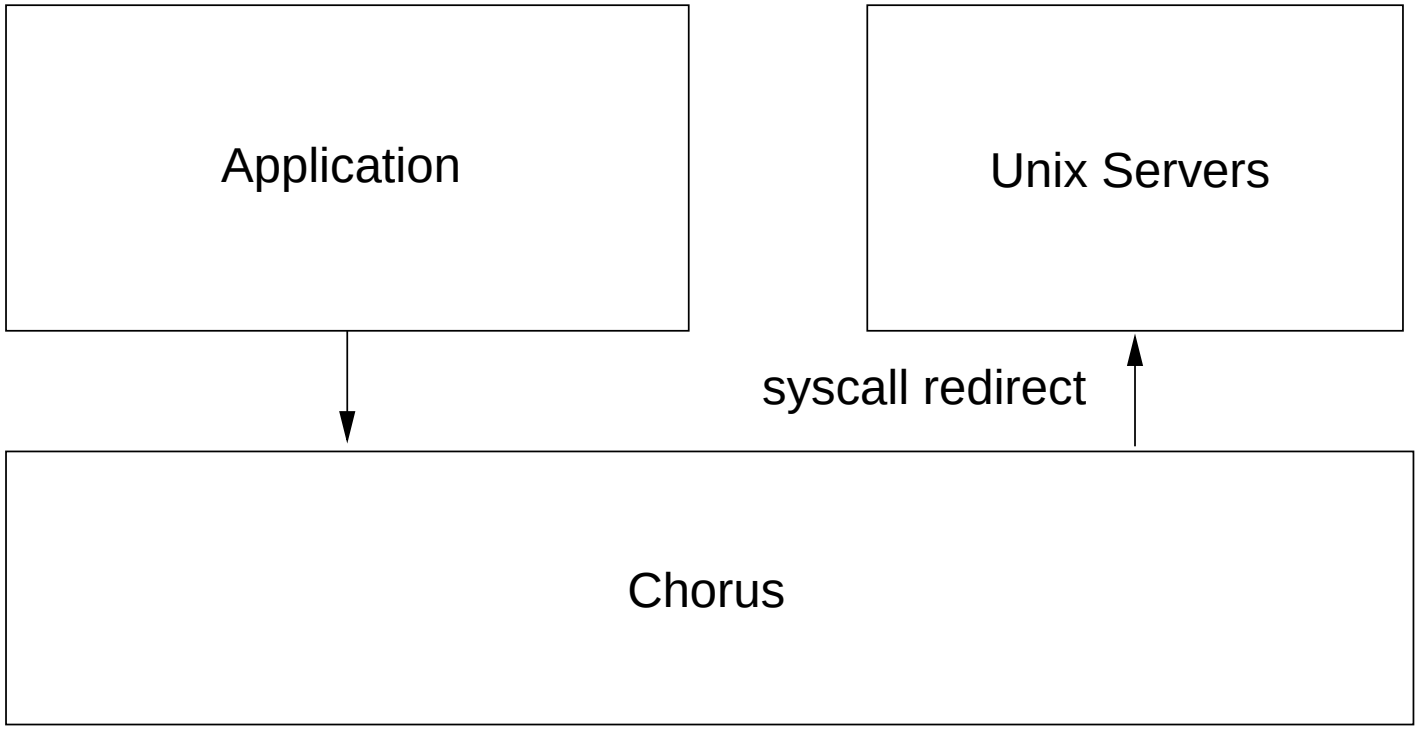
- Support for group communication (multicast, any of a group).
- Like Mach, kernel threads, port groups.
- Uses password capabilities
  - ➜ but servers use ACL based protection.
- Uses copy-on-write, but receiver controls placement of data.

CHORUS UNIX EMULATION



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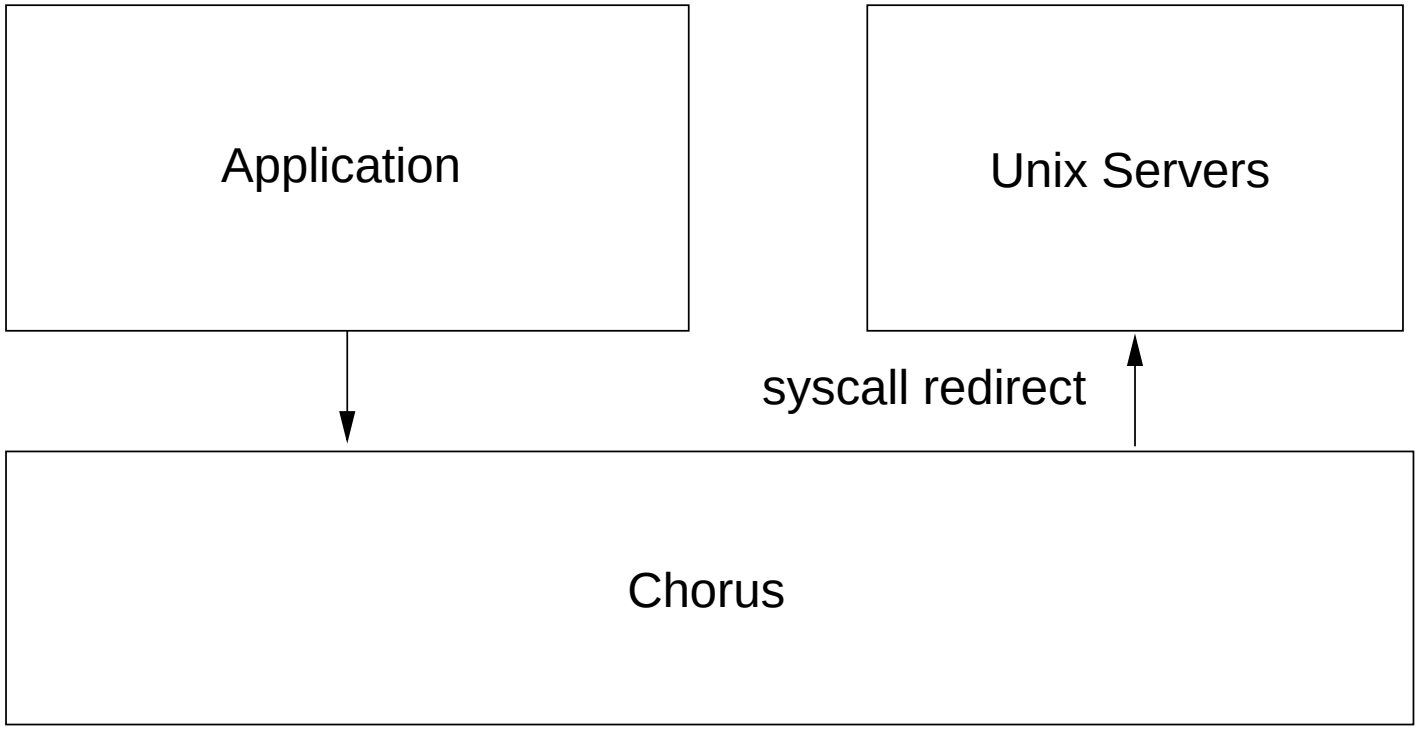

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- ➜ Further information in [DA92, RAA+90, RAA+92, CDK94, Sin97].

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- Most notable systems:

  Amoeba: Mullender, Tanenbaum (early 1980's)
  [TM81, TM84, MT86].

  Windows NT: Microsoft (early 1990's)
  [Cus93].

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