NTNU | Norwegian University of Science and Technology

# Operating Systems

## Lecture 17: Virtual machines and microkernels

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# Software architecture

- Definition:

> The basic organization of a system, expressed through its components, their relations to each other and the environment as well as the principles which define the design and evolution of the system.

Source: Gesellschaft für Informatik e.V. (https://gi.de/informatiklexikon/software-architektur)

- Intuitive view: "boxes and arrows" 😀
- Does not describe the ***detailed*** design
- Focus on the relation between the requirements and the system that is to be constructed

# Different operating system architectures

- **Isolation**
- **Interaction mechanisms**
- **Interrupt handling mechanisms**

- **Adaptability**
  - Portability, modifications
- **Extensibility**
  - New functions and services
- **Robustness**
  - Behavior in the presence of errors
- **Performance**

**Technical criteria** (principles)

**Observable criteria** (requirements)

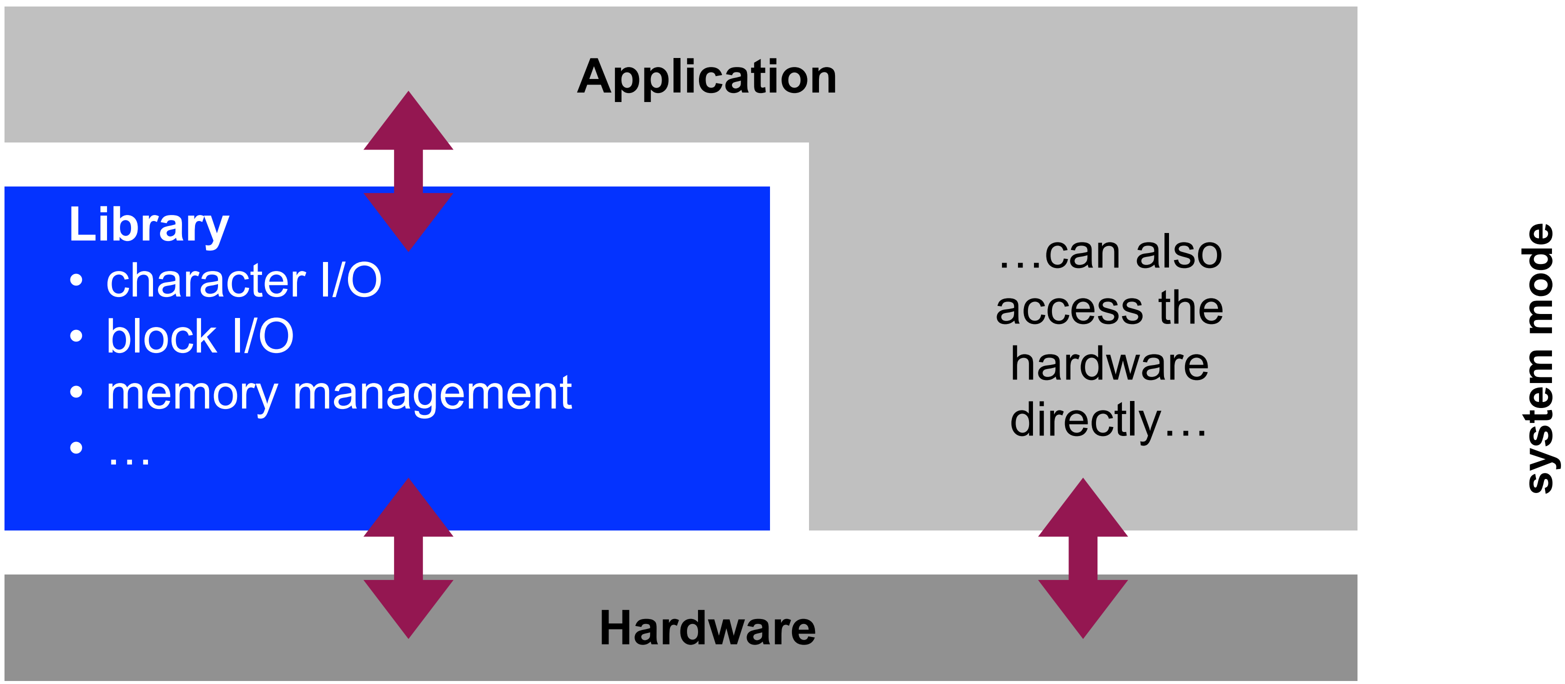
# Early operating systems

- The first computers had no operating system at all
  - **Every program** had to control all hardware on its own
  - Systems were running batch processing jobs controlled by an operator
    - Single tasking, punch card operated
  - Peripheral devices were rather simple
    - Tape drives, punch card readers/writers and printers connected over serial lines
- **Replication of code** to control devices in every application program
  - Waste of development and compile time as well as storage
  - Error prone

# Library operating systems

- Collect frequently used functions to control devices in **software libraries** which can be used by all programs
  - Call system functions like **regular program functions**
- Library could remain in the computer's main memory
  - Reduced program loading times, "**Resident Monitor**"
- Library functions were **documented and tested**
  - Reduced development overhead for application programmers
- Errors could be fixed **centrally**
  - Improved reliability

# Library operating systems



# Library OS: Evaluation

- **Isolation**
  - Ideal – **single tasking system** – but high time overhead to switch tasks
- **Interaction mechanisms**
  - Direct (function calls)
- **Interrupt handling mechanisms**
  - Sometimes interrupts were not in use → **polling**
- **Adaptability**
  - Separate libraries for each hardware architecture, no standards
- **Extensibility**
  - Depends on the library structure: global structures, "**spaghetti code**"
- **Robustness**
  - Direct control of all hardware: errors → system halt
- **Performance**
  - Very high due to direct operations on the hardware without privilege mechanisms

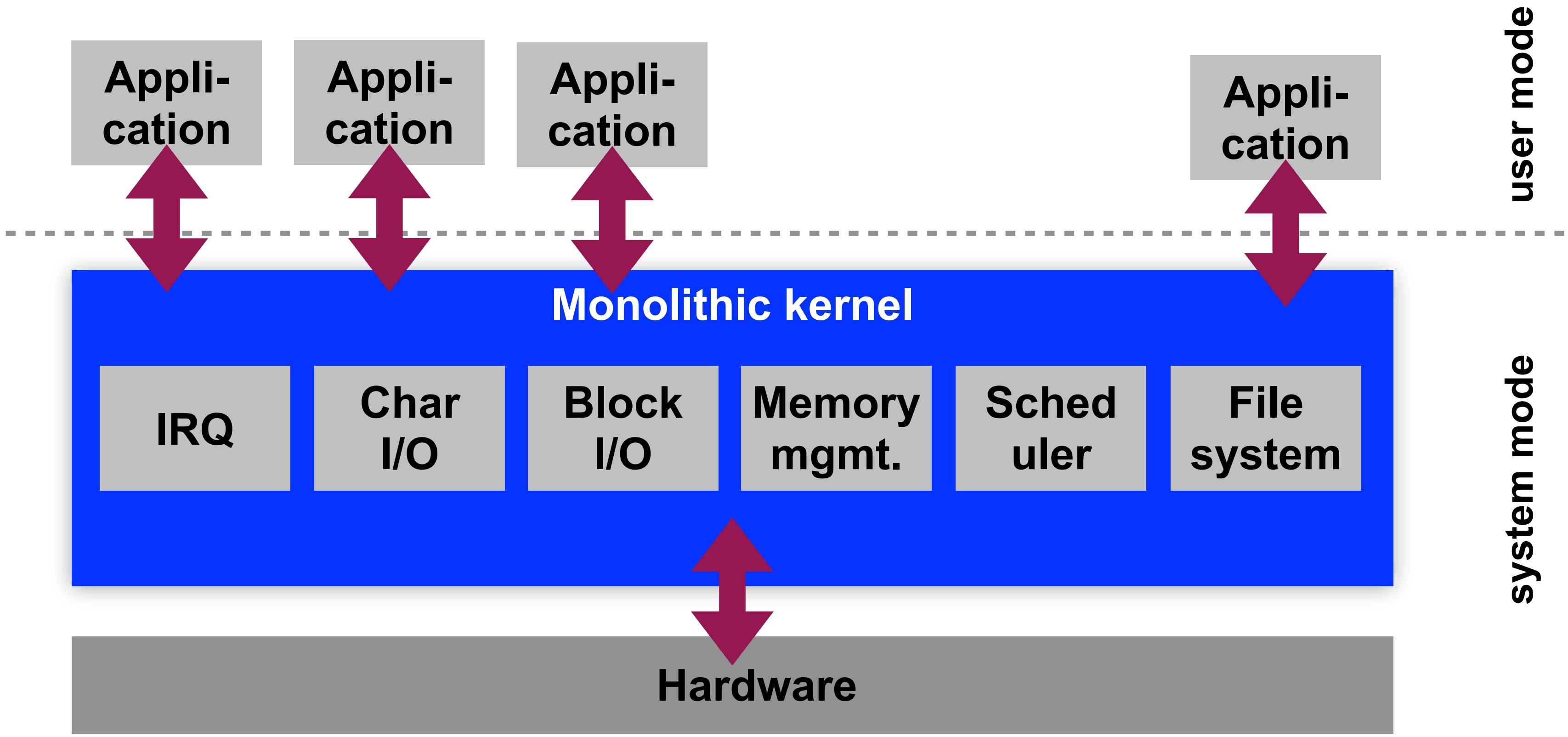
# Library OS: Discussion

- Expensive hardware could only be used "**productive**" for a **small fraction of the time**
  - High overhead to switch tasks
  - Waiting for I/O unnecessarily wastes time, since only one "process" runs on the system
- Results took a lot of time
  - Waiting queue, batch processing
- No interactivity
  - System run by an operator, no direct access to the hardware
  - Execution of a program could not be controlled at runtime

# Monolithic systems

- Management system for computer hardware
  - Standardized **accounting** of system resources
- **Complete** control of hard- and software
  - Applications run under system control now
  - Systems with multiple processes are feasible now: **multiprogramming**
- Introduction of a privilege system
  - System mode and application mode
  - Distinction and switch between modes hardware-supported
    Direct hardware access only in system mode
- System functions called using special mechanisms (**software traps**)
  - Requires context switching and saving

# Monolithic operating systems



# Monolithic systems: OS/360

- One of the first monolithic systems: IBM OS/360, 1966
- Objective: common batch processing OS for all IBM mainframes
  - Performance and memory differ by several orders of magnitude
- System available in different configurations:
  - **PCP** (primary control program): single process, small systems
  - **MFT** (multiprogramming with fixed number of tasks): mid-scale systems (256 kB RAM! 😀), fixed partitioning of memory between processes, fixed number of tasks
  - **MVT** (multiprogramming with variable number of tasks): high end systems, swapping, optional time sharing option (TSO) for interactive use
- Innovative properties:
  - Hierarchical file system
  - Processes can control sub-processes
  - MFT and MVT are compatible (API and ABI)

**IBM z/OS still supports OS/360 applications today**

# Monolithic systems: OS/360

- Problems in the domain of operating system development
  - Fred Brooks' "The Mythical Man-Month" described the problems that occurred during the development of OS/360 [1]
  - **Conceptual integrity**
    - Separation of architecture and implementation was difficult. Developers love to exploit all technical capabilities of a system → reduces comprehensibility and developer productivity
  - **"Second System Effect"**
    - Developers wanted to fix all errors of the previous system and add all missing features → never finished
  - **Dependencies** between components of the system were **too complex**
    - Starting with a certain size of the code, errors are unavoidable!

- Developments in software technology were driven by developments in operating systems

# Monolithic systems: Unix

- Unix was developed for systems with rather limited resources (AT&T Bell Labs)
  - Kernel size in 1979 (7th Edition Unix, PDP11): ca. 10,000 lines of code (straightforward, easy to handle!), compiled ca. 50 kB
  - Originally implemented by 2-3 developers
- Introduction of simple abstractions
  - Every object in the system can be represented as a **file**
  - Files are simple unformatted streams of bytes
  - Complex functionality can be realized by **combining simple system programs** (**shell pipelines**)
- New objective of system development: **portability**
  - Simple adaptability of the system to different hardware
  - Development of Unix in C – designed to be a domain specific language to develop operating systems

# Monolithic systems: Unix

- Further development of Unix was not predictable
  - Systems with large address spaces (VAX, RISC systems)
  - The Unix kernel also grew in size (System III, System V, BSD) – without significant structural changes
  - Very complex subsystems were integrated along the way
    - TCP/IP was about as complex as the rest of the kernel

- Linux was modelled after the structure of System V Unix

- Impact in academia: "**Open Source**" policy of Bell Labs
  - Weaknesses of Unix lead to new research questions
  - However, many projects (e.g. Mach) tried to remain **compatible** to Unix

# Monolithic systems: Evaluation

- **Isolation**
  - No isolation of components in kernel mode, only between application processes
- **Interaction mechanisms**
  - Direct function calls (in the kernel), Traps (application – kernel)
- **Interrupt handling mechanisms**
  - Direct handling of hardware interrupts by IRQ handlers
- **Adaptability**
  - Changes in one component influence other components
- **Extensibility**
  - Originally: recompilation required; today: kernel module system
- **Robustness**
  - Bad – an error in one component "kills" the complete system
- **Performance**
  - High – few copy operations required, since all kernel components use the same address space. System calls require a trap, however

# Monolithic systems: Discussion

- Complex monolithic kernels are difficult to work with
  - Adding or changing functionality often involves more modules than the developer intended

- Shared address space
  - Security problems in one component (e.g. **buffer overflows**) compromise the complete system
  - Many components unnecessarily run in system mode

- Reduced number of options for synchronization
  - Often only a "**Big Kernel Lock**", i.e. only a single process, can run in kernel mode at a time, all others have to wait
  - This is especially bad for the performance of multiprocessor systems

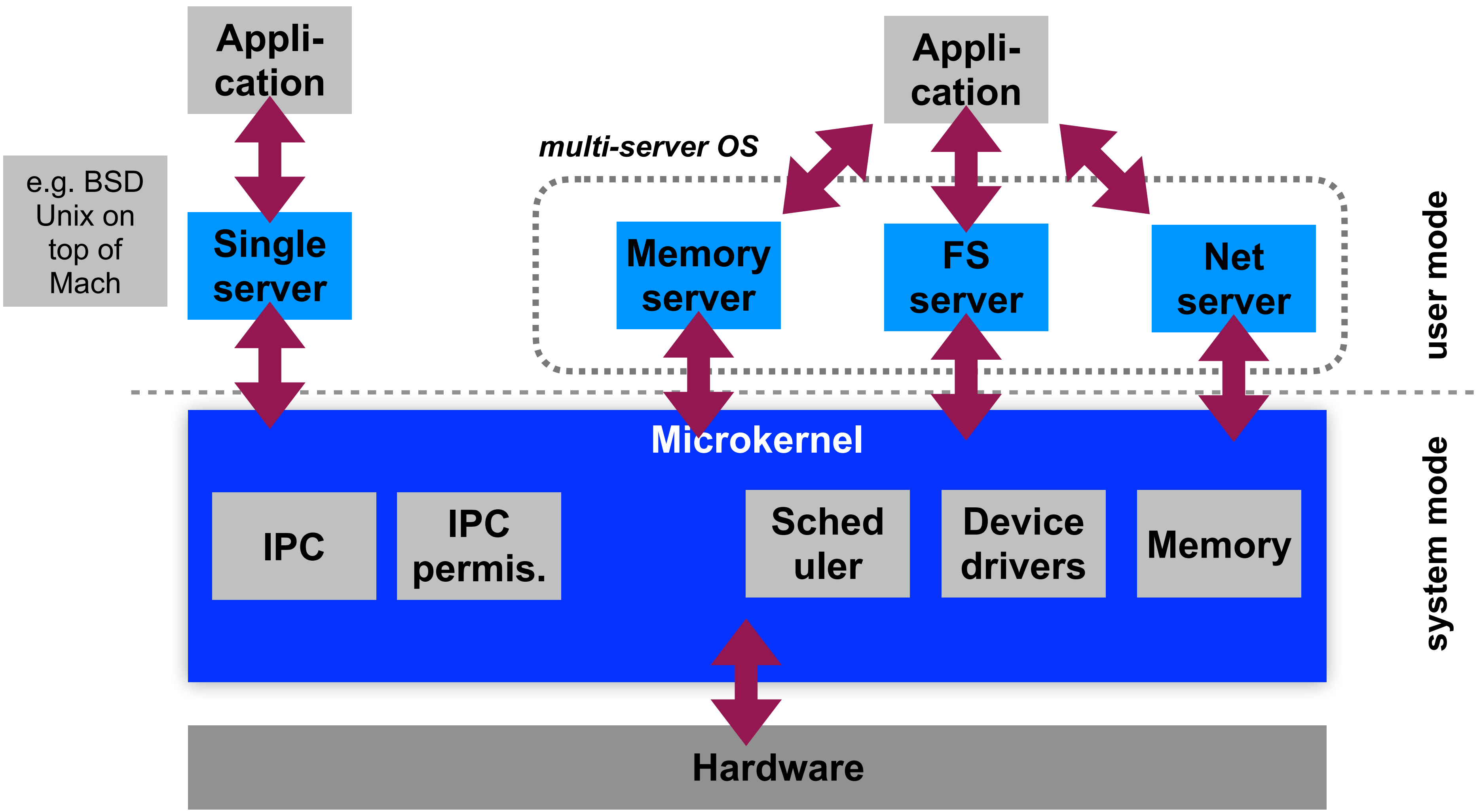
# Microkernel systems

- Objective: reduction of the **Trusted Computing Base (TCB)** size
  - Minimize functionality running in the privileged mode of the CPU
  - Isolate all other components against each other in non privileged mode
- Principle of least privilege
  - System functions are only allowed to have the privileges required to complete their task
- System calls and communication between processes using message passing (IPC – **inter process communication**)
- Reduced functionality in the microkernel
  - Lower code size (10,000 lines of C++ code in L4 vs. 5.5 million lines of C in Linux without device drivers)
  - Allows for formal verification of the microkernel (seL4)

# First-generation microkernels

- Example: CMU Mach [2]
- Initial idea: Separation of the features of (BSD) Unix into features requiring execution in the privileged mode of a CPU and all other features
- Objective: Creation of an extremely portable system
- Improvements to Unix concepts
  - New communication mechanisms using IPC and ports
    - Ports are secure IPC communication channels
    - IPC is optionally network transparent: support for distributed systems
  - Parallel activities inside of a single process address space
    - Support for threads → processes are now "containers" for threads
    - Better support for multiprocessor systems

# First-generation microkernels



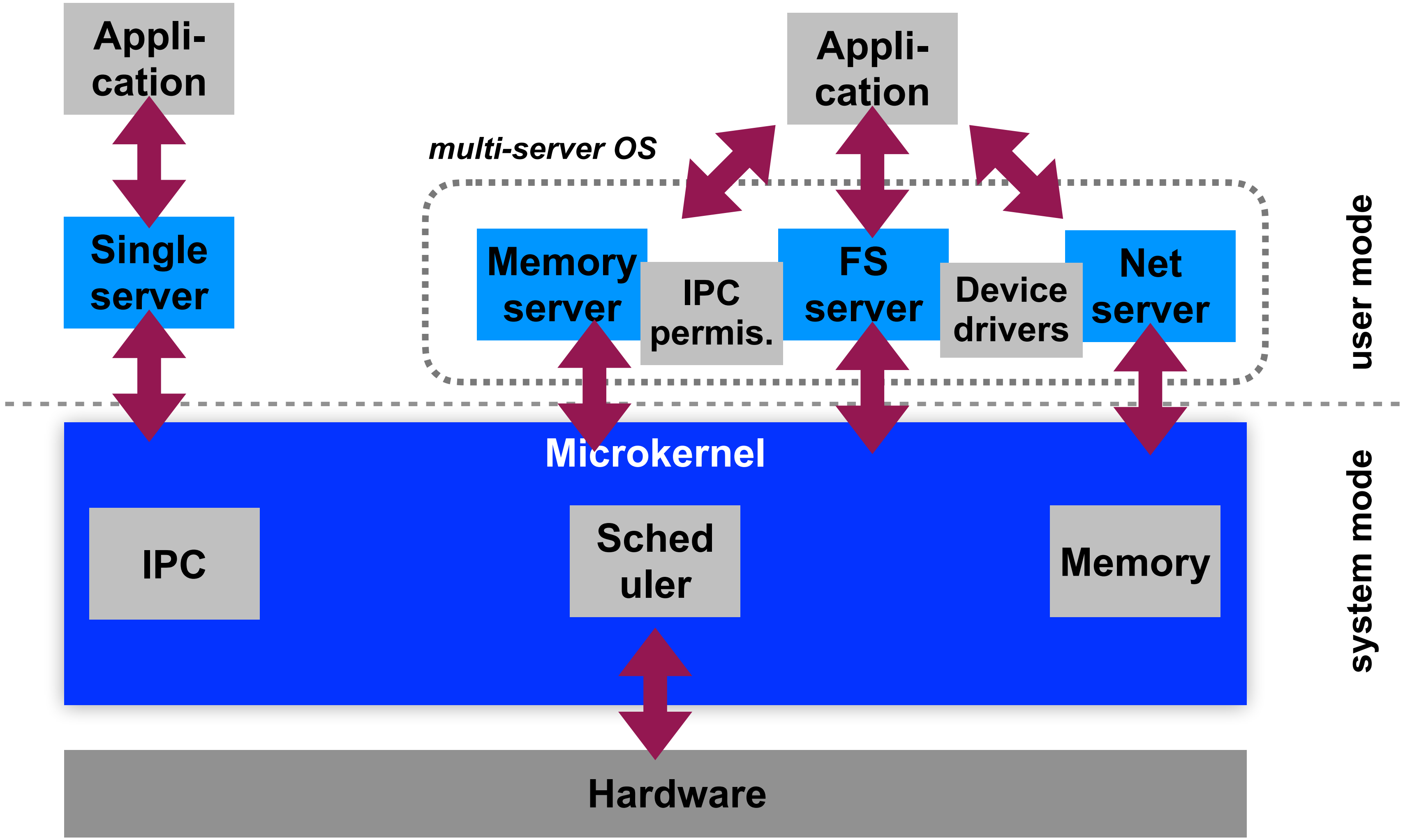
# First-generation microkernels

- Problems of Mach:
  - High overhead of IPC operations
    - System calls are a **factor of 10 slower** compared to a monolithic kernels
  - Sub-optimal decisions about which components should be implemented in the microkernel: large code base
    - Device drivers and permission management for IPC in the microkernel
  - Resulted in a bad reputation of microkernels in general
    - Practical usability was questioned
- The microkernel idea was **dead in the mid 1990s**
- Practical use of Mach mostly in hybrid systems
  - Separately developed components for microkernel and server
  - Colocation of the components in one address space, replacing of in-kernel IPC by function calls
  - Apple macOS: Mach 3 microkernel base + FreeBSD components

# Second-generation microkernels

- Objective: Remove disadvantages of first generation microkernels
  - Optimization of IPC operations
  - Jochen Liedtke: L4 (1996) [3]
    - *A concept is tolerated inside of a microkernel only if moving it outside of the kernel would prevent the implementation of functionality required in the system*
- Four basic mechanisms:
  - Abstraction of **address spaces**
  - A model for **threads**
  - Synchronous **communication** between threads
  - **Scheduling**
- Much of the functionality implemented in kernel mode in first generation microkernels now runs in user mode
  - e.g. checking of IPC communication permissions

# Second-generation microkernels



# Microkernel OS: Evaluation

- **Isolation**
  - Very good – separate address spaces for all components
- **Interaction mechanisms**
  - Synchronous IPC
- **Interrupt handling mechanisms**
  - The microkernel translates interrupts into IPC messages
- **Adaptability**
  - Originally hard to adapt – x86 assembler code, today in C/C++
- **Extensibility**
  - Very good and simple as components in user mode
- **Robustness**
  - Good – but dependent on the robustness of user mode components
- **Performance**
  - In general depending on the IPC performance

# Exokernel OS: Even smaller…

- Idea to simplify the OS even further [4]:
  - The lowest system software layers **does not implement strategies** or abstractions and does also not virtualize resources
  - One single task: **resource partitioning**
    - Every application is assigned its own set of resources
    - The assignment is enforced by the exokernel
    - Everything else is implemented according to demand using **application-specific library operating systems** inside of resource containers

- Problem: Library operating systems are specific to the respective exokernel

# Virtualization

- Objective: Isolation and **multiplexing** of resources below the operating system layer [5]
  - Simultaneous use of **multiple** **guest operating systems**

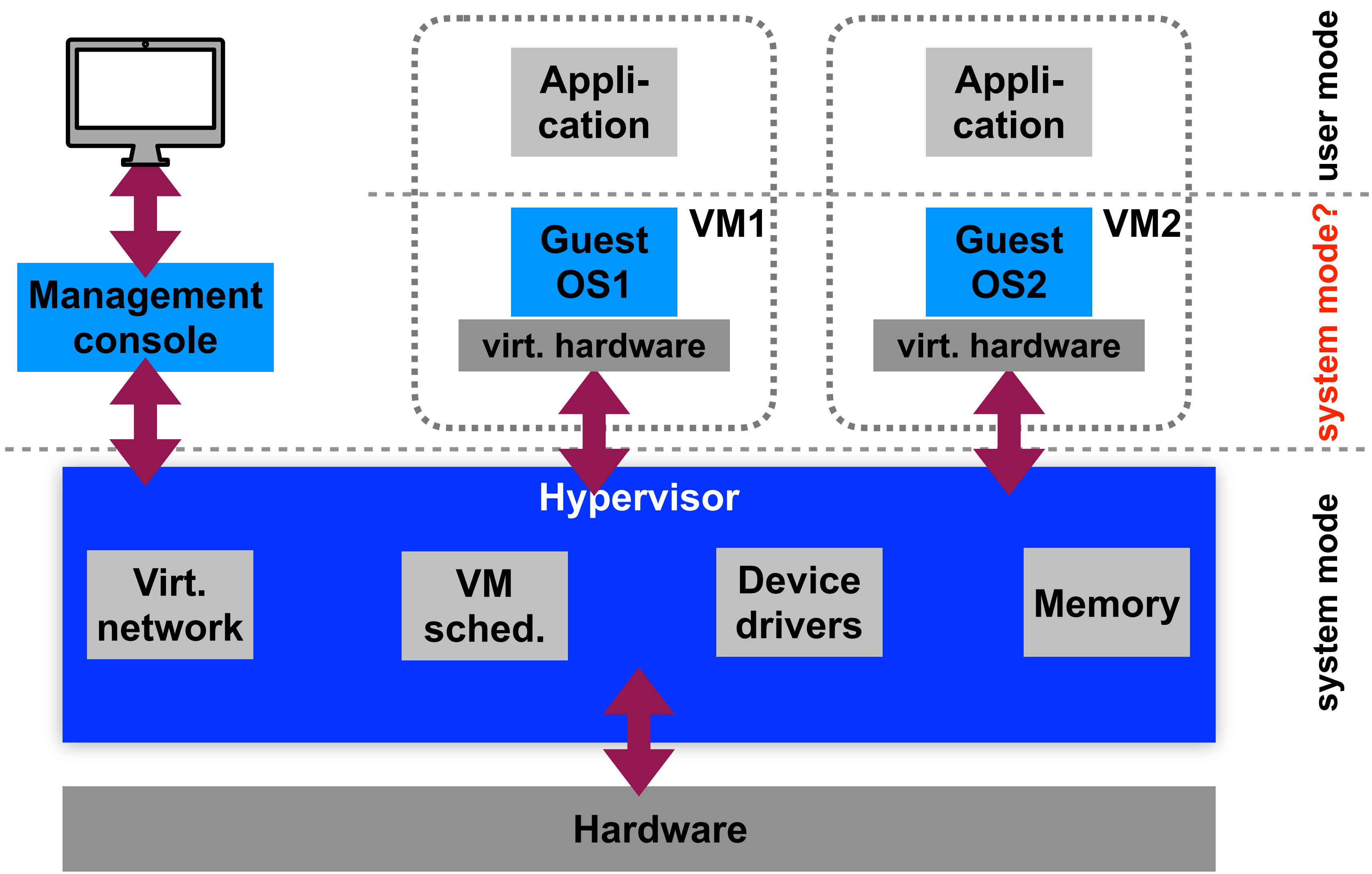
- Virtual machines (VMs) on system level virtualize hardware resources such as:
  - Processor(s), main memory and mass storage resources, peripheral devices

- A **virtual machine monitor** (VMM) or **hypervisor** is the software component that provides the virtual machine abstraction

# Virtualization: IBM VM

- IBM S/360 mainframes: many different operating systems
  - DOS/360, MVS: batch processing library operating systems
  - OS/360+TSO: Interactive multi user system
  - Customer-specific extensions
- Problem: How to use all systems simultaneously?
  - Hardware was expensive (millions of US$)
  - OS expect to have control over the complete hardware
    → This illusion has to be maintained for every OS
- Development of the first system virtualisation "VM" as a combination of emulation and hardware support
  - Enabled simultaneous operation of batch processing and interactive operating systems

# Virtualization with a type 1 hypervisor



# Hardware-supported virtualization

- Example x86: Privileged instructions in ring 0 can be caught
  - Intel "Vanderpool" (Intel VT-x), AMD "Pacifica" (AMD-V)
  - Additional logical privilege mode: often called "ring -1"
- Guest OS kernel runs in ring 0 as before
- "Critical" instructions in ring 0:
  - Trap to the hypervisor
  - The hypervisor **emulates** critical instructions
  - or stops the OS using them (if not permitted)
- Allows to use multiple completely unchanged OS instances on a single hardware system at the same time
  - Peripheral devices of the respective VMs still have to be emulated, since the virtualized systems are not aware of the presence of the other OSes

# Paravirtualization

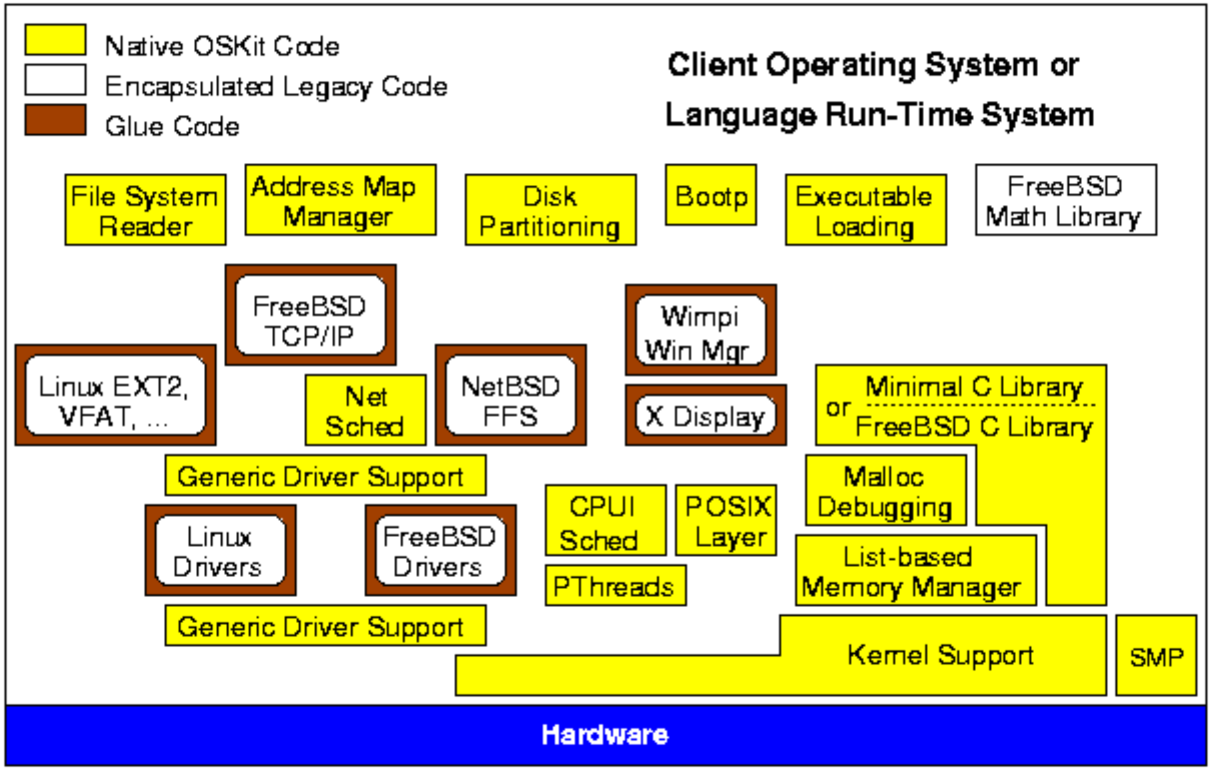
- Applications of the virtualized OS run unchanged, but the virtualized OS itself requires a **special kernel**
- Guest kernel runs (on x86) in a protection ring > 0 (e.g. ring 3)
  - not in system mode
- Realization:
  - "critical" instructions (interrupt handling, memory management, etc.) in the guest kernel are replaced by **hypercalls** (explicit calls to the hypervisor)
    - VMware approach: kernel binary code is adapted when loading the guest OS
    - Xen approach: modification of the OS source code
  - Performance improvement: Hypercalls also used to access peripherals and the network – no more slow hardware emulation required

# Virtualization: Evaluation

- **Isolation**
  - Very good – but coarse granularity (between VMs)
- **Interaction mechanisms**
  - Communication between VMs only via TCP/IP (virtual network cards!)
- **Interrupt handling mechanisms**
  - Forwarding of IRQs to guest kernel inside of the VM (simulated hardware interrupts)
- **Adaptability**
  - Specific adaptation for a CPU type required, paravirtualization has a lot of overhead
- **Extensibility**
  - Difficult – not commonly available in VMMs
- **Robustness**
  - Good – but coarse granularity (whole VMs affected by crashes)
- **Performance**
  - Good – 5-10% lower compared to direct execution on the same hardware

# Libraries of OS functionality

- "**Unikernels**" are used to efficiently execute *a single application* inside of a virtual machine
  - mirageOS, Mini-OS, Unikraft, …
- Example: Utah OSKit [6]
  - "best of" of different operating system components
  - Interfaces adapted to conform to a single standard
  - Language support (interface generator) enables easy integration of components



# OS architectures: Conclusion

- OS architectures are still a current area of research
  - "old" technologies such as virtualization find new applications today, e.g. in cloud computing
  - Hardware and applications change all the time, e.g.
    - Energy awareness (energy harvesting)
    - Scalability (multi-/manycore processors)
    - Heterogeneity (ARM big.LITTLE, GPUs, ...)
    - Adaptability (mobile systems, resource constrained systems)
    - Persistent main memories (TI FRAM, Intel DCPMMs)
- Compatibility requirements and high development costs prevent the fast acceptance of new developments
  - Virtualization is used as compatibility layer

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