Operating System Structure

- Broad goals of an operating system
  - Make it easier for a user to use the system
  - Manage the system resources efficiently among multiple users
- What is a “resource”?
  - Any logical component that a OS manages
  - A user has to request the use of the resource from the OS, cannot directly access it
  - Ex. CPU, memory, devices, files, …
  - Allows the details of the hardware operations and management to be hidden from the user

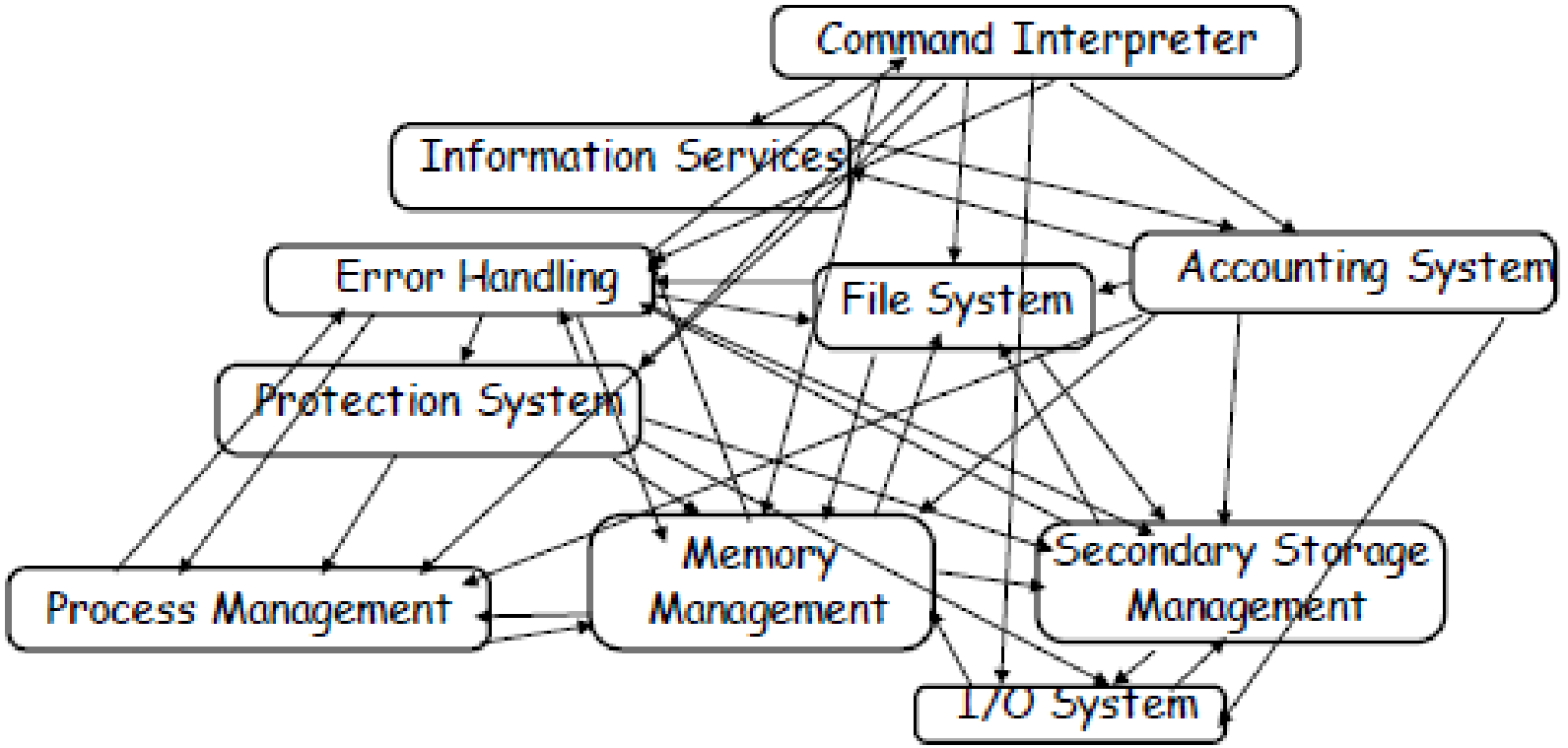
- Resource management can be complex
  - Allocation and deallocation of limited resources among multiple processes
  - Some resources may be shared between processes
    - Requires mechanisms for exclusive use
      - Software, hardware, software+hardware?
  - Reclaiming unused resources
  - Dependency between resources
- Resource manager can be a combination of complex, interacting programs

Functionalities of an OS

- Process and associated resource management
  - Provide illusions of multiple virtual machines
- Memory management
  - Allocation to processes
  - Reclaiming unused memory
  - Protection from unauthorized access
  - Mechanisms for sharing
- Device Management
  - Provides controlling functions to many devices
- File Management
  - Provides organization and storage abstractions

- Communication
  - Between processes
  - Between machines
- Protection and Security
- Accounting
- Error detection and reporting
- User interface

A collection of interacting programs provide these services



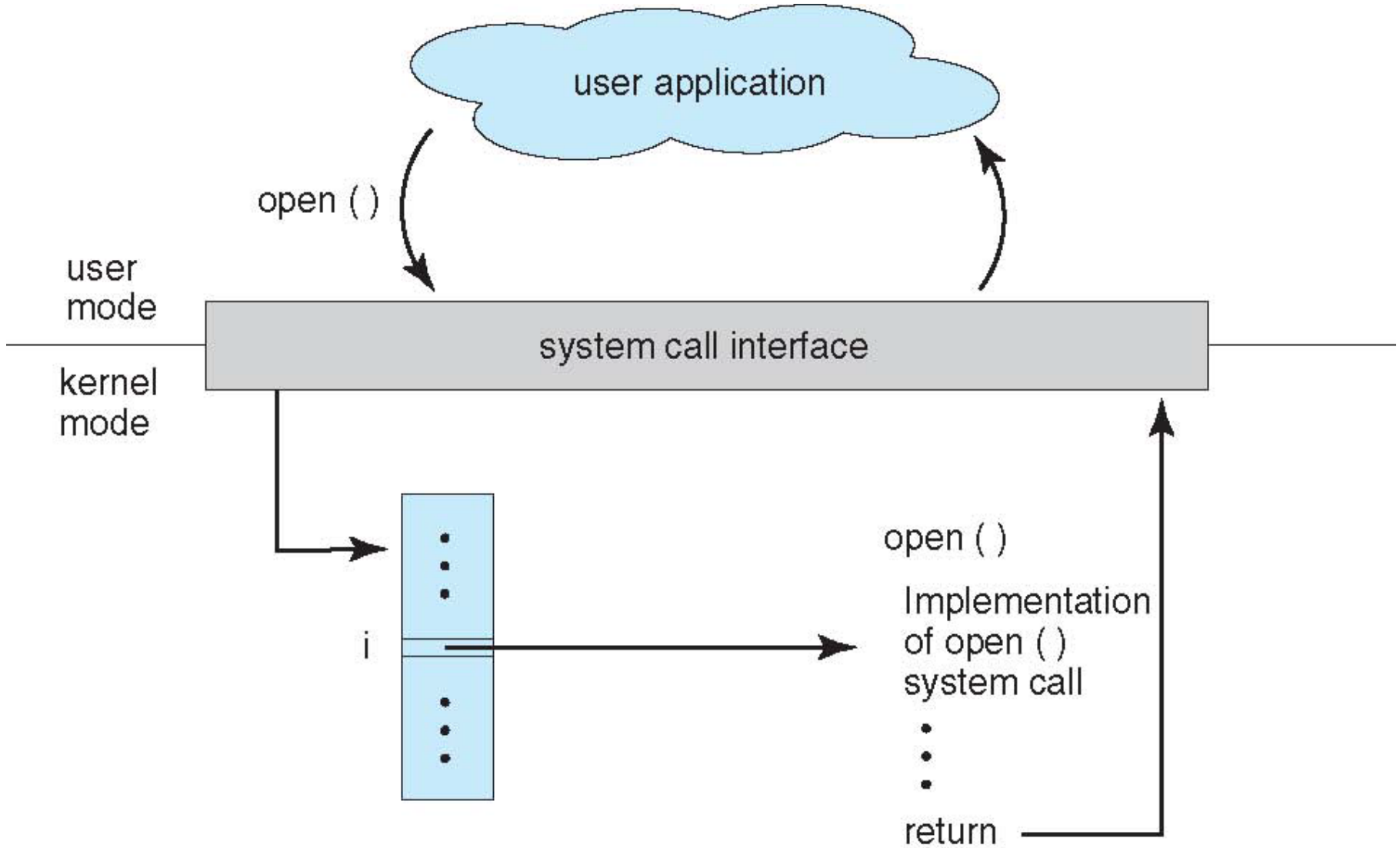
How do we put them all together?

OS Organization

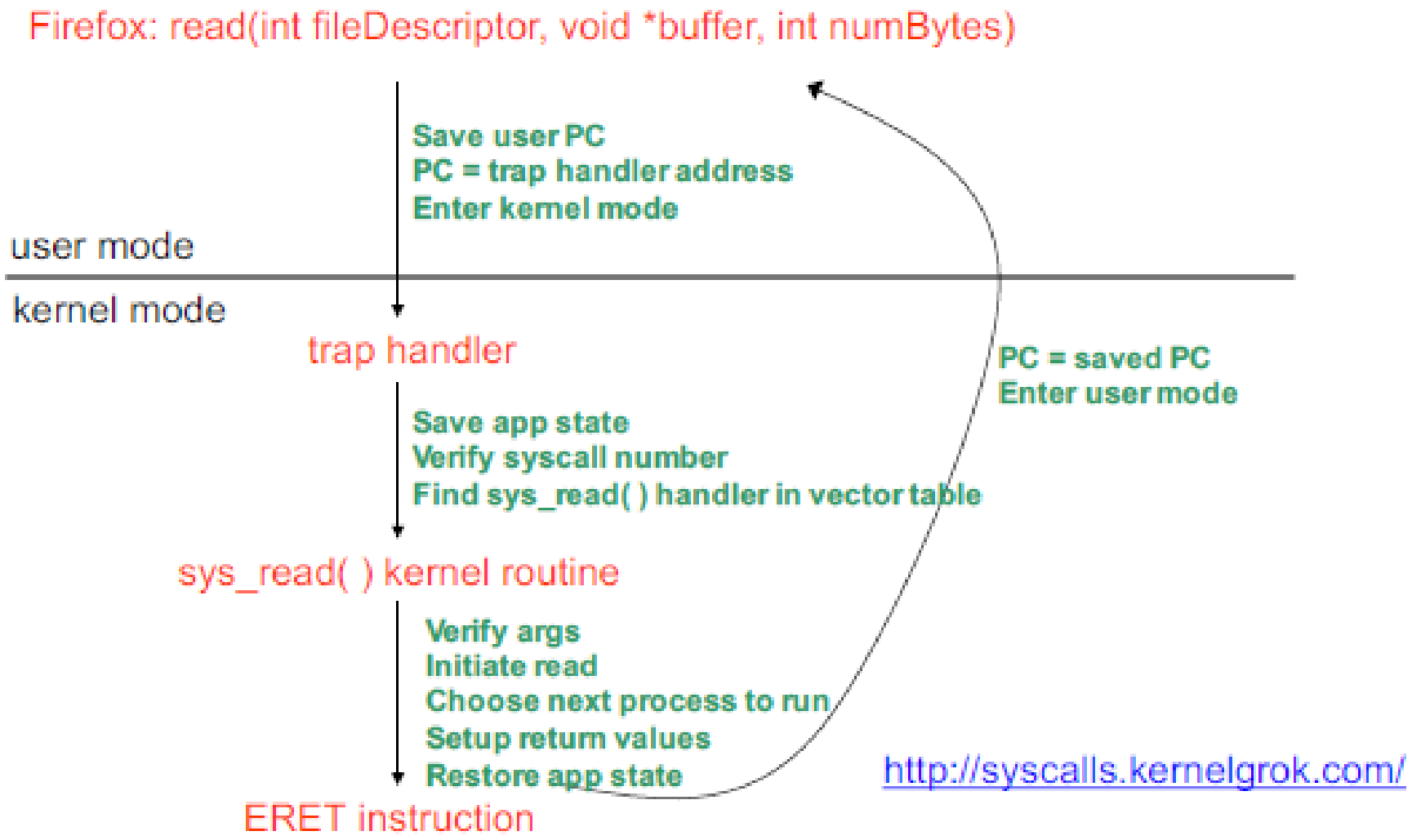
- Kernel
  - A protected part of the OS, user programs cannot access it directly
- User programs
  - Application programs/services built using the services provided by the kernel
- Why this division needed?
    - To prevent direct access to devices and memory for protection
- How is protection implemented?
  - Uses hardware supported special privileged instructions that can only be executed in a privileged mode
  - Kernel programs are allowed to execute them
  - User programs are not allowed to execute them

- So how can user programs do something protected
  - No direct way, need to ask the OS
  - System Calls – special functions that user programs can call to request kernel services
- How do system calls work?
  - Set of known system calls, each with a specific id (number)
  - Calling function puts all parameters in predefined places (registers)
  - Calling function puts the system call id also in a register
  - Makes a special call (same for all system calls; ex syscall)

- The special call
  - Saves current PC
  - Changes execution mode to privileged
  - Sets PC to a handler function
- Handler function
  - Checks the system call id
  - Verifies the arguments
  - Jumps to the specific system call handler
- After the system call is executed, a special return instruction is executed that sets the PC to the return address in the user program code
  - Also sets execution mode back to non-privileged.


user application
open ( )
user mode
system call interface
kernel mode
i
open ( )
Implementation of open ( ) system call
return

Example

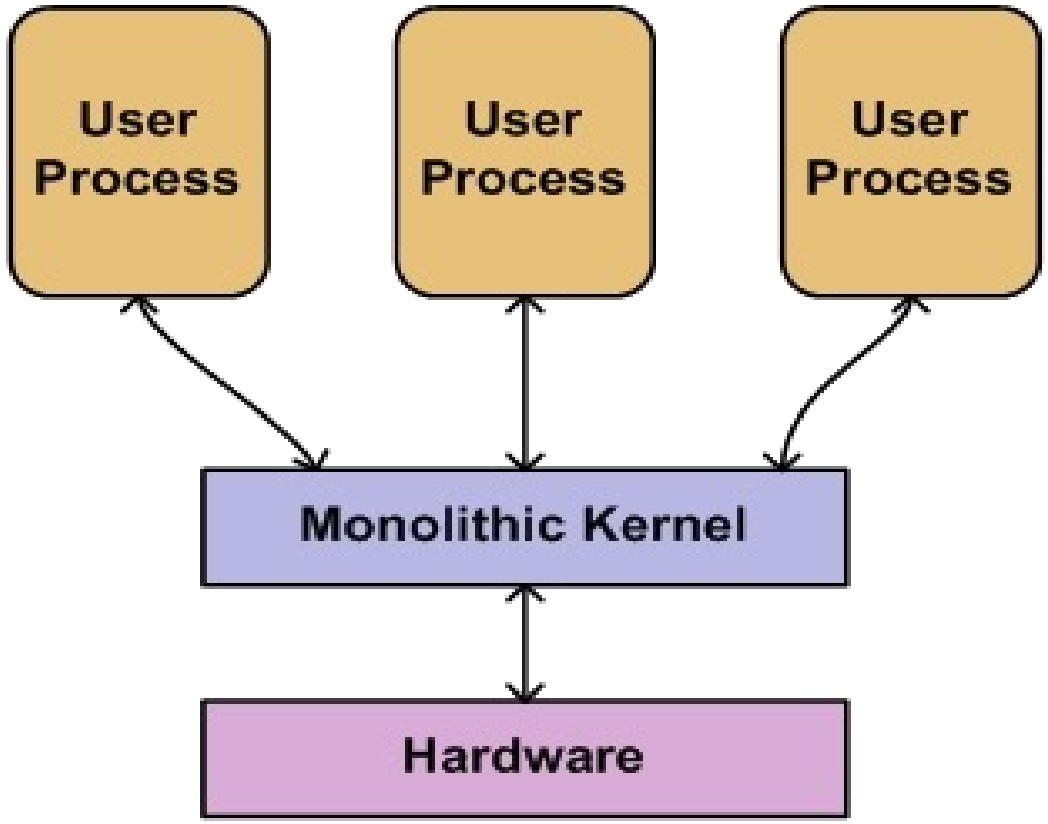

Firefox: read(int fileDescriptor, void *buffer, int numBytes)
Save user PC
PC = trap handler address
Enter kernel mode
user mode
kernel mode
trap handler
PC = saved PC
Enter user mode
Save app state
Verify syscall number
Find sys_read( ) handler in vector table
sys_read( ) kernel routine
Verify args
Initiate read
Choose next process to run
Setup return values
Restore app state
ERET instruction
http://syscalls.kernelgrok.com/

Structure of an OS

- General design goals of an OS
  - User goals – should be easy to use, easy to learn, reliable, secure, fast
  - System goals – should be easy to design, easy to implement, easy to maintain, reliable, flexible, secure, fast
- Given the above goals
  - How do we organize all the programs that make up an OS?
  - How do we decide what goes in the kernel and what goes in user mode?
  - Different approaches

Monolithic OS

- Put everything in the kernel
- Only application programs in the user space
- Kernel handles all system tasks, applications have no control
- Example: Windows 9x, FreeBSD, Unix variants



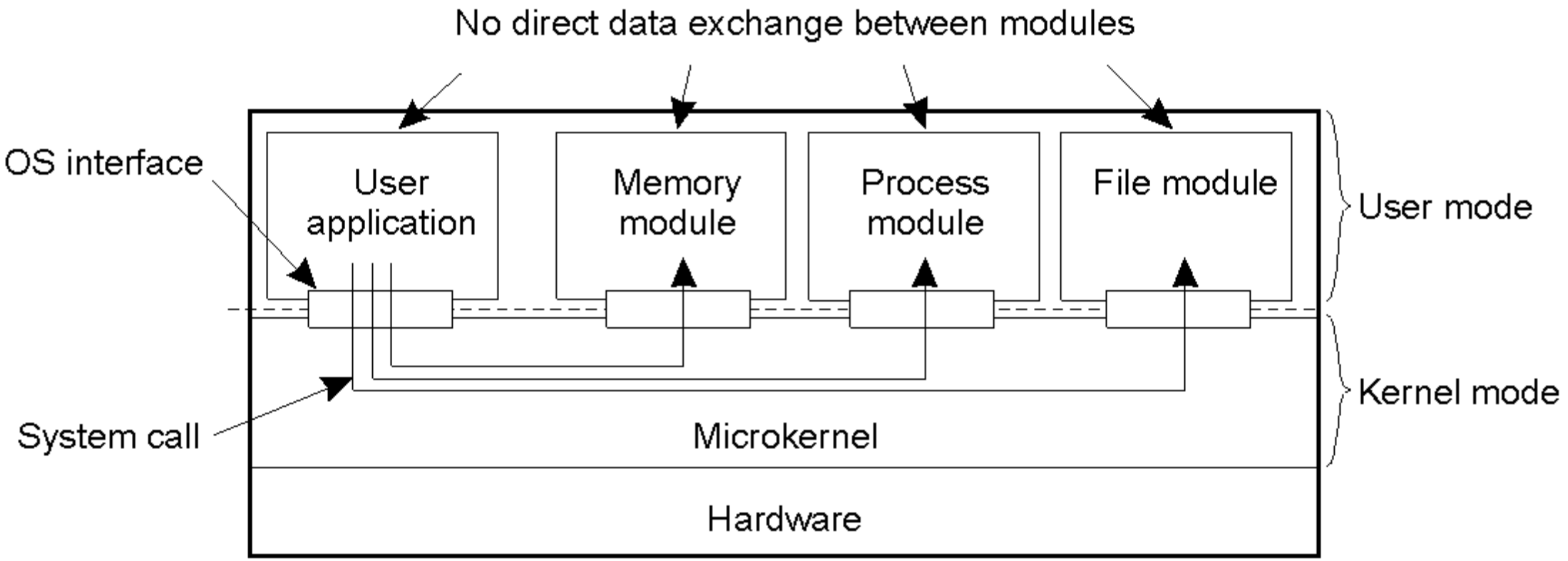
Ref: Kaashoek et al.

- Advantages
  - Lower overhead possible between multiple kernel modules due to direct interaction
  - Strong protection from user programs
  - Application programs can get all services from one place
- Disadvantages
  - Bulky code that is hard to implement and maintain
  - Hard to change anything or add new components/services
  - Slower, as system calls are made for everything, and system calls are costly
  - Little isolation between different OS modules

Microkernel based OS

- Only minimal services implemented in the kernel
  - Example: CPU scheduling, interprocess communication, memory allocation/deallocation
- Rest are implemented in user space as needed
  - Example: Memory management, File system management, Networking,…
- Example: L4 Microkernel, MACH (precursor of MacOS), QNX

Microkernel based OS



Ref: Tanenbaum's distributed systems.

Microkernel based OS

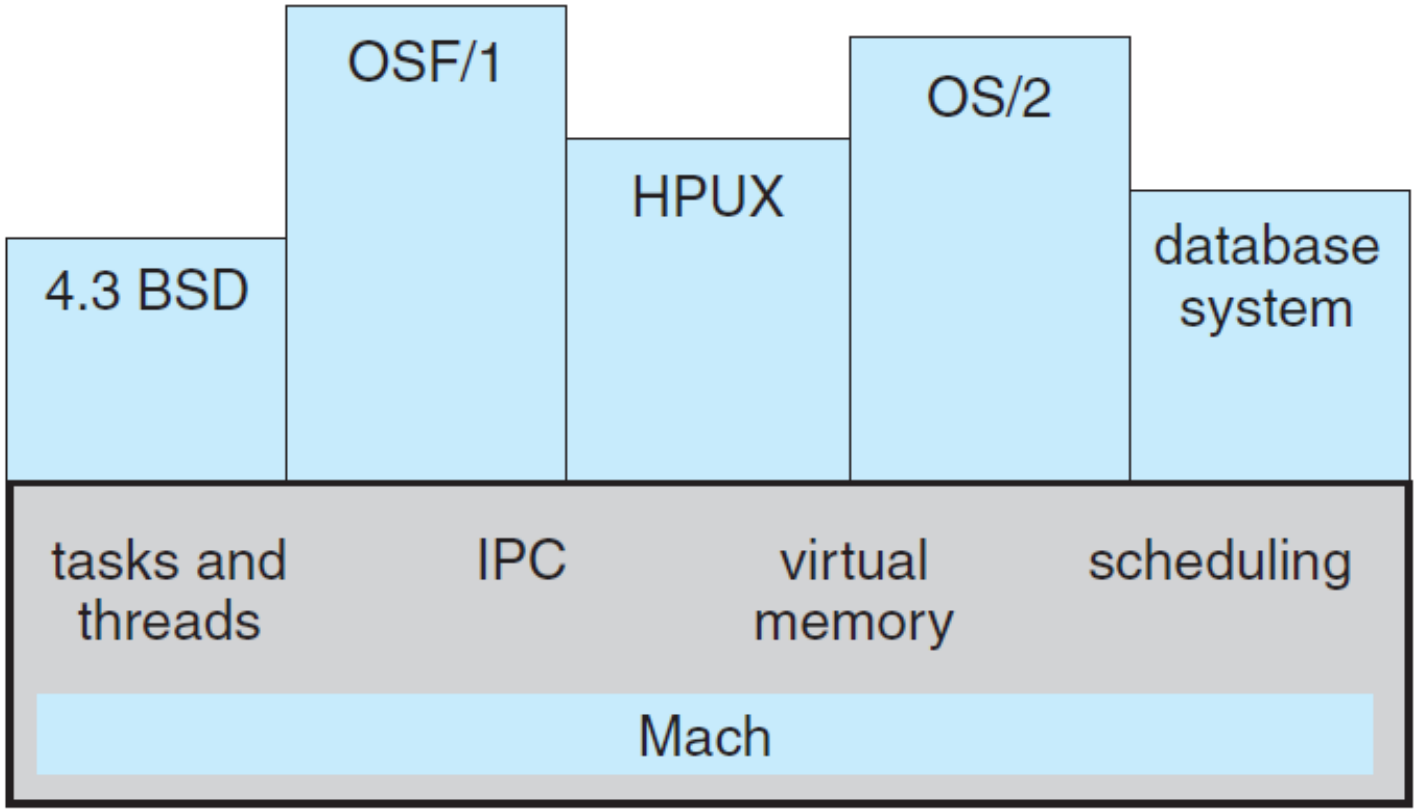
- Advantages
  - Smaller code that can be easily implemented, tested, and maintained
  - Easier to modify/add/remove services
  - Easier to port OS to new architectures
  - More reliable (less code is running in kernel mode)
  - More secure
- Disadvantages:
  - Too much user space to kernel space communication

Example: Mach

- Project at CMU in 80's
- Mach 2
  - Many improvements over an earlier OS, Accent, developed in CMU
    - Threads, better IPC, multiprocessor support, virtual memory support
  - Native support for 4.2/4.3 BSD code
    - Large kernel, but fully compatible with BSD, which was a DARPA requirement
- Mach 3 (1990-94)
  - Removes all BSD code from kernel and puts it in user space
  - User level OS emulator for BSD Unix

Basic Approach

- Has a very thin kernel, with most OS functionality moved out of the kernel
- Object oriented approach, however, objects cannot directly call functions on other objects, they have to communicate by message passing
  - Individual, well-defined components (in effect, subsystems) communicate with one another by means of messages
- Mach provides a very thin kernel, most OS functionalities are built on top of it in user space
  - Sort of a kernel-within-a-kernel
  - Several OS implementations exist that use Mach at the bottom
    - BSD implementation
    - XNU, an OS implemented on top of Mach


OSF/1
OS/2
HPUX
4.3 BSD
database system
tasks and threads
IPC
virtual memory
scheduling
Mach

- In Mach, everything is implemented as its own object
- Processes (which Mach calls tasks), threads, and virtual memory are objects, each with its own properties
- Mach implements object-to-object communication by means of message passing
- Unlike other architecture, Mach objects cannot directly invoke or call on one another, rather they are required to pass messages

- The source object sends a message, which is queued by the target object until it can be processed and handled
- Similarly, the message processing may produce a reply, which is sent back by means of a separate message
- Messages are delivered reliably in a FIFO manner
- The content of the message is entirely up to the sender and the receiver to negotiate

Mach Kernel Abstractions

- A small set of abstractions of that is simple but powerful
  - Tasks
    - Provides an environment for program execution
    - Units of resource ownership
    - Each task consists of a virtual address space, a port right namespace, and one or more threads (Similar to a process.).
    - Allocation of resources to individual threads or groups
    - The task itself does no execution, it is a framework for running threads
  - Threads
    - Basic unit of execution/scheduling
    - All threads of a task share the same virtual address space and port rights
    - Multiple threads from one task can execute simultaneously

Mach Kernel Abstractions

- Address space
  - In conjunction with memory managers, Mach implements the notion of a sparse virtual address space and shared memory.
- Memory objects
  - The internal units of memory management.
  - Memory objects include named entries and regions; they are representations of potentially persistent data that may be mapped into address spaces
  - Provides for allocating/deallocating memory to tasks
  - Can specify specific access rights (like read-only) on parts of the address space, or which parts should to be inherited if a task is cloned

Mach Kernel Abstractions

- Ports
  - Secure, simplex communication channels (message queues)
  - There is send/receive access rights defined for each port
  - Tasks, threads, and other resources are associated with ports
  - Tasks and threads can also have access rights to task ports and thread ports of other tasks and threads
  - Any number of tasks/threads can have send rights on a port, but at a time only one task/thread can have receive rights
  - Access rights can be passed rom one task (thread) to another also through the ports (again by sending message)
  - Access rights to a task/thread port allows calling Mach functions on that port
  - Port have unique names
  - Network-wide name service to look up port
    - Allows for messages to be passed over the network to another machines
  - Messages are data streams with header and content, format known to sender and receiver

Mach Kernel Abstractions

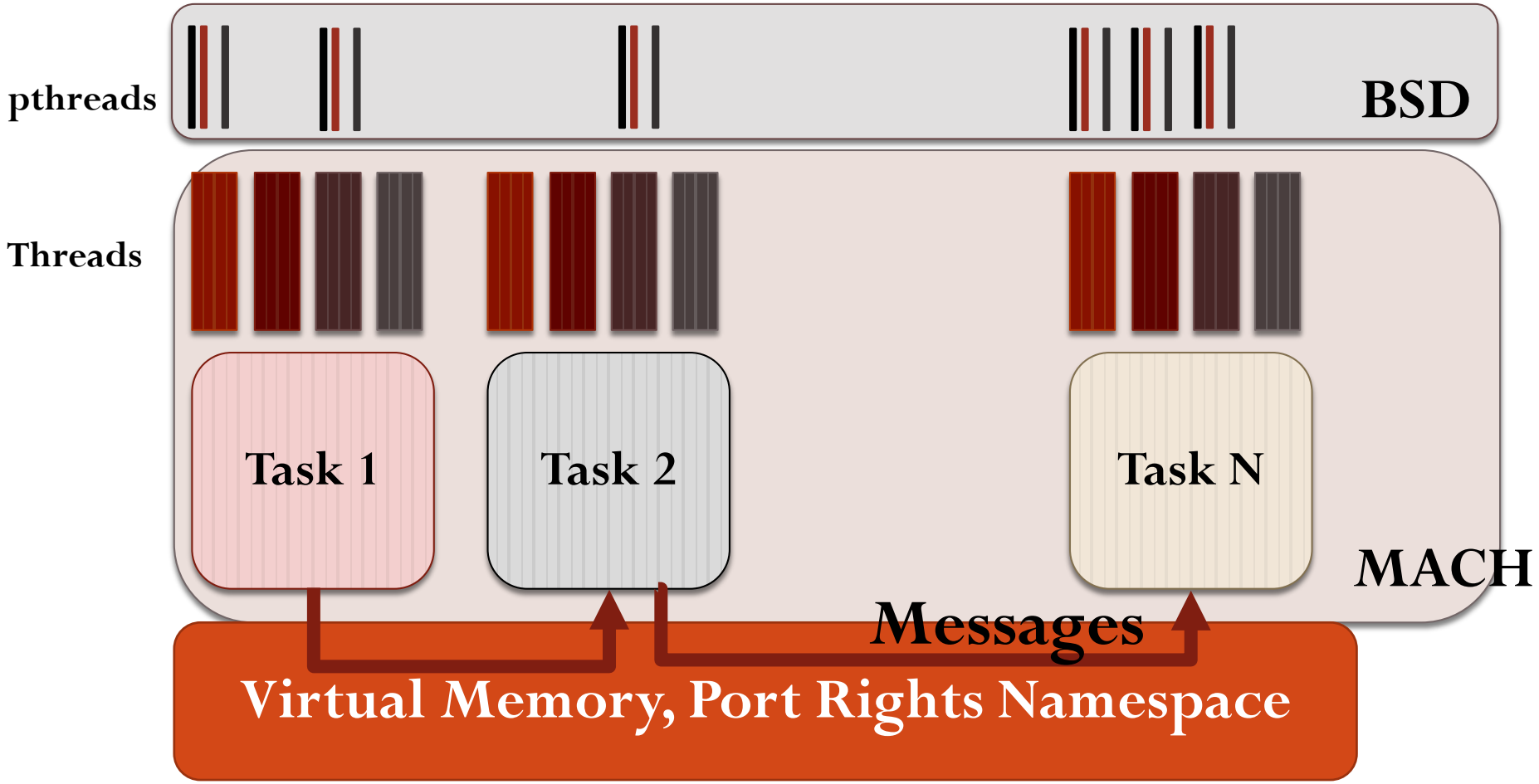
- IPC
  - Message queues
  - Remote procedure calls
  - Notifications
  - Semaphores
  - Lock sets
- Time
  - Clocks, timers, and waiting.

Mach Interface

- Set of calls to access Mach services
  - Bootstrap
  - IPC
  - Messaging
  - Port manipulation
  - Virtual memory
  - Tasks and threads
  - Scheduling
  - Processor
  - Device

https://www.gnu.org/software/hurd/gnumach-doc/

https://web.mit.edu/darwin/src/modules/xnu/osfmk/man/

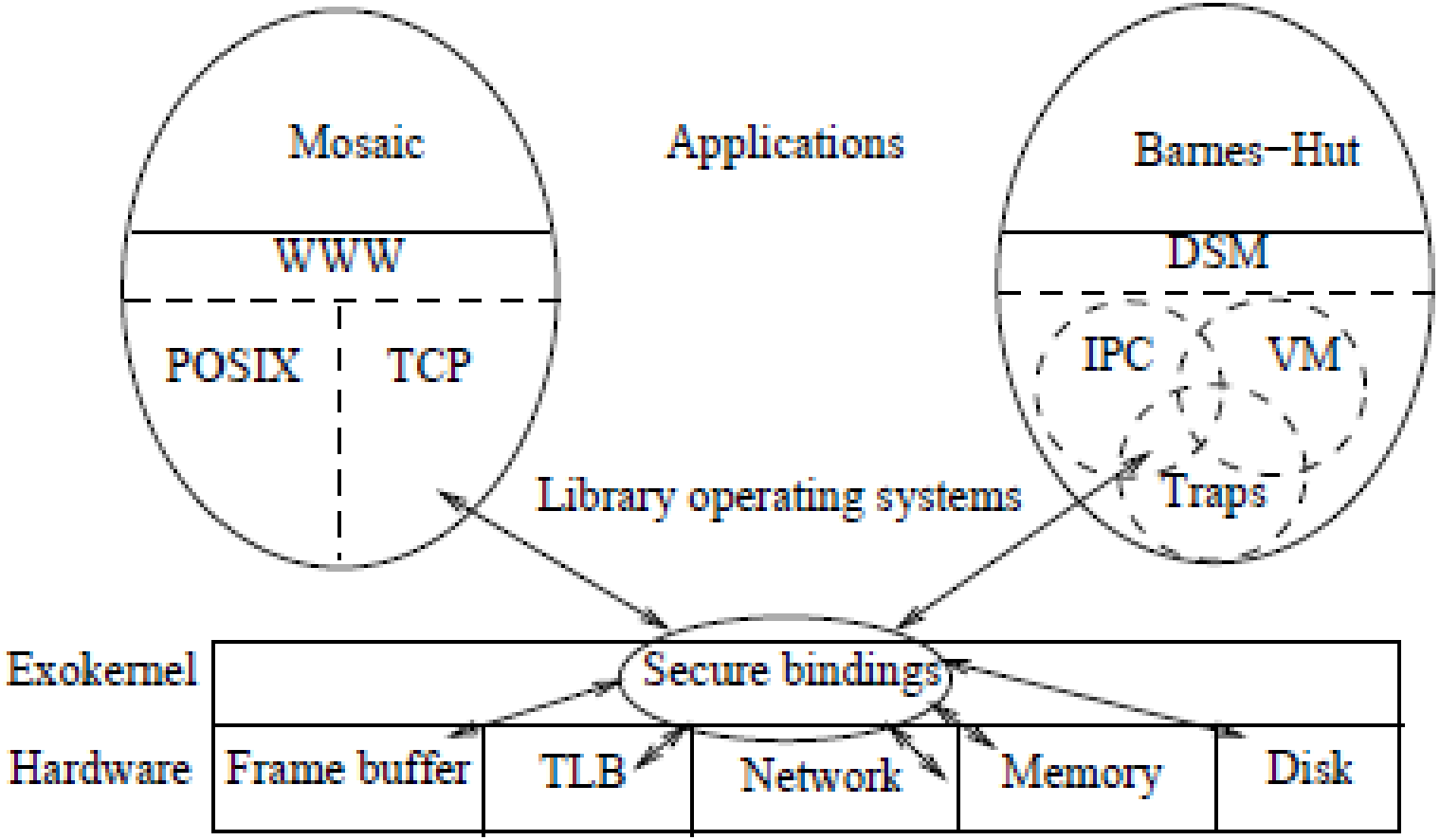

pthreads
BSD
Threads
Task 1
Task 2
Task N
MACH
Messages
Virtual Memory, Port Rights Namespace

Exokernel Architecture

- Philosophy: "*Applications know better than operating systems what the goal of their resource management decisions should be and therefore, they should be given as much control as possible over those decisions*"
- Traditional implementations have hardcoded abstractions
  - Processes, files, address spaces, IPC,…
- Different applications may have different needs
  - Hard to do domain specific optimizations
  - Examples
    - Applications may know their file access patterns but internal file caching policies in filesystem implementations may be different
    - Data access patterns may not match page replacement strategies

- Separate out management and protection
  - ***Management:*** Allocate resources based on the requirement
    - Example: An application asks for a memory block
    - However, read-write strategy over that memory block will be decided by the application
    - Done primarily by application
  - ***Protection*:** Ensures no conflict in resource allocation
    - Maintain ownership of resources
    - Example: Do not allocate a memory block if it is already allocated to another application
    - Done by Exokernel
    - Management done only for what is needed for protection

- Approach
  - Multiplex and Export hardware resources with low level primitives
    - Interrupts, timers, device I/O, physical memory, TLB, …
  - Library OS's implement the higher level abstractions using these primitives
- Three important tasks
  - *Secure binding*: allows Library OS's to securely bind to machine resources'
  - *Visible revocation*: allows Library OS's to participate in resource revocation protocols
  - *Abort*: allows Exokernel to break bindings of uncooperative Library OS's by force

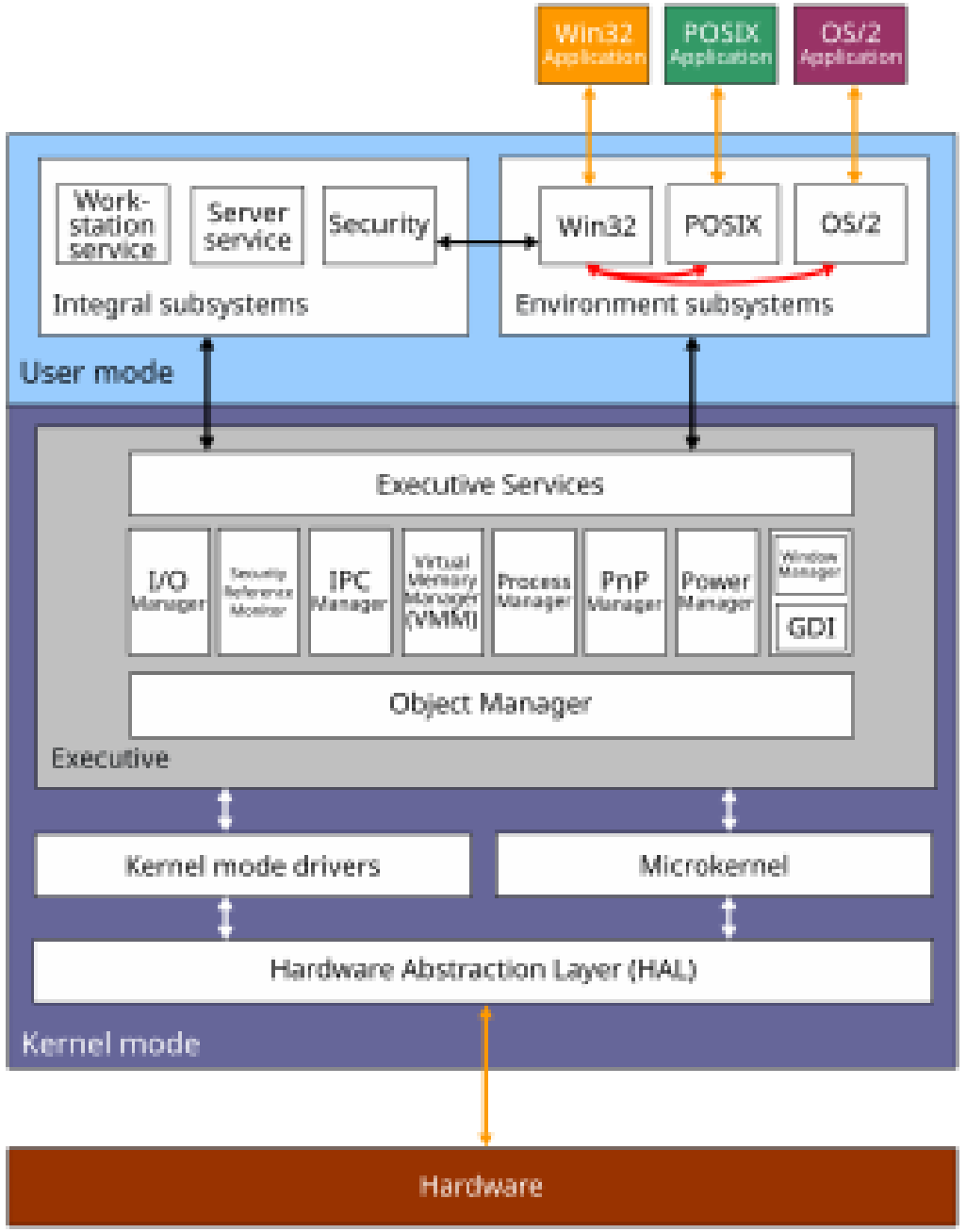

Mosaic
Applications
Barnes−Hut
WWW
DSM
POSIX
TCP
IPC
VM
Traps
Library operating systems
Exokernel
Secure bindings
Hardware
Frame buffer
TLB
Network
Memory
Disk

- An example
  - Library asks for physical memory from Exokernel
  - Exokernel allots the physical memory
    - Same memory is not allotted to two Library OSs
  - Library OS implements its own virtual memory system using it
  - When a TLB miss happens, Library OS finds the mapping using its virtual memory implementation
  - Asks Exokernel to put it in TLB
  - Exokernel checks if the physical memory in the mapping is in the range allocated to that Library OS
  - Add if yes, reject if now

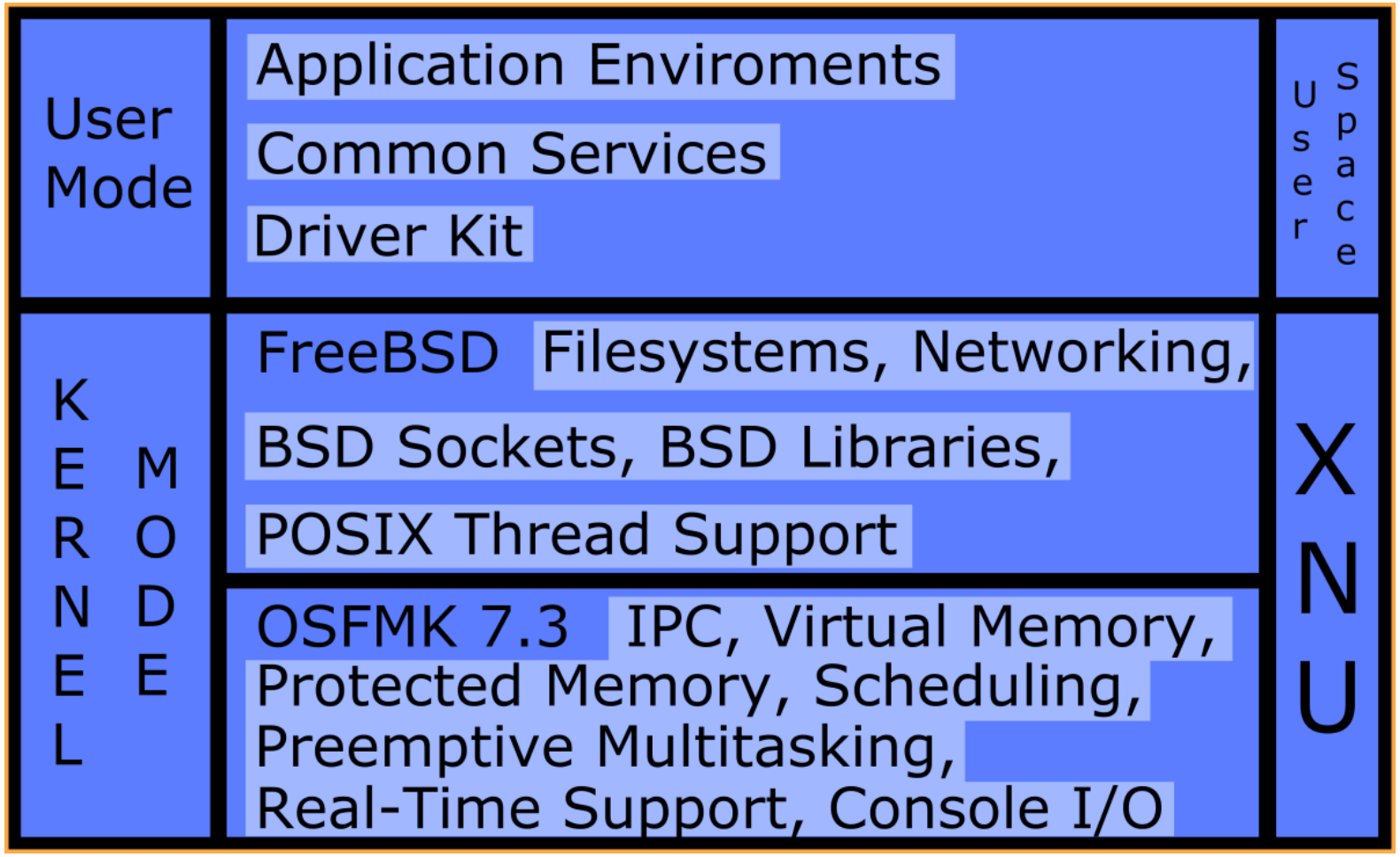
Hybrid Systems

- Attempts to combine monolithic and microkernel approaches
- Not a very standard term
- Examples
  - Linux is mainly monolithic, but allows Loadable Kernel Module for adding additional functionalities to the kernel easily
  - Windows is monolithic, but design inside has clear separation between core kernel services and executive services on top o it
  - XNU has Mach-based microkernel and BSD (and some other things) on top of it, all in kernel mode

Windows


Win32 Application
POSIX Application
OS/2 Application
Work-station service
Server service
Security
Integral subsystems
Win32
POSIX
OS/2
Environment subsystems
User mode
Executive Services
I/O Manager
Security Reference Monitor
IPC Manager
Virtual Memory Manager (VMM)
Process Manager
PnP Manager
Power Manager
Window Manager
GDI
Object Manager
Executive
Kernel mode drivers
Microkernel
Hardware Abstraction Layer (HAL)
Kernel mode
Hardware

XNU


User Mode
Application Enviroments
Common Services
Driver Kit
User space
KERNEL MODE
FreeBSD Filesystems, Networking,
BSD Sockets, BSD Libraries,
POSIX Thread Support
OSFMK 7.3 IPC, Virtual Memory,
Protected Memory, Scheduling,
Preemptive Multitasking,
Real-Time Support, Console I/O
XNU