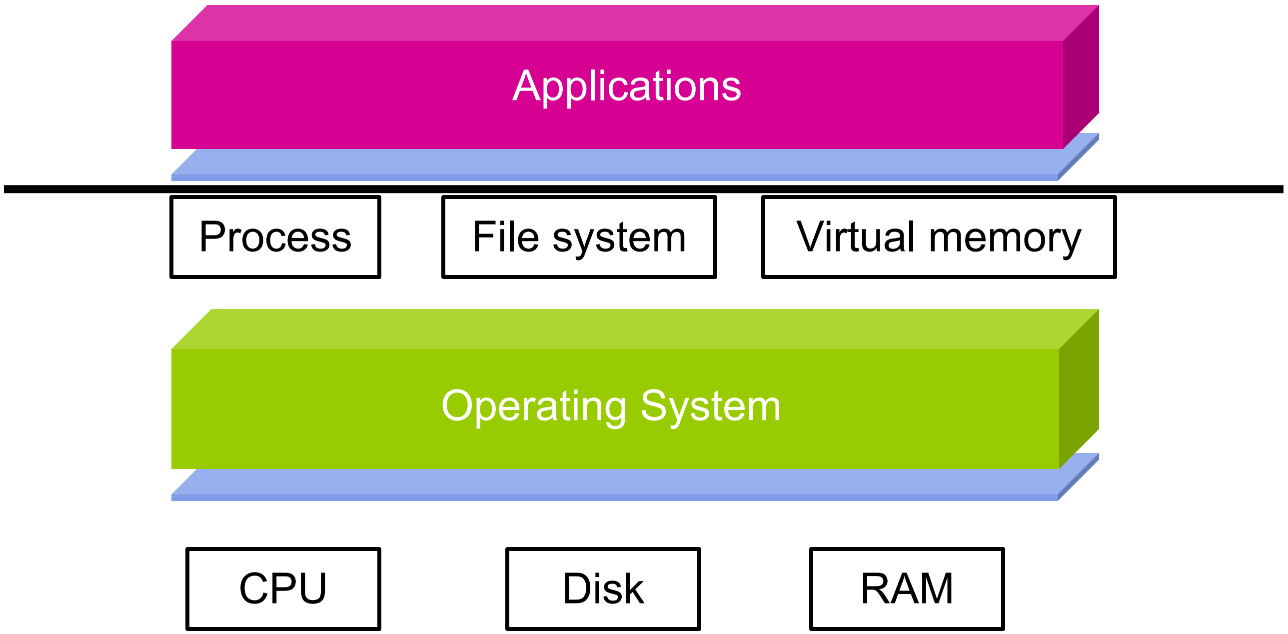
Extensible OS Design

CS 202: Advanced Operating Systems

UCR
UNIVERSITY OF CALIFORNIA, RIVERSIDE

Recall: OS Organization



Separate OS and User space

Why is the structure of an OS important?

- Protection
  - User from user and system from user
- Performance
  - Does the structure facilitate good performance?
- Flexibility/Extensibility
  - Can we adapt the OS to the application
- Scalability
  - Performance goes up with more resources
- Agility
  - Adapt to application needs and resources
- Responsiveness
  - How quickly it reacts to external events
- Can it meet these requirements?

Extensibility

- What do we mean by extensibility?
  - Flexible to add new features/functionalities
  - Customization
  - Good efficiency
  - Good security

- Can you give a few examples?
  - Browser plugins/extensions
  - Device drivers
  - Virtual memory policy, OS scheduler, …

Simple extensions

Extensibility context

- Traditional OS provide standard
  - Fixed set of abstractions
    - Processes, threads, VM, Files, IPC
    - Reachable through syscalls
  - Resource allocation and management
  - Protection and security

- Industry complaining of OS large overheads
  - Research community started asking how to provide customization

Motivation

- OS does not perform well for specific applications
  - Applications are very different (e.g., video game vs. number crunching application)
  - Scheduling policies, memory management, file systems, ...

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- Traditional centralized resource management cannot be specialized, extended or replaced
  - Substantial advantages achievable from specializing resource allocation
- Fixed high-level abstractions too costly for good efficiency
- Privileged software must be safely used by all applications
  - But protection and management interfere with performance and flexibility

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- Mode switch:
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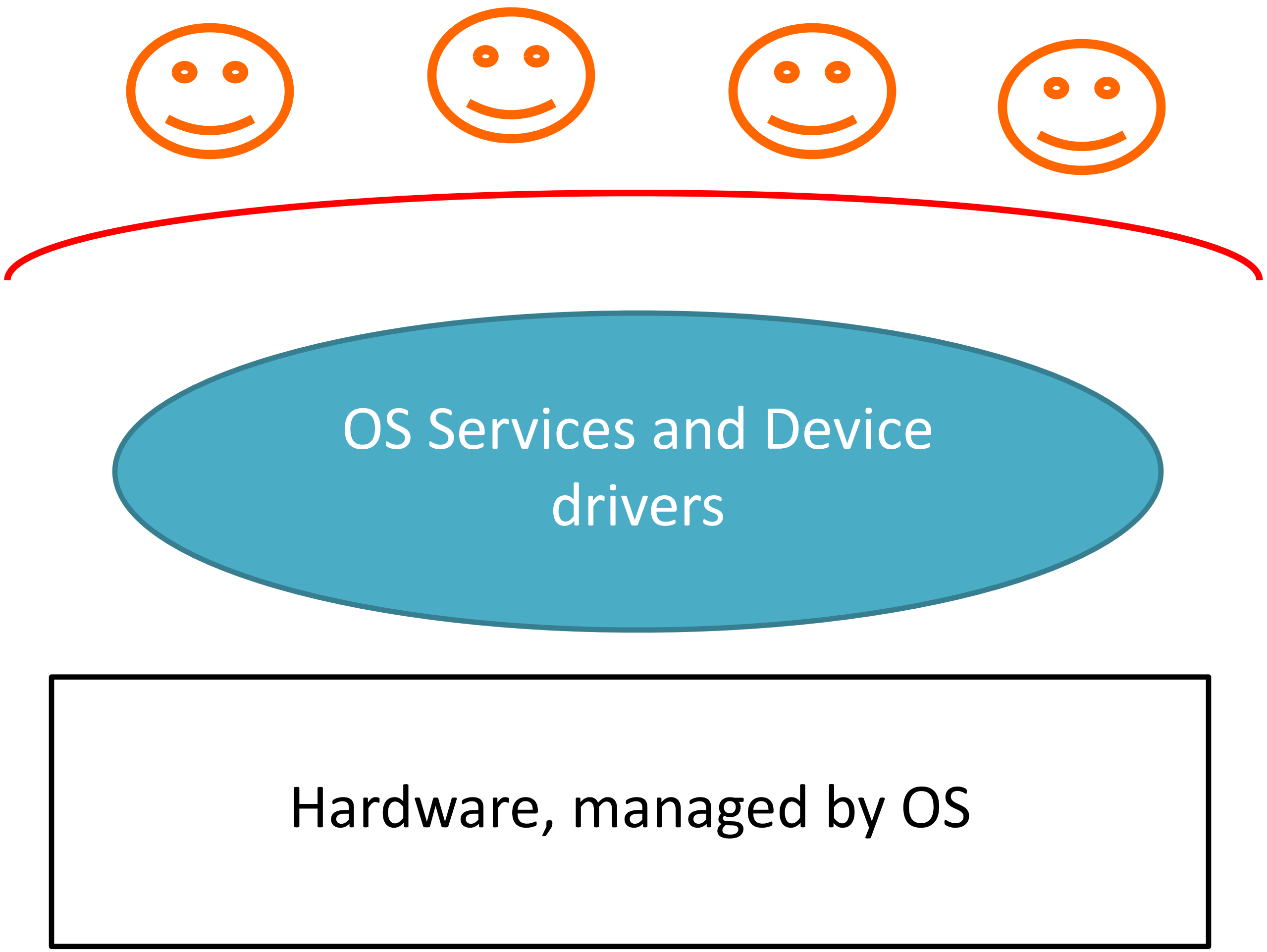
  - Switch to kernel stack
  - Switch some registers
  - 100s of ns
- Context switch:
  - Change address space
    - Expensive: flush TLB, caches…
  - Save and restore all registers
  - Few microsecs

OS design models

- Monolithic Kernel
- Library OS
- Micro Kernel

Monolithic Kernel



Applications

Each app has its own address space

User/kernel boundary

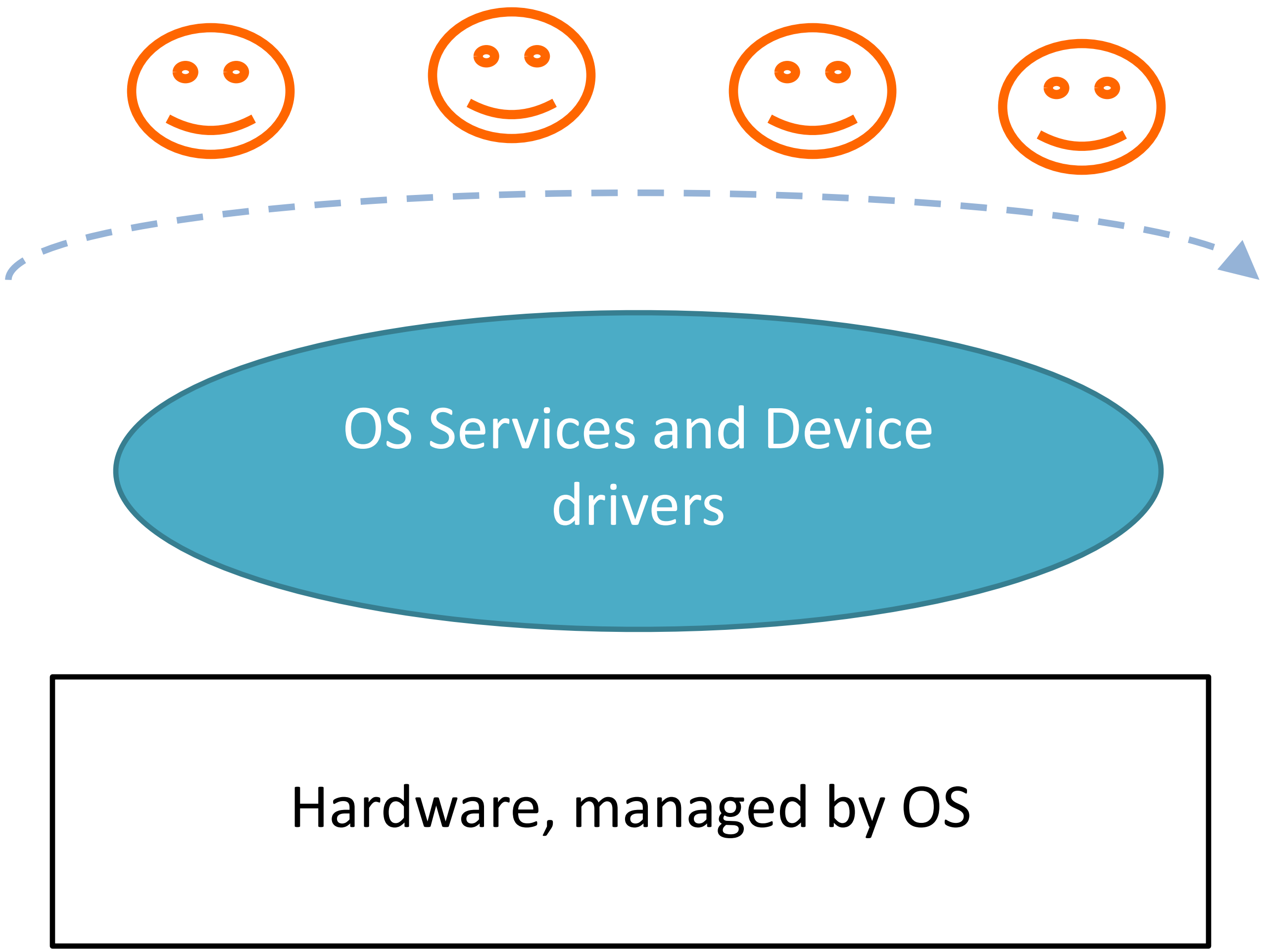
Monolithic kernel

OS in its own address space

All OS services are consolidated to reduce performance loss

Bad extensibility

Library OS (DOS-like)



Applications

Single address space. No user/kernel mode switching

Applications have direct control on hardware → Fast

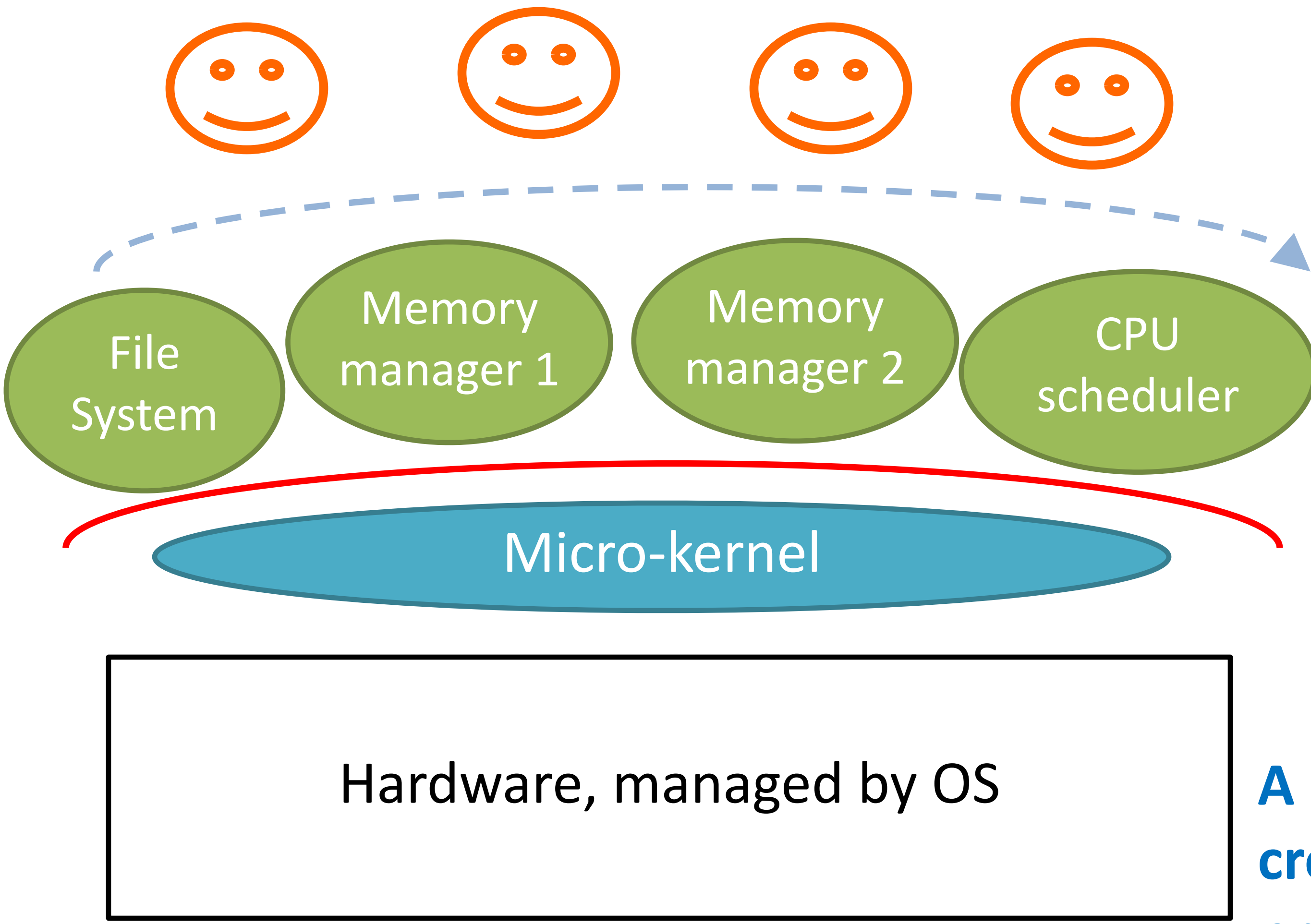
Bad protection

No protection between applications and OS

OS design models

- Dos-like library kernel
  - No protection
- Monolithic kernel
  - Reduce performance loss by consolidating all services, thus reducing the number of border crossings
- Extensibility?

Micro-kernel for extensibility



Applications

Each app has its own address space

OS Services

Each service has its own address space
Non-privileged mode!

Microkernel

Runs in privileged mode
Essential abstractions (IPC, address space)

A lot of boarder crossings to ensure protection!

Micro-kernel for extensibility

- Potential performance loss
  - A lot of boarder crossings (mode & context switching)
  - Separate address spaces for OS services
    - Explicit cost: address space switching cost
    - Implicit cost: change in locality (recall caches in memory hierarchy)

Micro-kernel for extensibility

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  - Separate address spaces for OS services
    - Explicit cost: address space switching cost
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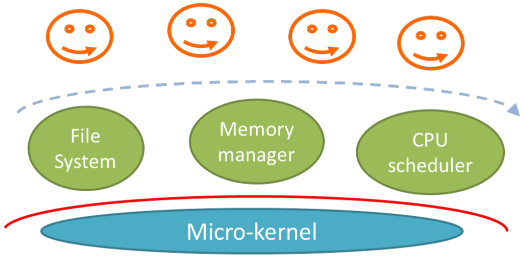
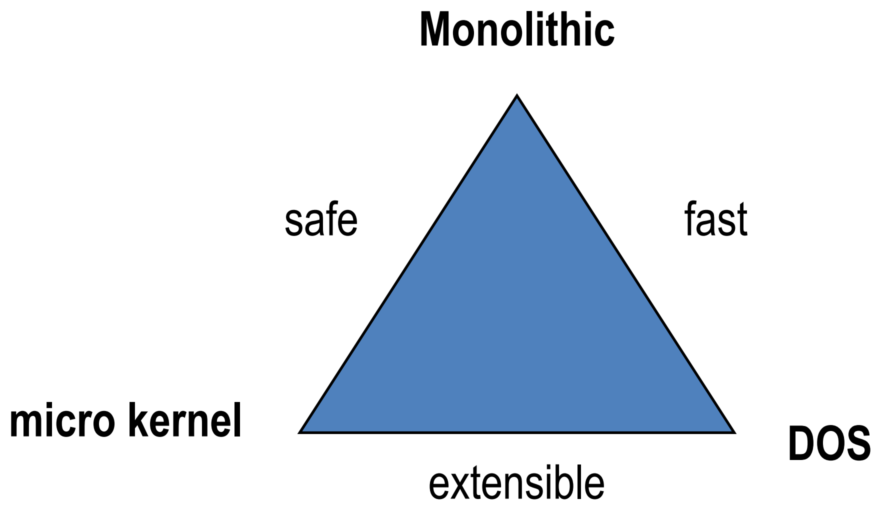
- Let's consider an example of a file system call
  - Application uses system call to microkernel
  - Microkernel sends message to file server
  - File server does work, then uses IPC to send results back to application
  - Finally switch back to app
  - Each step is a <u>border crossing</u>



Comparison

- Library OS (DOS like):
  - Very good performance and extensibility
  - Bad (no) protection
    - Unacceptable for a general-purpose OS
- Monolithic kernels:
  - Good performance and protection
  - Bad extensibility
- Microkernels
  - Very good protection
  - Good extensibility
  - Bad performance



What should an extensible OS do?

- It should be thin (like micro-kernel)
  - Only mechanisms
  - no policies; they are defined by extensions
- Fast access to resources (like DOS)
  - Eliminate border crossings
- Flexibility (like micro-kernel) without sacrificing protection or performance (like monolithic)

- Basically, *fast, protected and flexible*

Exokernel

Exokernel: An Operating System Architecture for Application-Level Resource Management

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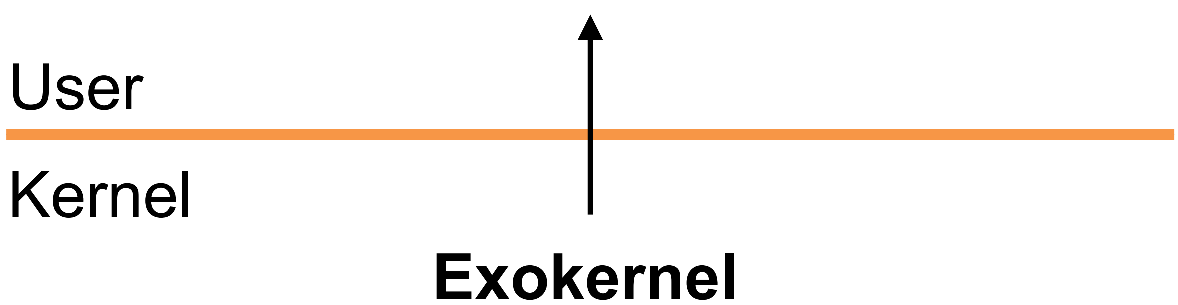

- Key idea: make kernel barrier as low as possible

Context (1990s)

- Windows (Win95) was dominating the market
  - MacOS (few %)
  - Unix market (few %)
- OS research limited impact
  - "Is OS research dead?"
- A set of papers, including SPIN and Exokernel, represent an effort to reboot the OS research, particularly OS structure

Main Challenge

- Fixed interfaces/abstractions
  - Fixed interfaces provide protection yet hurt performance
  - Deny domain-specific optimization
- Exokernel:
  - *"Fixed high-level abstractions hurt application performance because there is no single way to abstract physical resources or to implement an abstraction that is best for all applications."*
- Idea: make kernel barrier as low as possible

Problems in traditional OS kernels

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- Extensibility
  - Fixed implementation (e.g., LRU for general page replacement)
  - Apps cannot dictate management
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- Performance
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  - Hiding information of machine resources impact performance
- Protection and management offered with sacrifice in extensibility and performance

Symptoms

- Very few of innovations making into commercial OSes
  - E.g., scheduler activations, efficient IPC, new virtual memory policies, …
- Apps struggling to get better performance
  - Apps knew better how to manage and utilize resources, yet the OS was standing in the way

Exokernel Philosophy

- A nice illustration of the end-to-end argument:
  - "general-purpose implementations of abstractions force applications that do not need a given feature to pay substantial overhead costs.''
  - *"An exokernel should avoid resource management. It should only manage resources to the extent required by protection (i.e., management of allocation, revocation, and ownership)."*
  - Kernel just safely exposes resources to apps
  - Apps implement everything else, e.g., interfaces/APIs, resource allocation policies

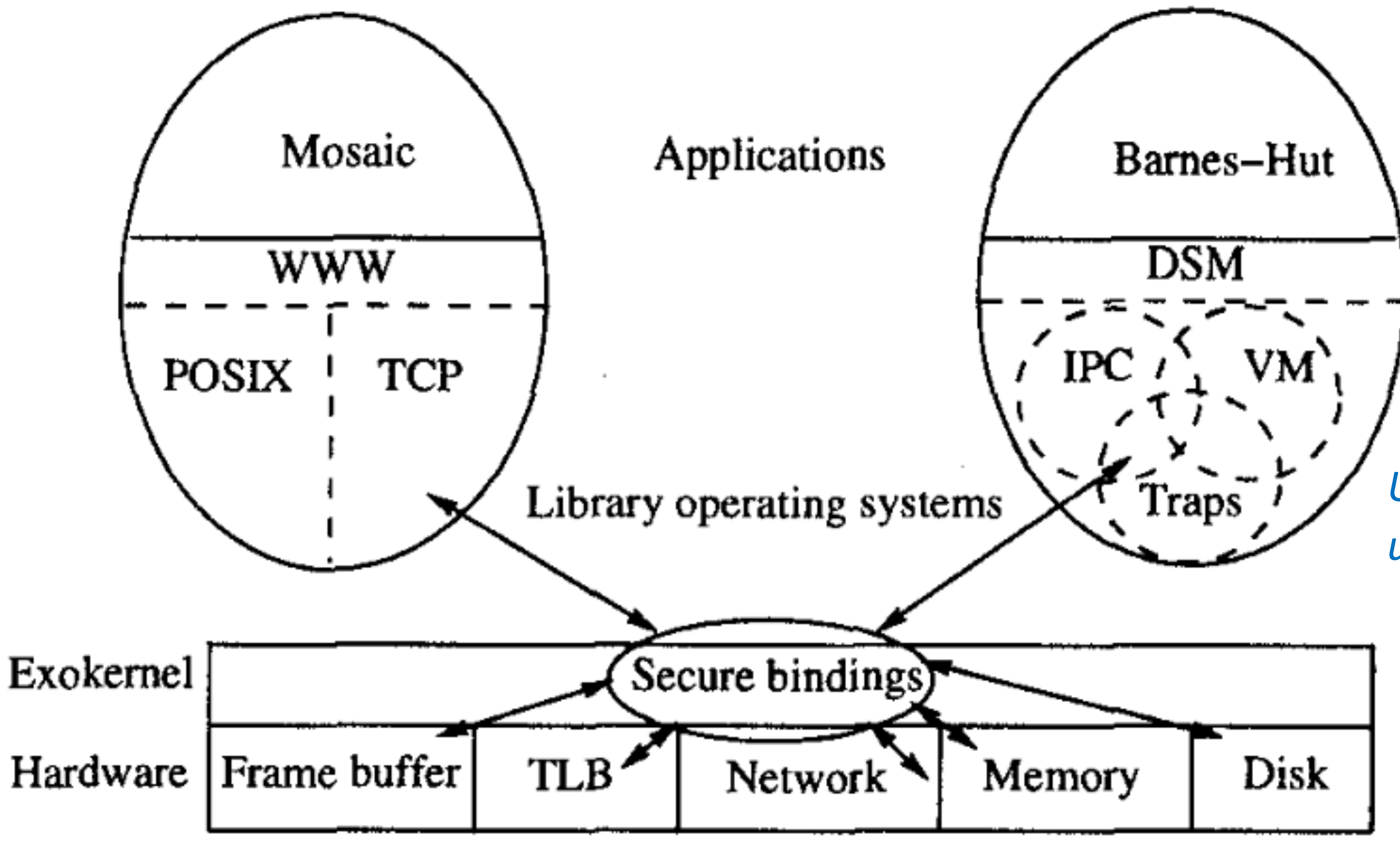
Exokernel Ideas

- Decouples the authorization to a hardware resource from its actual use
  - Kernel: resource sharing, not policies
- Higher-level abstractions are implemented in applications
  - Each application has its own Library OS
  - Exokernel grants hardware resources to Library OS
  - Library OS implements resource management policies
- Safety ensured by secure bindings
  - Safely expose machine resources

Exokernel Principles

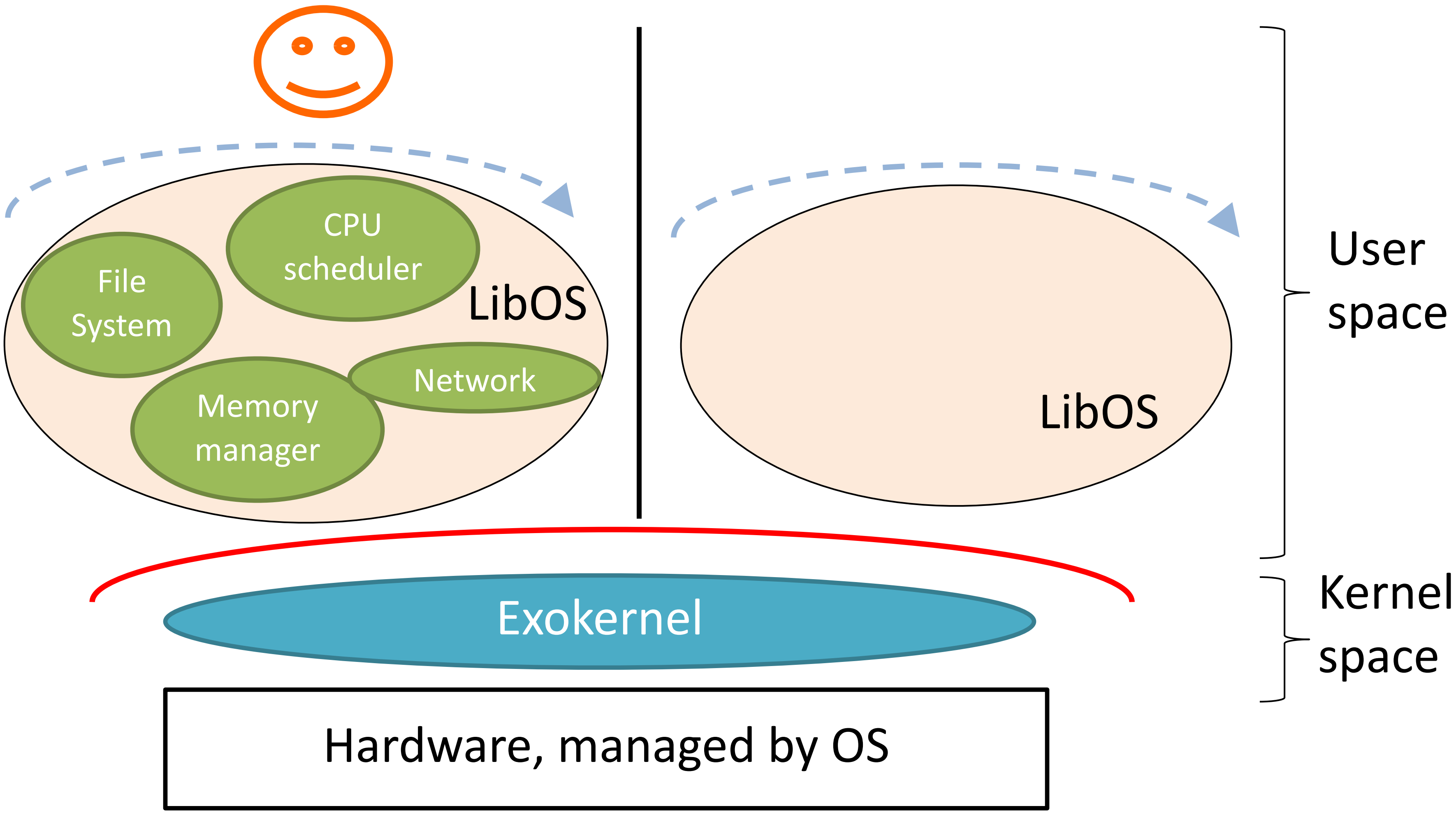
- Separate protection and management
  - Provide low-level primitives, e.g., disk blocks, context identifiers, TLB, etc.
- Expose names
  - Export physical names wherever possible, e.g., a physical page number, disk blocks, etc.
- Expose allocation
  - Apps allocate resources explicitly
- Expose revocation
  - Let apps choose which instance of a resource to give up

Exokernel Architecture



User-level, untrusted

Exokernel



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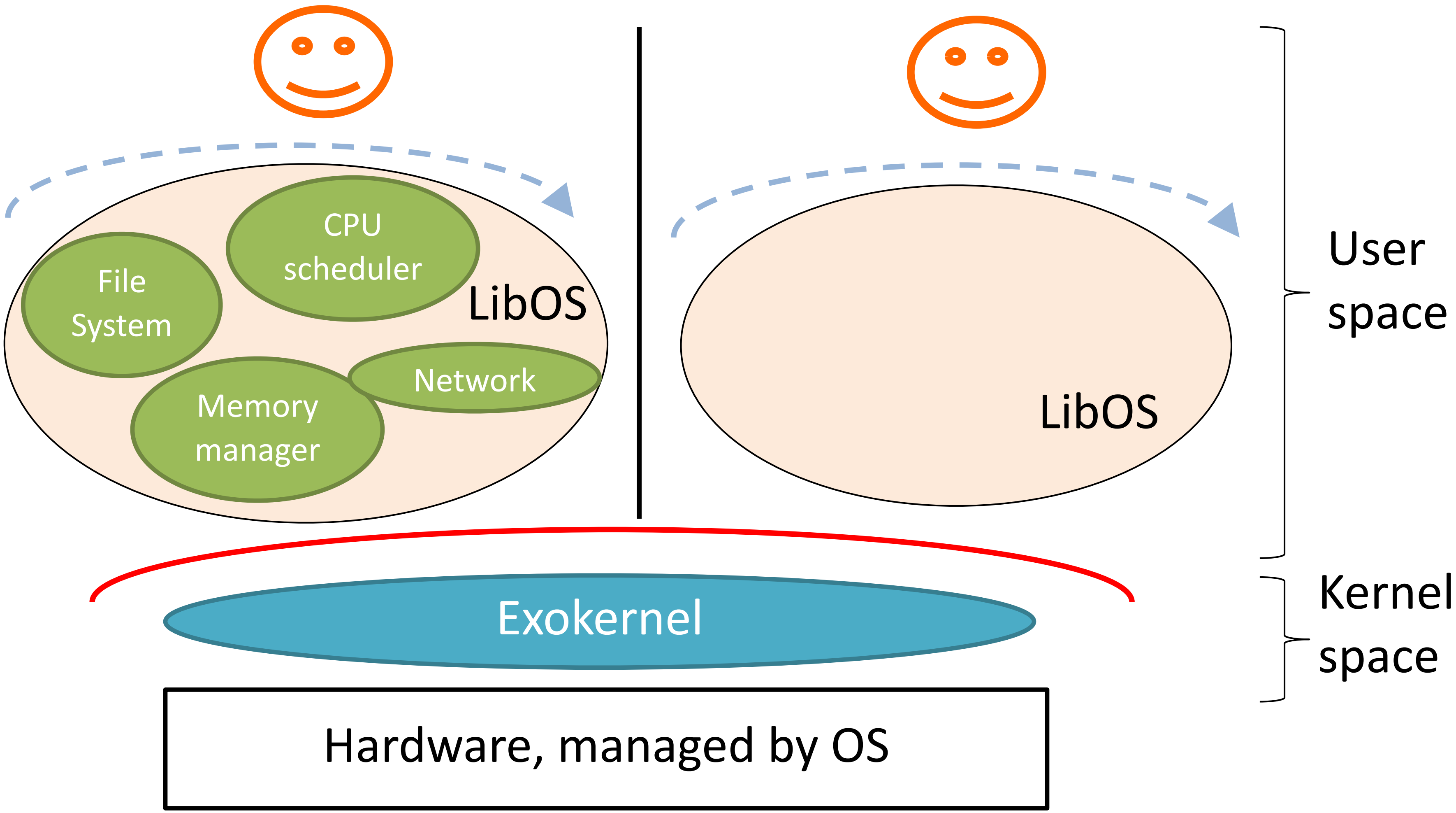
LibOS
Network
Memory
manager
LibOS
User
space
Exokernel
Kernel
space
Hardware, managed by OS

Exokernel



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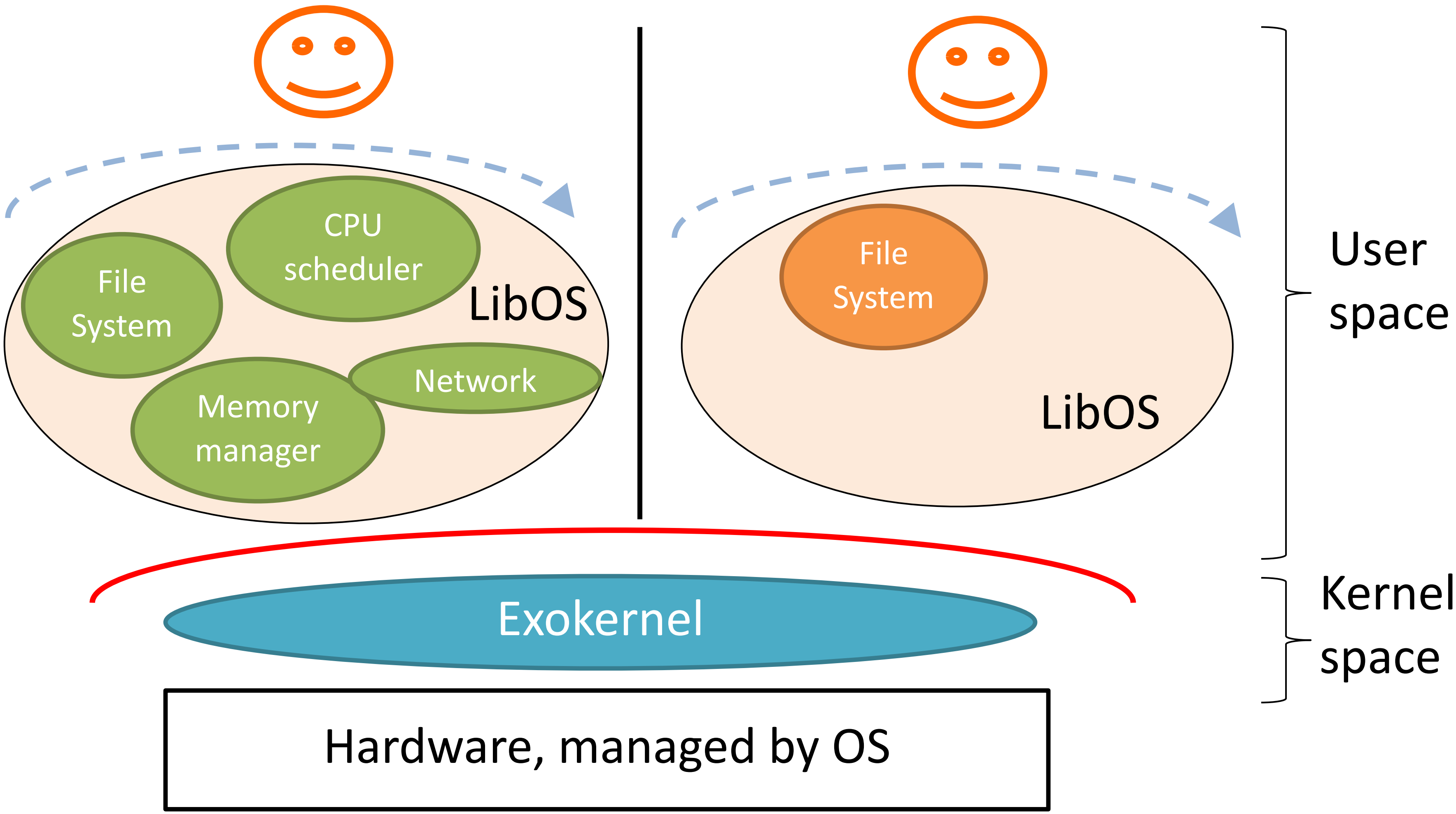
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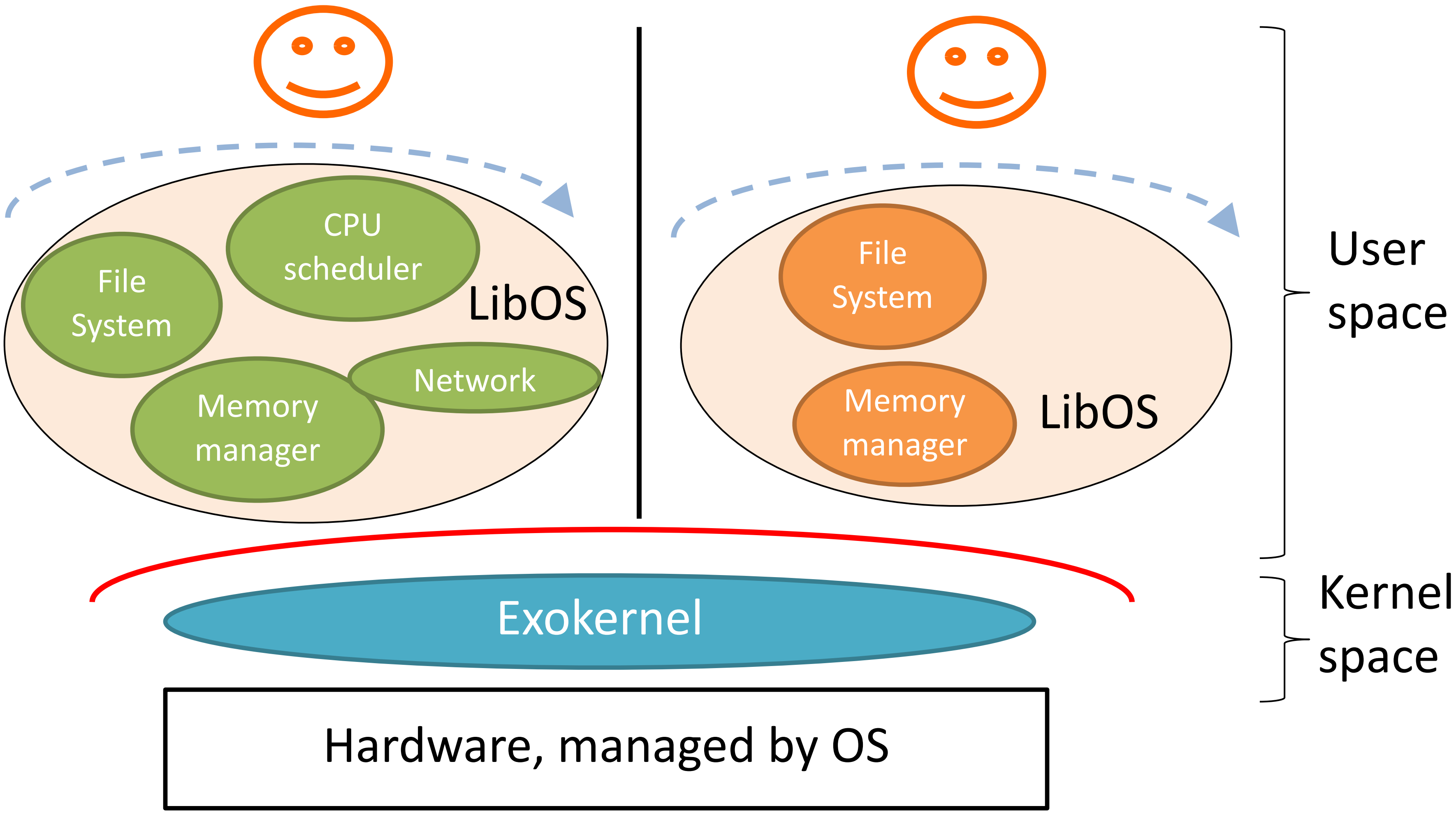
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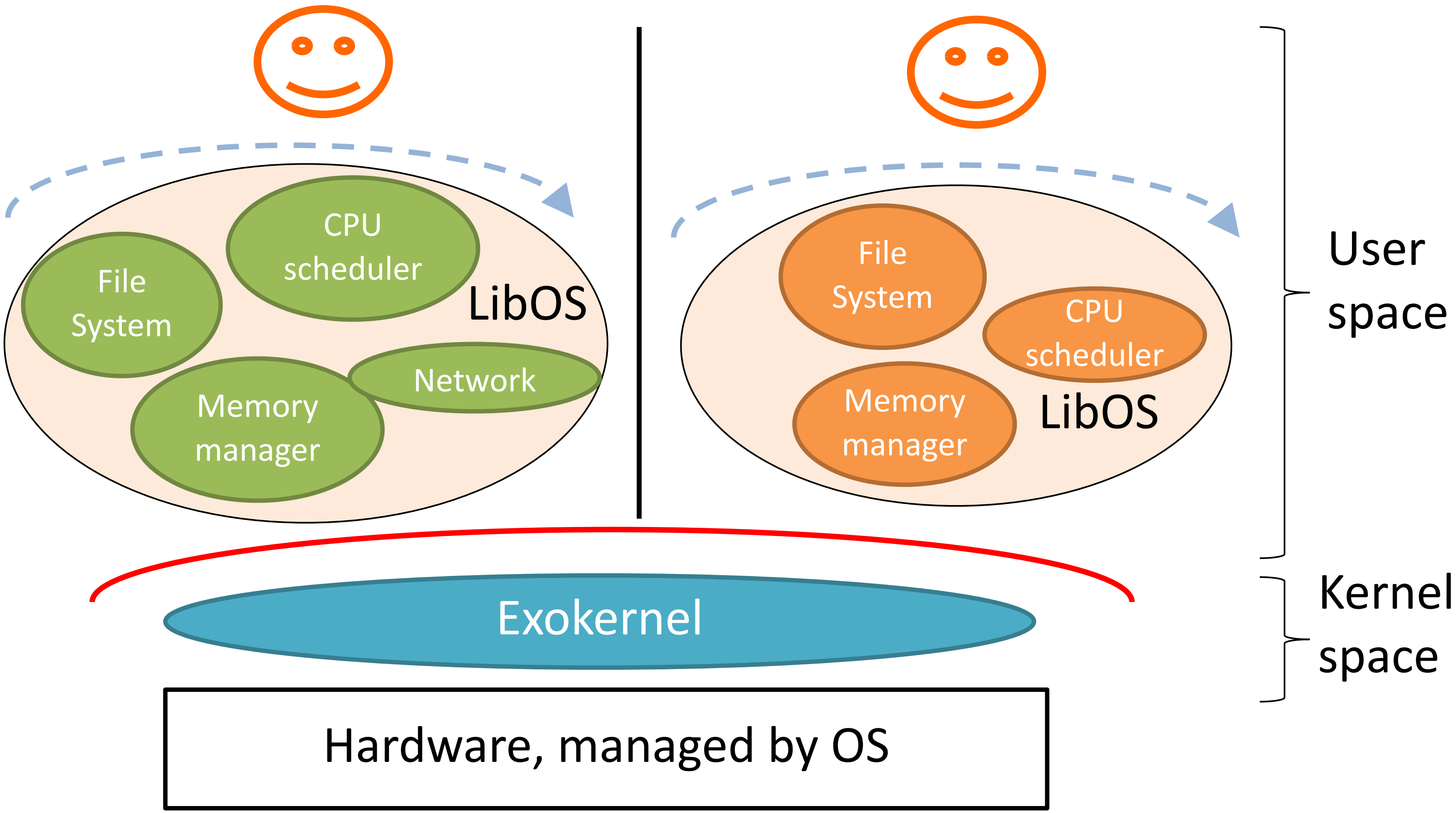

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Services Provided by Exokernel

- Tracking ownership of resources
- Guarding all resource usage or binding points
- Revoking access to resources

How?

- Secure bindings
  - Allow libOSes to bind to machine resources
- Visible revocation
  - Allow libOSes to participate in resource revocation
- Abort protocol
  - Break bindings of uncooperative libOSes

Secure Bindings

- Decouples authorization from actual use of resources
- *Authorization* performed only at bind time
  - E.g., a libOS must translate a virtual to physical address
- *Protection checks* performed at access time
  - Simple operations without understanding details of application-level semantics & management policies
  - E.g., when the address translation is used by the TLB
- "Simply put, a secure binding allows the kernel to protect resources without understanding them"

Example resource

- TLB Entry
  - When a TLB fault occurs, a virtual-to-physical mapping is performed by LibOS
  - Binding presented to Exokernel
    - Each physical page: owner and read/write capabilities
    - Exokernel validates capabilities
  - Exokernel puts it in hardware TLB (why not by libOS?)
  - Applications (processes in LibOS) can then access it without Exokernel intervention

Implementing Secure Bindings

- Why?
  - Library OSes are untrusted
- How to implement?
  - Hardware mechanisms:
    - If appropriate hardware support is available; e.g., TLB entry
  - Software caching:
    - E.g., large software TLB in the kernel as a cache of frequent bindings
    - Avoid context switch when exokernel switches among libOSes
  - Downloading application code to improve performance:
    - Bindings are invoked on every event to determine ownership and kernel actions (e.g., packet filter)
    - Avoid boarder crossing

Secure Binding Example

- Multiplexing physical memory
  - A libOS allocates a physical memory page
  - Exokernel creates a secure binding for that page by recording capabilities: ownership, R/W permissions (authorization at bind time)
  - Guards every access to a physical memory page by checking capabilities (protection at access time)

Secure Bindings via Downloading Code

- libOSes "download" code into exokernel
  - Providing code for exokernel to execute on the apps behalf
  - E.g., code to determine which pages to swap out when memory is needed
  - E.g., code to schedule multiple threads within the process

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- Performance boost by eliminating boarder crossings
- Runtime of certain operations predictable a priori
- Cons: potentially unsafe!!
  - Lots of other work around this time on extensible OS designs that tried to implement this feature (with various degree of success)

Visible Resource Revocation

- Traditional OS: resources revoked invisibly
- Exokernel: visible deallocation of resource
  - So that library OS has a chance to react
    - e.g. under memory pressure, libOS can choose a victim page
  - But could be less efficient when revocations happen frequently
    - Can be combined with invisible revocation (esp. when it happens frequently): e.g., process address space identifiers which is a stateless resource

Abort Protocol

- Visible resource revocation is good... But what if application does not cooperate?
  - "An exokernel must also be able to take resources from libOSes that fail to respond satisfactorily to revocation requests"
- Abort protocol
  - Forced resource revocation
  - Break secure bindings to the resource
  - Uses 'repossession vector' to record the forced loss of resources

Managing core services

- Virtual memory
  - Secure binding: using self-authenticating capabilities
  - When accessing page, owner needs to present capability
  - Page owner can change capabilities associated and deallocate it

Managing core services: scheduling

- Processor time represented as linear vector of time slices
  - Round robin allocation of slices
- Secure binding: allocate slices to LibOS
  - Simple, powerful technique: donate time slice to a particular process
  - A LibOS can donate unused time slices to its process of choice
- If process takes excessive time, it is killed (revocation)

Evaluation

- A full implementation; it works and scales
- How to make sense from the quantitative results?
  - Absolute numbers are typically meaningless given that we are part of a bigger system
    - Trends are what matter
- Emphasis is on space and time
  - Takeaway→ at least as good as a monolithic kernel, sometimes much faster

Conclusions

- Performance vs Extensibility vs Protection
  - DOS provided no protection. Without protective checks, you get performance and apps could directly hack the core to get extensibility.
  - Monolithic kernels implemented performance and protection, but were hard to extend
  - Microkernels provided good protection and were extensible, but performance suffered

Conclusions

- Simplicity and limited exokernel primitives can be implemented efficiently
- Hardware multiplexing can be fast and efficient
- Traditional abstractions can be implemented at application level
- Applications can create special purpose implementations by modifying libraries

Why people don't use exokernels today?

- Today's OSes give applications far greater control over low-level mechanisms than in 1990s
- LibOS concepts are used reasonably frequently (look up the Unikernel)
- Hypervisors have exokernel-like low-level interfaces to guest OSes

Discussions

- Much of computer system research is about tradeoffs
  - Efficiency v.s. Extensibility
  - Efficiency v.s. Security
  - Efficiency v.s. Fairness
  - Efficiency v.s. Correctness