OS Structure

OS Structure Overview

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* Operating System Services
    1. Process/thread management and scheduling
    2. Memory management (protection, sharing, demand paging)
    3. Interprocess communication (IPC)
    4. File system
    5. Access to I/O devices such as microphones and speakers
    6. Access to the network
* OS Structure: The way the operating system software is organized with
respect to the applications that it serves and the underlying hardware that
it manages
* Goals of OS Structure
    1. Protection: Within and across users and to the OS itself
    2. Performance: Time taken to perform the services
    3. Flexibility: Extensibility (not one size fits all)
    4. Scalability: Performance improves with more hardware resources
    5. Agility: Adapting to changes in application needs and/or resource
    availability
    6. Responsiveness: Reacting to external events
* Commercial OS: Don't meet all goals laid out above
    - Linux
    - MacOS
    - Windows
* Monolithic Structure
    - Each app has its own hardware address space
    - OS also has its own hardware address space (protected from apps)
    - Hardware is managed by the OS
    - OS services and device drivers are all contained in one blob
    - Reduces performance loss by consolidation
        + All of the components are aware of each other and interactions can
        be optimized
    - Con: Less extensible (no customization, useful for different apps)
        + Video games: Responsiveness is desired
        + Computing prime numbers: Sustained CPU time is desired
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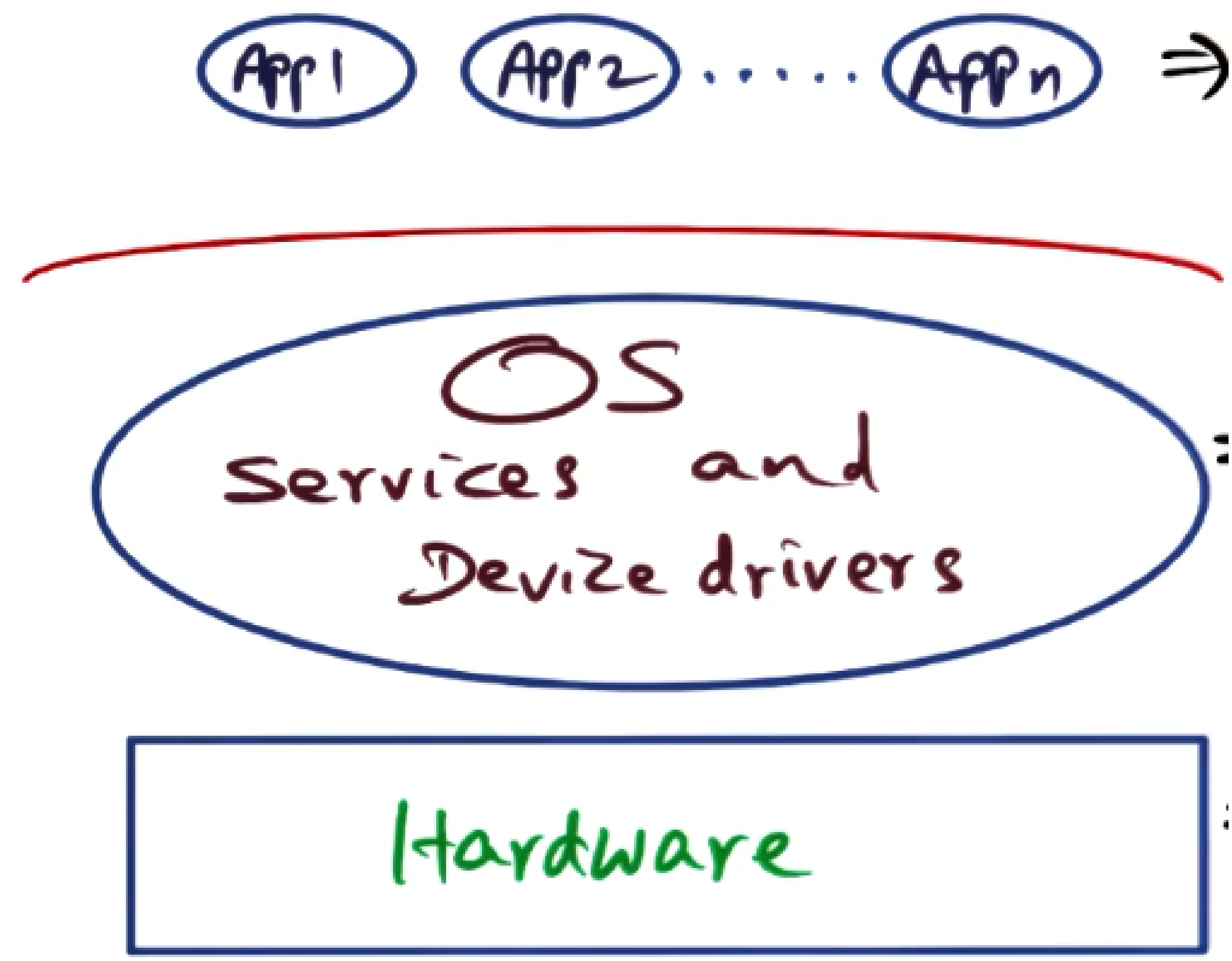

Monolithic OS Structure

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* DOS-like Structure
    - Disk operating system
    - No protection layer between the application and the OS
    - Pro: Improved performance (access to system services is like a
    procedure call)
    - Con: Decreased protection (an errant application can corrupt the OS)
    - In the early days of computing, only one process could run at a time
        + Simplicity and performance took precedence
        + No overhead for system calls vs developer procedures
    - Loss of proection is unacceptable for a general-purpose OS
* Opportunities for Customization
    - Memory management (page fault)
        1. OS finds a free page frame (page replacement algorithm)
        2. OS updates page table for faulty process
        3. Resume process
    - The page replacement algorithm can't be ideal for every application
    - Can customize how page replacement is handled
* Microkernel Structure
    - Each app in its own hardware address space
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- Microkernel runs in priveleged mode and provides simple mechanisms
    + Threads
    + Address space
    + IPC
- OS services are implemented on top of microkernel (same privelege as
applications)
- No distinction between OS services and applications in terms of how
they run
- Pro: Extensibility; services can be easily replaced
- Con: Performance; in a monolithic structure, filesystem and memory
management are all within the kernel. In a microkernel structure, an
app might go through the kernel, to the filesystem service, back to the
microkernel, and back to the app. All of this is IPC overhead.
- Border crossings
    + User space <-> system space copying
    + Explicit costs in changing context
    + Implicit costs due to cache misses (change in locality)
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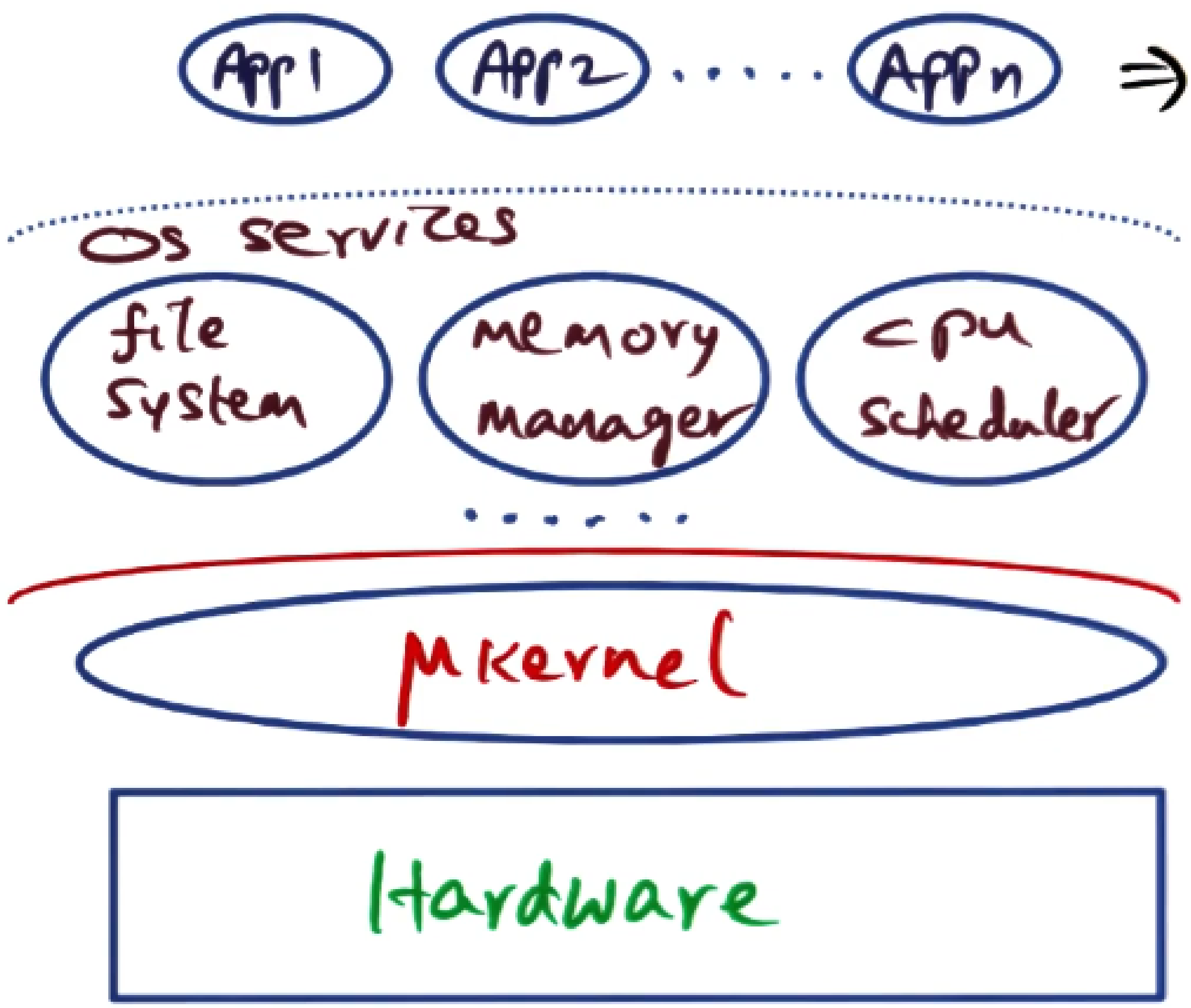

Microkernel OS Structure

Feature	Monolithic	DOS-like	Microkernel
Extensibility		X	X
Protection	X		X
Performance	X	X	

The SPIN Approach

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* Two Premises:
    1. Microkernel design compromises on performance due to frequent border
    crossings
    2. Monolithic design does not lend itself to extensibility
* Goals
    1. Thin (like microkernel) -> only mechanisms, not policies
    2. Access to resources without border crossing (like DOS)
    3. Flexibility for resource management (like microkernel) without
    sacrificing protection and performance (like monolithic)
* Approaches to Extensibility
    - Hydra OS
        + Kernel mechanisms for resource allocation
        + Capability-based resource access
        + Resource management as coarse-grained objects to reduce border
        crossing overhead
    - Mach OS
        + Microkernel-based
        + Focused on extensibility and portability
        + Performance wasn't prioritized
* SPIN's Approach to Extensibility
    - Co-location of kernel and extensions to avoid border crossings
    - Compiler enforced modularity (strongly typed language, Modula)
    - Logical protection domains (not hardware address spaces)
    - Dynamic call binding -> flexibility
    - Make extensions as cheap as a procedure call
* Logical Protection Domains
    - Modula-3 safety and encapsulation mechanisms
        + Type safety, automatic storage management
        + Objects, threads, exceptions, generic interfaces
    - Fine-grained protection via capabilities
        + Hardware resources (page frame)
        + Interfaces (page allocation module)
        + Collection of interfaces (entire virtual memory subsystem)
    - Capabilities implemented as language supported pointers
        + Modula-3 pointers are type-specific (no casting)
* SPIN Mechanisms for Protection Domains
    - Create: initialize with object file contents and export names that are
    contained as entry point methods into the object to be externally visible
    - Resolve: Names between source and target domains
        + Once resolved, resource sharing at memory speeds
    - Combine: To create an aggregate domain from smaller domains
* Customized OS with SPIN
    - No border crossing between services and mechanisms provided by SPIN
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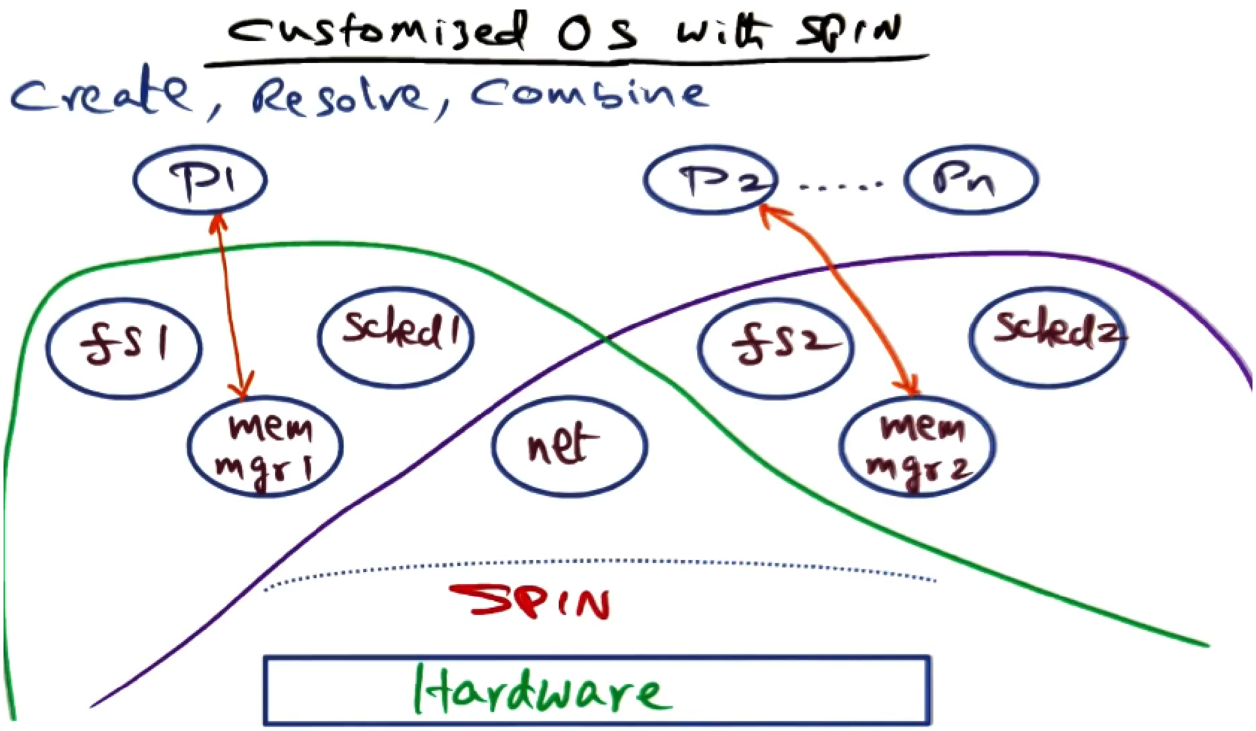
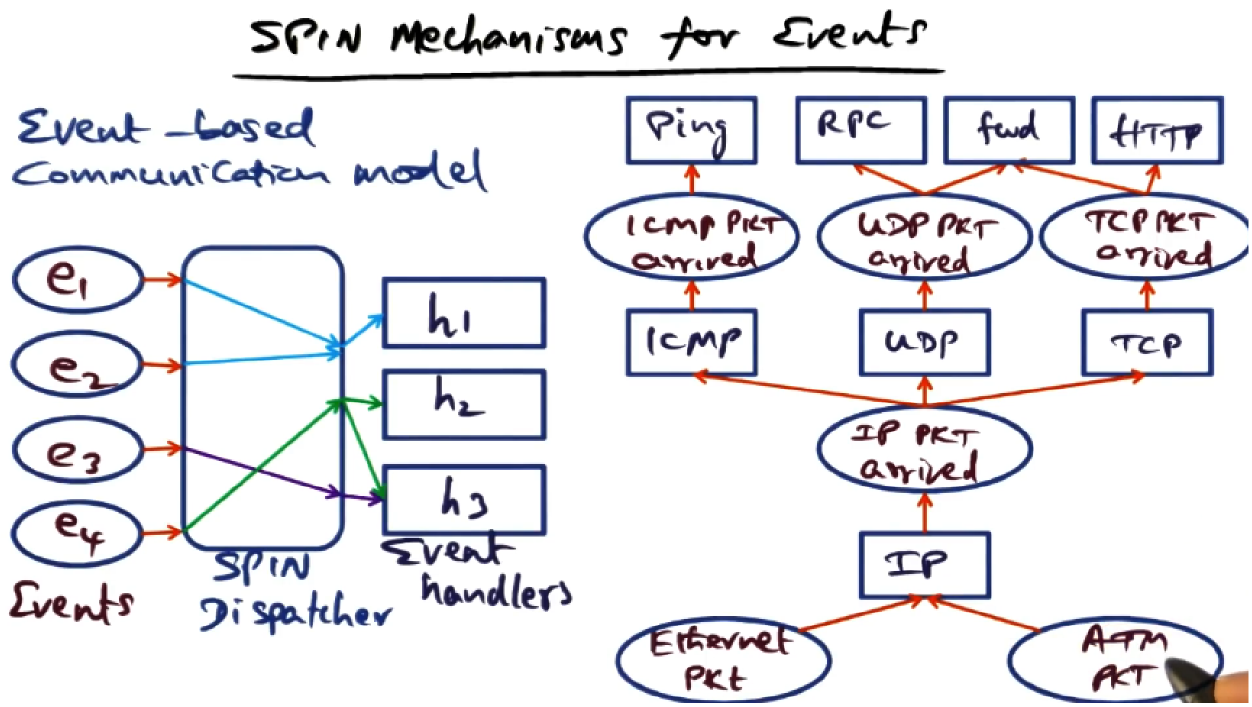


SPIN OS Structure

* SPIN Mechanisms for Events
    - OS needs to be able to field events (interrupts, system calls)
    - Event-based communication model
        + Services register event handlers (one-to-one, one-to-many, many-to-one)



SPIN Event Handlers

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* Default Core Services in SPIN
    - SPIN provides interface procedures for implementing these services
    - Automatically invoked when the hardware event occurs
    - Memory management
        + Physical address (allocate, deallocate, reclaim)
        + Virtual address (allocate, deallocate)
        + Translation (create/destroy address space, add/remove mapping)
        + Event handlers (page fault, access fault, bad address)
    - CPU Scheduling
        + SPIN abstraction: strand (semantics defined by extension)
        + Event handlers (block, unblock, checkpoint, resume)
        + SPIN global scheduler (interacts with application threads package)
    - Core services are trusted because they provide access to hardware
    mechanisms
        + Services may need to step outside the language-enforced protection
        model to control the resources
        + Applications that run on top of extensions must trust extension
        + However, these are isolated (don't impact things that don't rely
        on the extension)
```

The Exokernel Approach

```
* Exokernel: Kernel exposes hardware explicitly to OS extensions
    - Decouple authorization of hardware from actual use
    - Expose hardware through secure binding (binds library OS to hardware
    resources)
    - Gives encrypted key to library OS; semantics of use are up to library
        + Can't be forged or transferred
    - Library gives key to exokernel to validate it can use the resource
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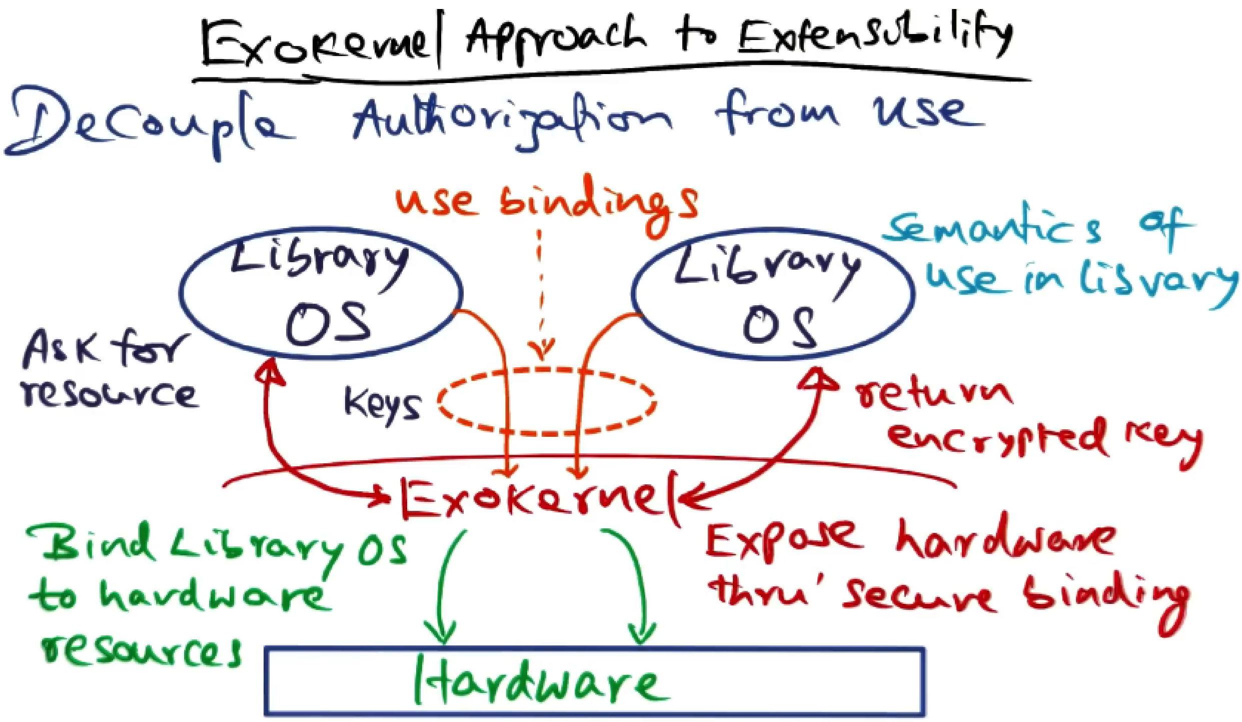

Exokernel OS Structure

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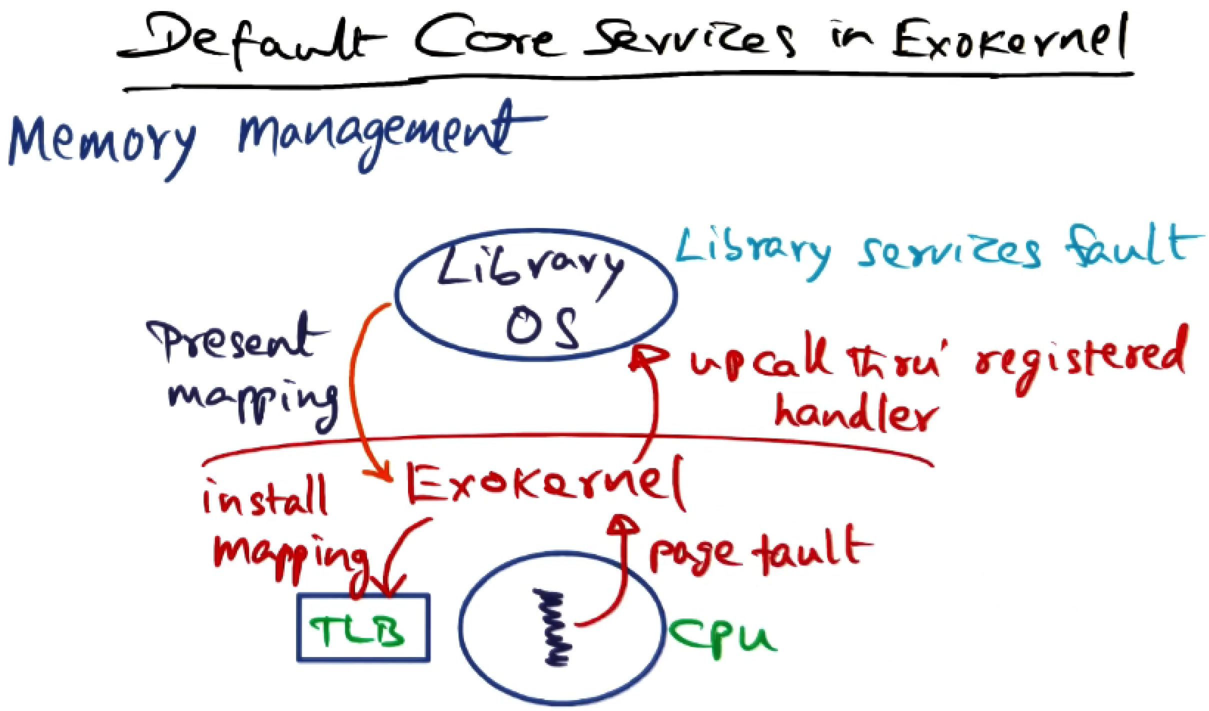
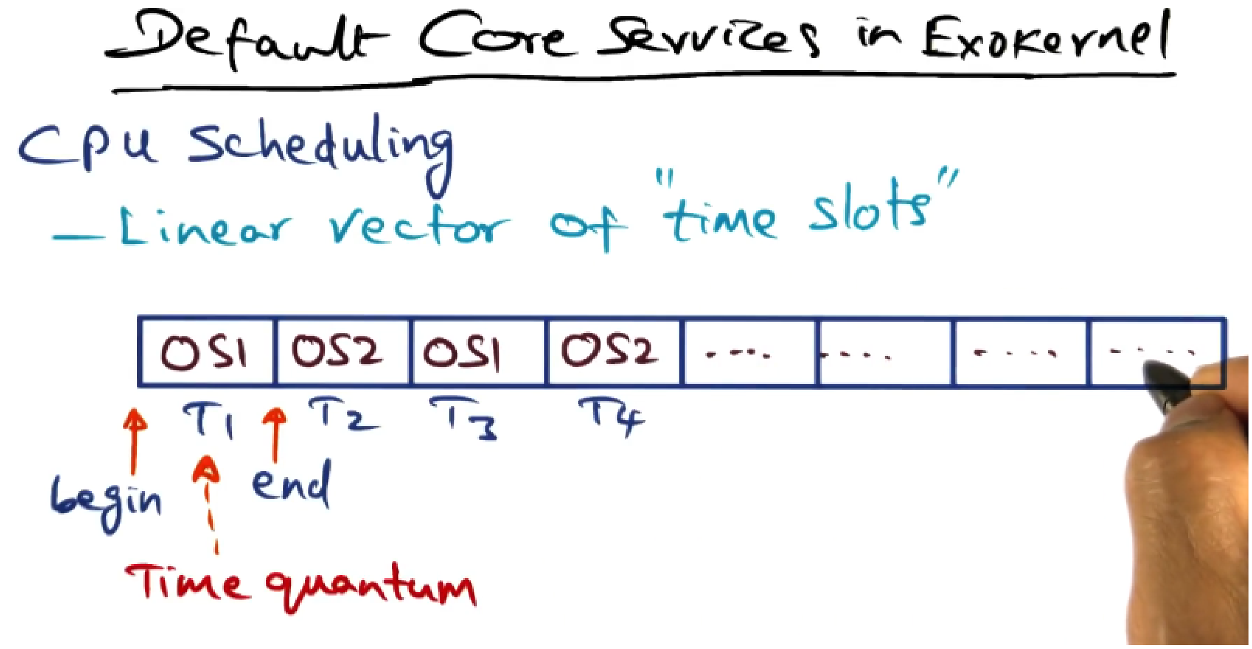
* Examples of Candidate Resources
    - TLB Entry
        + Virtual to physical mapping done by library
        + Binding presented to exokernel
        + Exokernel puts it into hardware TLB
        + Process in library OS uses multiple time without exokernel
        intervention
    - Packet filter
        + Predicates loaded into kernel by library OS
        + Check on packet arrival by Exokernel
* Implementing Secure Bindings
    1. Hardware mechanisms (TLB entry, physical page frame, frame buffer)
    2. Software caching
        + "Shadow" TLB in software for each library OS
        + Exokernel dumps hardware TLB into software TLB data structure on
        context switch
    3. Downloading code into kernel
        + Functionally equivalent to SPIN extensions
        + Compromises protection more than SPIN; as long as SPIN's logical
        protection domains are following Modula-3's compile and runtime
        verification, no compromise. Exokernel doesn't make this guarantee
* Memory Management in Exokernel
    - When a thread incurs a page fault, it's caught by Exokernel
    - Then, it's passed to the library OS through the registered handler
    - Library services fault (might require requesting a page frame from
    Exokernel)
* Memory Management Using Software TLB
    - On context switch, much of performance hit comes from loss of
```

cache locality
- To mitigate this overhead, Exokernel implements a software TLB
- Software TLB: Data structure representing a snapshot of the hardware TLB; captured on context switch for the library OS
- On context switch, Exokernel preloads TLB with software TLB



Exokernel Memory Management

* CPU Scheduling in Exokernel
  - Linear vector of "time slots"
  - Each library OS will get one time quantum at a time
  - When timing interrupt occurs, Exokernel will switch to next library OS
  - Some time between switching when library OS gets to save state
  - Exokernel only interferes for page faults



Exokernel CPU Scheduling

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* Secure Binding - How can a library OS securely insert code into the kernel?
    - Performance optimization to avoid border crossings
    - In both SPIN and Exokernel, the ability to add extensions must be
    restricted to a trusted set of users
* Revocation of Resources
    - Exokernel needs a way of revoking resources (space/time) that have
    been allocated to a library OS
    - Revoke call is an upcall into library OS (repossession vector)
    - Library OS must clean up when it recevies a repossession vector
        + Stash data in a page to disk when Exokernel reclaims
    - Library can "seed" Exokernel for "autosave"
* Code Usage by Exokernel - Library OS gives code to run on specific events
    1. Packet filter for de-multiplexing of network packets
    2. Run code in Exokernel on behalf of library OS not currently scheduled
    (e.g., garbage collection for an application)
* Summary; Achieving extensibility, protection, and performance
    1. Performance: Exokernel allows for performance critical code in
    library OS to be downloaded securely into Exokernel
    2. Extensibility: Exokernel exposes hardware resources to library OS to
    allow them to implement functionality however is needed
    3. Protection: Exokernel provides encrypted keys to ensure that only the
    intended libary OS can access hardware
    4. Exokernel must be involved when interrupts occur
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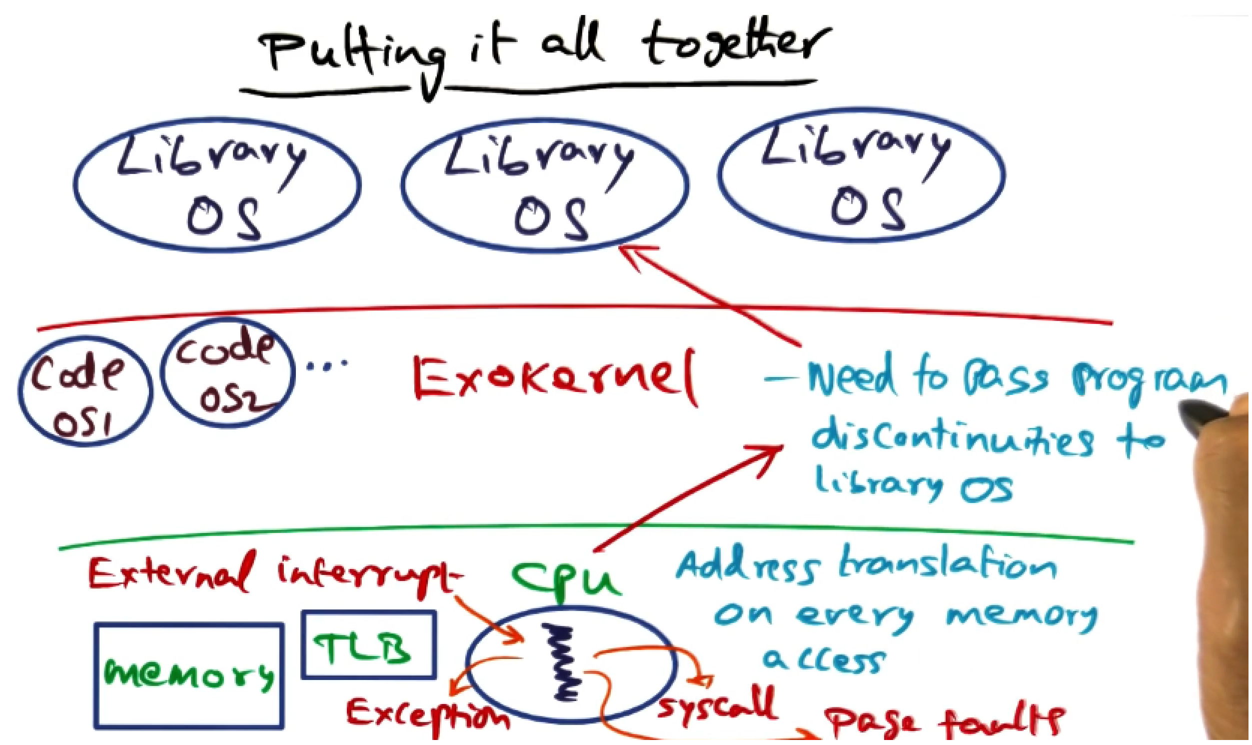

Exokernel Summary

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* Exokernel Data Structures
    - PE data structure: Handler entry points for different event types
        + Exceptions, interrupts, system calls, memory mappings
    - Software TLB to preserve page mappings
        + Must specify a set of guaranteed mappings for Exokernel to maintain
        + Not all hardware TLB entries, just the specified ones
    - Similar to event handler structure in SPIN OS
* Performance Results of SPIN and Exokernel
    - Can qualitatively argue that extensibility is provided, but must prove
    quantitatively that performance isn't being sacrificed
    - UNIX: Monolithic
    - Mach: Microkernel (CMU)
    - Both SPIN and Exokernel outperform Mach regarding changing protection
    domains
    - Both SPIN and Exokernel do as well as Unix for dealing with system
    calls
```
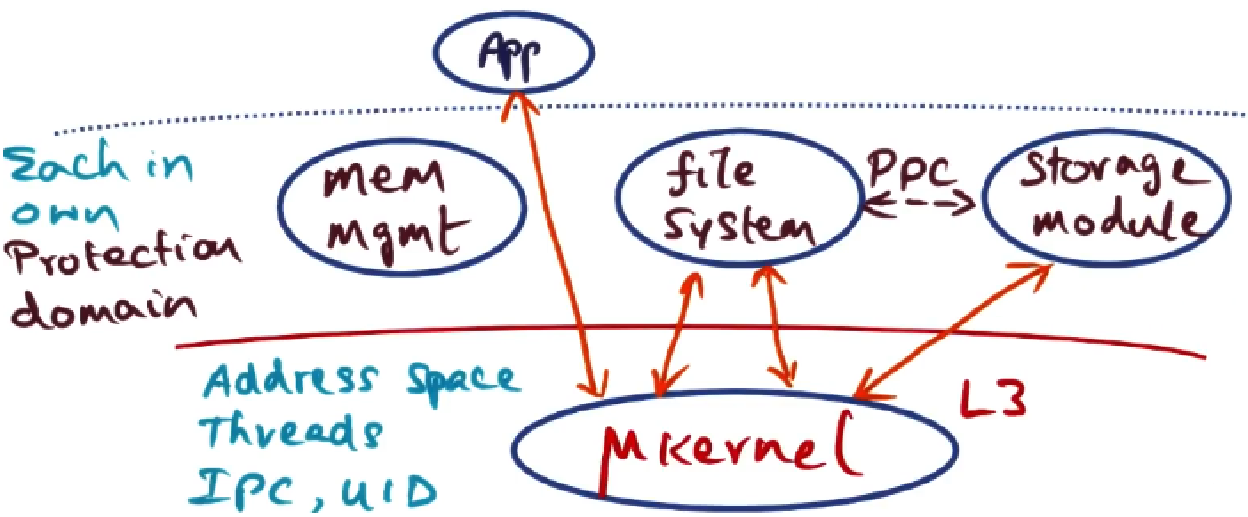

The L3 Microkernel Approach

```
* SPIN and Exokernel were comparing against CMU's Mach, a microkernel
approach with a focus on portability
    - However, can we design a microkernel with a focus on performance?
* Microkernel: Each service in its own address space
    - Applications sit on top of OS services
    - OS services: Memory management, file system, storage module
    - Microkernel provides simple abstractions (address space, IPC)
* Potentials for Performance Loss
    - Border crossings: Implicit and explicit costs
```

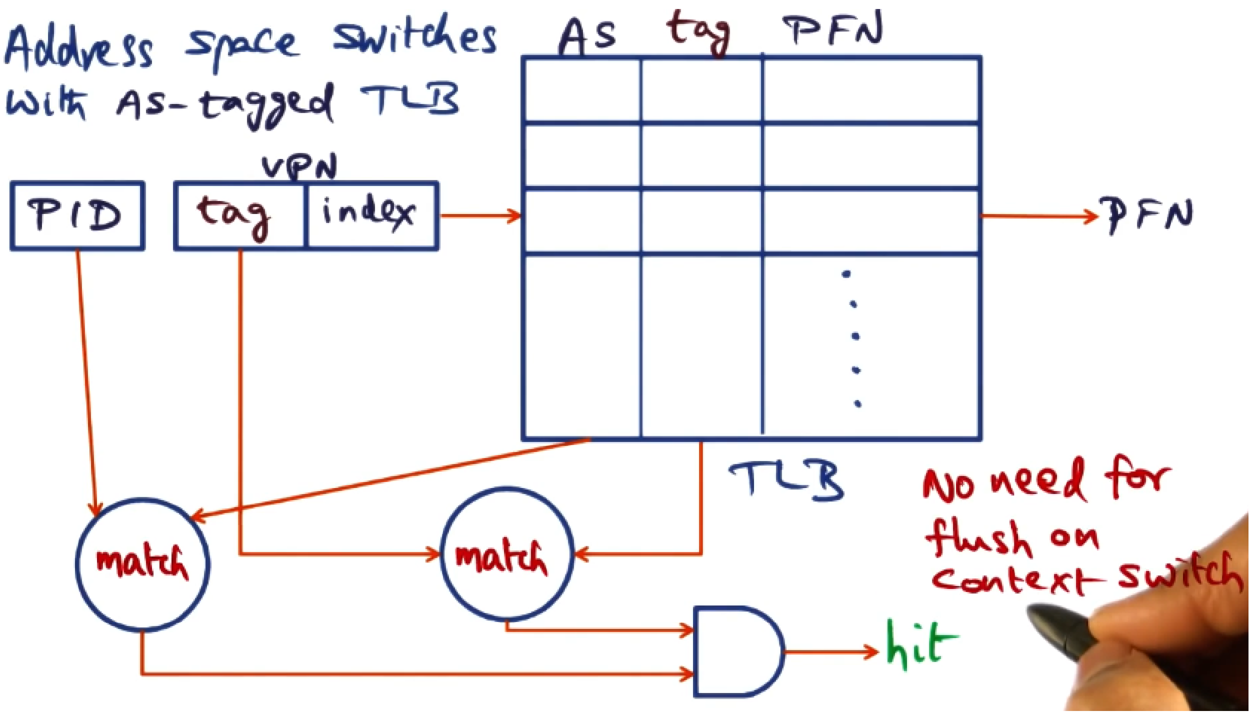
    + Applications and microkernel in different privelege levels
    + System services have to consult other services (cross address space)
  - Protected procedure calls: 100x normal procedure calls
* L3 Microkernel
  - Aimed to debunk myths about microkernel-based OS structure
  - L3 microkernel provides address space, threads, IPC, and unique IDs
  - L3 puts each service in its own protection domain, not necessarily different address spaces
  - All about efficient implementation!



L3 OS Structure

* Strikes Against Microkernel
  - Kernel-user switches (border crossing cost)
  - Address space switches
    + Basis for protected procedure calls for cross protection domain calls
    + Crossing address spaces requires flushing the TLB
  - Thread switches and IPC
    + Kernel mediation for protected procedure calls (PPC)
  - Memory effects
    + Locality loss
* L3 Solution to User Border Crossing
  - L3 accomplishes border crossing in 123 processor cycles
    + Includes TLB and cache misses
  - L3 calculated that the absolute minimum number of cycles on their architecture was 107; 123 is pretty good
  - Border crossing isn't inherently slower in their microkernel design
  - For reference, CMU's Mach took 900 cycles on the same architecture
* L3 Solution to Address Space Switches
  - Address space tagged TLBs: in addition to the tag and index, the TLB contains the process for which a particular TLB is present (MIPS)
  - This means the TLB doesn't have to be flushed on context switch
  - Liedtke's recommends exploiting architectural features if TLB is not address space-tagged
    + Use segment registers to designate which addresses are valid for one running process (segment bounds are hardware enforced); this

works well if no process needs the entire address space
        + Shared hardware address space for protection domains
    - Large protection domain: If a process needs the entire address space and the hardware doesn't support address-tagged TLBs, a TLB flush is required
    - However, this only addresses the explicit cost; loss in cache locality is significantly more expensive than the explicit cost
        + Explicit cost << implicit cost
        + TLB flush takes 864 cycles in Pentium processor
    - Small protection domains
        + Switches can be made efficient by careful construction
    - Large protection domains
        + Switching cost not important
        + Cache effects and TLB effects dominate



Address Space Tagged TLB

* Thread Switches and IPC
    - Shown to be competitive to SPIN and Exokernel by construction
    - Switch involes saving all volatile state of processor
* Memory Effects
    - Assmuption os that loss of locality in a microkernel-based design >> monolithic design
    - Liedtke says that splitting the hardware address space into small protection domains using segment registers will result in warmer caches on context switches
        + Each process only occupies a small memory footprint, which results in a smaller footprint in the caches as well
        + Unavoidable if protection domains are large, regardless of how the operating system is designed
* Mach's Expensive Border Crossing

- Focus on portability (can run on different processor architectures)
    + Code bloat -> large memory footprint -> Less locality -> more cache misses -> longer latency for border crossing
- Kernel memory footprint is the culprit, not microkernel itself

* Thesis of L3 for OS Structuring
    1. Minimal abstractions in microkernel
        + Address spaces, threads, IPC, unique IDs
        + These four abstractions are needed by any subsystem that provides functionality to end users
    2. Microkernels are processor-specific in implementation (not portable)
    3. Right set of microkernel abstractions and processor-specific implementation -> efficient processor-independent abstractions at higher layers
        + Processor-dependent kernel with processor-independent abstractions