Extensible OSes
Exokernel and SPIN
Lecture 19, cs262a

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Today's Papers

"Exokernel: An Operating System Architecture for Application-Level Resource Management", Dawson R. Engler, M. Frans Kaashoek, and James O'Toole Jr.
https://pdos.csail.mit.edu/6.828/2008/readings/engler95exokernel.pdf

"SPIN: An Extensible Microkernel for Application-specific Operating System Services", Brian N. Bershad, Craig Chambers, Susan Eggers, Chris Maeda, Dylan McNamee, Przemysław Pardyak, Stefan Savage, and Emin Gün Sirer
www.cs.cornell.edu/people/egs/papers/spin-tr94-03-03.pdf

Traditional OS services – Management and Protection

Provides a set of abstractions

- Processes, Threads, Virtual Memory, Files, IPC
- APIs, e.g.,: POSIX

Resource Allocation and Management

Protection and Security

- Concurrent execution

Abstractions

What is an abstraction?

- Generalization. Often an API in CS. Hides implementation details.

What are the advantages of abstractions?

- Simpler. Easy to understand and use. Just follow the contract. How we fight complexity.
- Standardization. Many implementations all satisfy the abstraction. Loose coupling, e.g. Unix' everything is a file, many implementations and all apps benefit from this standardization.

What are the disadvantages of abstractions?

- Contract is a compromise. Least common denominator. Not perfect for each use case
- Performance often suffers (if you only could tweak an implementation detail of a particular implementation)
- Can create bloated software.

Context for These Papers (1990s)

Windows was dominating the market

- Mac OS downward trend (few percents)
- Unix market highly fragmented (few percents)

OS research limited impact

- Vast majority of OSes proprietary
- **“Is OS research dead?”**, popular panel topic at systems conferences of the era

An effort to reboot the OS research, in particular, and OS architecture, in general

Challenge: “Fixed” Interfaces

Both papers identify “fixed interfaces” provided by existing OSes as main challenge

- Fixed interfaces provide protection but hurt performance and functionality

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.*”
- “*Fixed high-level abstractions limit the functionality of applications, because they are the only available interface between applications and hardware resources*”

Challenge: “Fixed” Interfaces

Both papers identify “fixed interfaces” provided by existing OSes as main challenge

- Fixed interfaces provide protection but hurt performance and functionality

SPIN:

- “*Existing operating systems provide fixed interfaces and implementations to system services and resources. This makes them inappropriate for applications whose resource demands and usage patterns are poorly matched by the services provided.*”

Problems in existing OSes

Extensibility

- Abstractions overly general
- Apps cannot dictate management
- Implementations are fixed

Performance

- Context switching expensive
- Generalizations and hiding information affect performance

Protection and Management offered with loss in Extensibility and Performance

Symptoms

Very few of innovations making into commercial OSes

- E.g., scheduler activations, efficient IPC, new virtual memory policies, …

Applications struggling to get better performances

- They knew better how to manage resources, and the OS was “standing” in the way

Examples Illustrating the need for App Control

Databases know better than the OS what pages they will access

- Can prefetch pages, LRU hurts their performance, why?

Two Papers, Two Approaches

Exokernel:

- Very minimalist kernel, most functionality implemented in user space
- Assumed many apps have widely different requirements, maximal extensibility

SPIN:

- Dynamically link extensions into the kernel
- Rely on programming language features, e.g. static typechecking
- Assumed device drivers need flexibility, so focused on how to enable them while staying protected

Exokernel

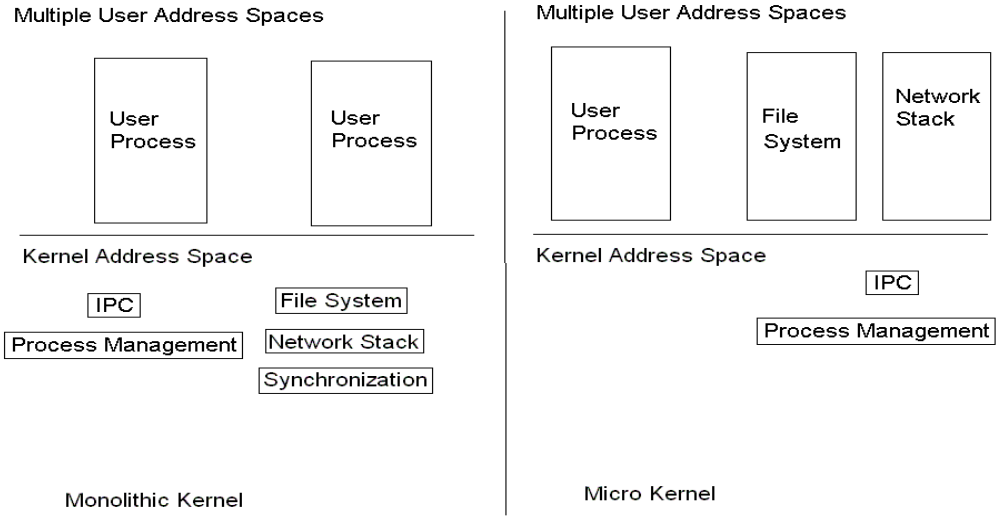
A nice illustration of the end-to-end argument:

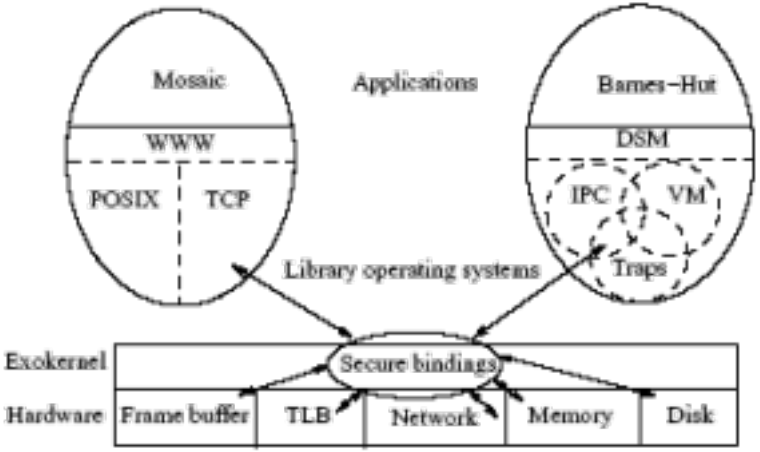
- ``general-purpose implementations of abstractions force applications that do not need a given feature to pay substantial overhead costs.''
- In fact the paper is explicitly invoking it (sec 2.2)!

Corollary:

- Kernel just safely exposes resources to apps
- Apps implement everything else, e.g., interfaces/APIs, resource allocation pollcies

OS Component Layout





Exokernel

www.cs.cornell.edu/courses/CS6410/2011fa/lectures/08-extensible-kernels.pdf
(Hakim Weatherspoon, Cornell University)

Exokernel Main Ideas

Kernel: resource sharing, not policies

Library Operating System: responsible for the abstractions

- IPC
- VM
- Scheduling
- Networking

Lib OS and the Exokernel

Lib OS (untrusted) can implement traditional OS abstractions (compatibility)

Efficient (LibOS in user space)

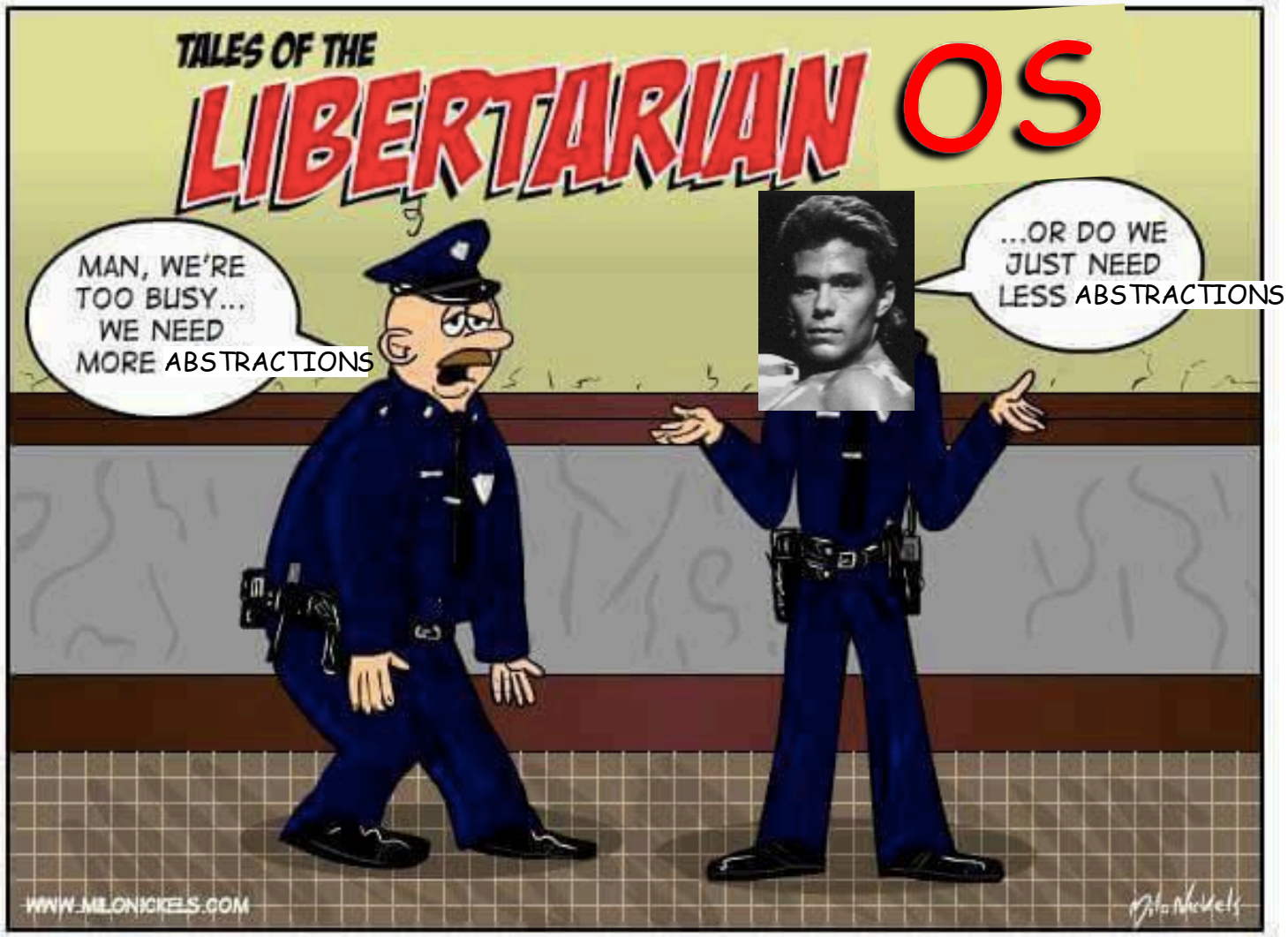
Apps link with LibOS of their choice

Kernel allows LibOS to manage resources, protects LibOSes

Philosophy

"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)."

The motivation for this principle is our belief that distributed, application-specific, resource management is the best way to build efficient flexible systems.


TALES OF THE
LIBERTARIAN OS
MAN, WE'RE TOO BUSY... WE NEED MORE ABSTRACTIONS
...OR DO WE JUST NEED LESS ABSTRACTIONS
WWW.MILONICKELS.COM

Exokernel design

Securely expose hardware

- Decouple authorization from use of resources
- Authorization at bind time (i.e., granting access to resource)
- Only access checks when using resource
- E.g., LibOS loads TLB on TLB fault, and then uses it multiple times

Expose allocation

- Allow LibOSes to request specific physical resources
- Not implicit allocation; LibOS should participate in every allocation decision

Exokernel design

Expose names (CS trick #1^{-1})

- Remove one level of indirection and expose useful attributes
  - E.g., index in direct mapped caches identify physical pages conflicting
- Additionally, expose bookkeeping data structures
  - E.g., freelist, disk arm position (?), TLB entries

Expose revocation

- “Polite” and then forcibly abort

Example: Memory

Self-authenticated capability

Guard TLB loads and DMA

- Secure binding: using self-authenticating capabilities
  - For each page Exokernel creates a random value, check
  - Exokernel records: {Page, Read/Write Rights, MAC(check, Rights)}
- When accessing page, owner need to present capability
- Page owner can change capabilities associated and deallocate it

Large Software TLB (why?)

- TLB of that time small, LibOS can manage a much bigger TLB in software
- Expensive checks during page fault can be reduced with a larger TLB

Example: Processor Sharing

Process time represented as linear vector of time slices

- Round robin allocation of slices

Secure binding: allocate slices to LibOSes

- 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)

Example: Network

Downloadable filters

Application-specific Safe Handlers (ASHes)

- Can reply directly to traffic, e.g., can implement new transport protocols; dramatically reduce

Secure biding happens at download time

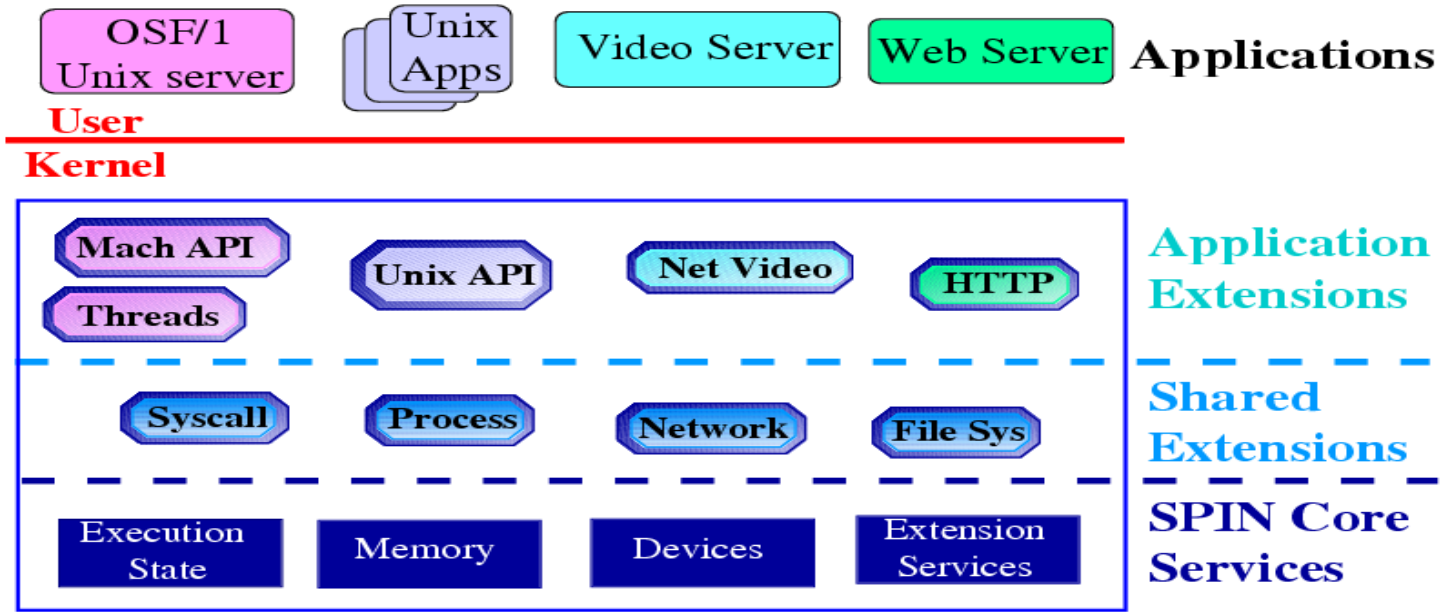
SPIN

SPIN

Use of language features for **extensions**

- Extensibility
  - Dynamic linking and binding of extensions
- Safety
  - Interfaces; type safety; extensions verified by compiler
- Performance
  - Extensions not interpreted; run in kernel space

SPIN structure



From Stefan Savage's SOSP 95 presentation

SPIN Main Ideas

Extend the kernel at runtime through statically-checked extensions

System and extensions written in Modula-3

Event/handler abstraction

Language: Modula 3

Designed by DEC and Olivetti (1980s)

- Descendent from Mesa

Modern language (at that time)

- Interfaces
- Type safety
  - E.g., Array bounds checking, storage management, GC
- Threads
- Exceptions

“Died” together with DEC (acquired by Compaq in 1998)

SPIN design

Co-location

- Extensions dynamically linked into same memory-space as kernel
- Fast communication

Enforced modularity

- Modula 3 extensions provide compile-time protection (memory and privileged instructions protected)

SPIN design

Local protection domains

- Namespaces for extensions
- Avoid context switch through a function-call that decides which interfaces (extensions) can be accessed

Dynamic call binding

- Binds events to extensions
- Handler pattern through function call

Events and Handler

Event: a message that announces a change in
the state of the system or a request for service

(Event) Handler: a procedure that receives the message

An extension installs a handler on an event by explicitly registering the handler with the event through a central dispatcher

- Essentially a callback mechanism

Example: Memory

The kernel controls allocation of physical and virtual addresses capabilities

Extensions:

- Event: page fault
- App provides handle for page faults

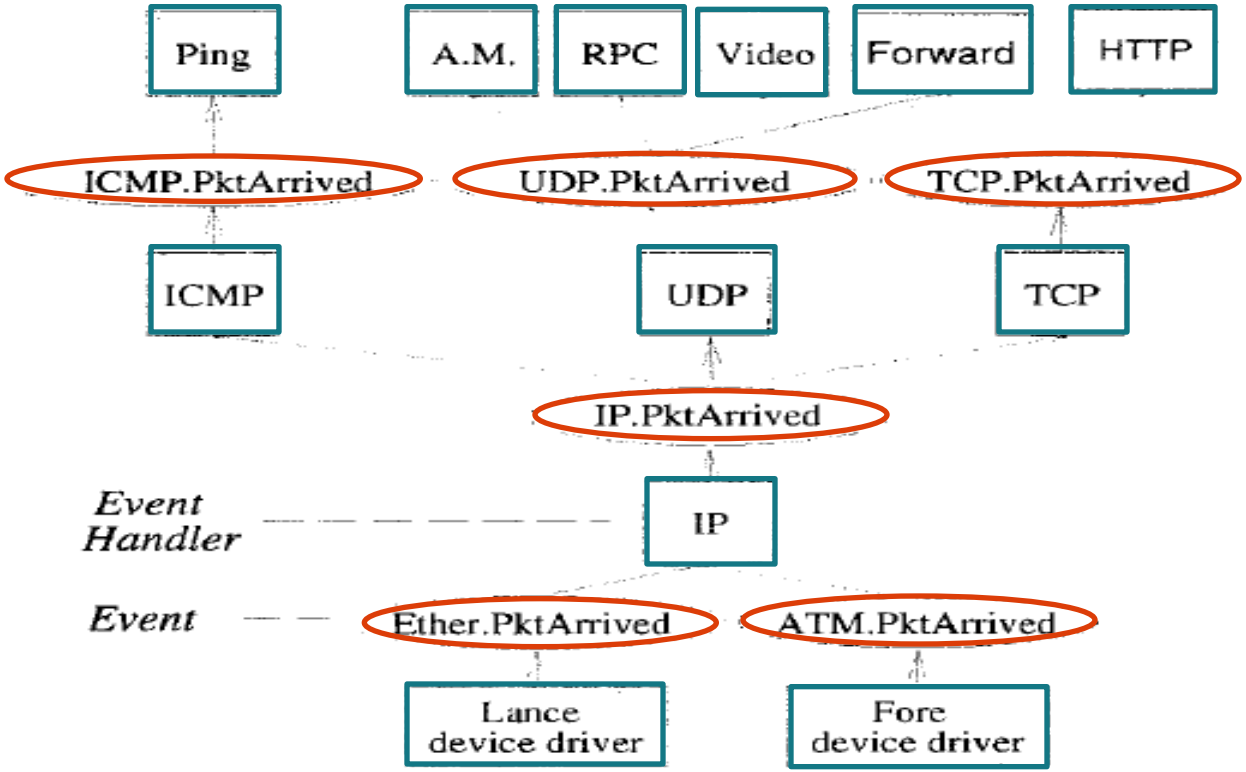
Example: Processor Sharing

Based on Modula-3 threads

Scheduler multiplexes processor among competing strands

- A strand is similar to a thread in traditional operating but no kernel state
- Use preemptive round-robin to schedule strands

Example: Network Stack



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SPIN vs Exokernel

SPIN uses programming language facilities and communicates through procedure calls

Exokernel uses hardware specific calls to protect system calls

Zooming out

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

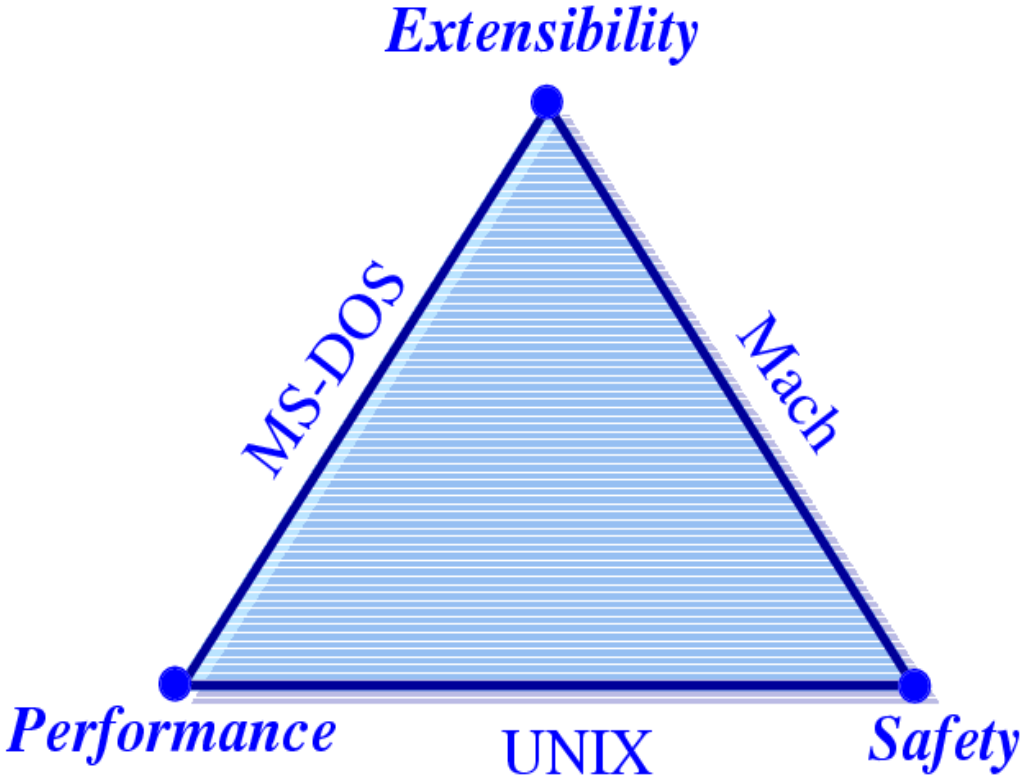
Exokernel and SPIN try to achieve all three!

Challenges

Extensibility

Security

Performance



From Stefan Savage's SOSP 95 presentation

Exokernel and SPIN attempt to have all 3 in one OS!

Zooming out further

- Much of computer system research is about tradeoffs
  - Efficiency vs Security
  - Efficiency vs Modularity (Extensibility)
  - Efficiency vs Fairness
  - Efficiency vs Correctness
- Papers that show that you can have your cake and east it too get attention!

Microkernels vs Exokernels vs VMs vs Containers?

- Exokernels provide secure bindings to hardware directly
- What about microkernels?
  - Microkernels implement IPC and process management **abstractions**, they are fixed and cannot be changed
- What about VMs?
  - VMs emulate full machine and also typically run another monolithic kernel inside of it (c.f. paravirtualization?)
- What about containers?

Summary

Extensibility without loss of security or performance

Exokernels

- Safely export machine resources
- Decouple protection from management to get performance, no layers of indirection to slow things down

SPIN

- Kernel extensions (imported) safely specialize OS services
- Safety through Programming Language support