Operating System Structure

Joey Echeverria joey42+os@gmail.com
modified by: Matthew Brewer mbrewer@andrew.cmu.edu

Nov 15, 2006

Overview

- Motivations
- Kernel Structures
  - Monolithic Kernels
    - Kernel Extensions
  - Open Systems
  - Microkernels
  - Exokernels
  - More Microkernels
- Final Thoughts

Motivations

- Operating systems have a hard job.
- Operating systems are:
  - Hardware Multiplexers
  - Abstraction layers
  - Protection boundaries
  - Complicated

Motivations

- Hardware Multiplexer
  - Each process sees a “computer” as if it were alone
  - Requires allocation and multiplexing of:
    * Memory
    * Disk
    * CPU
    * IO in general (network, graphics, keyboard etc.)
- If OS is multiplexing it must also allocate
  - Priorities, Classes? - HARD problems!!!

Motivations

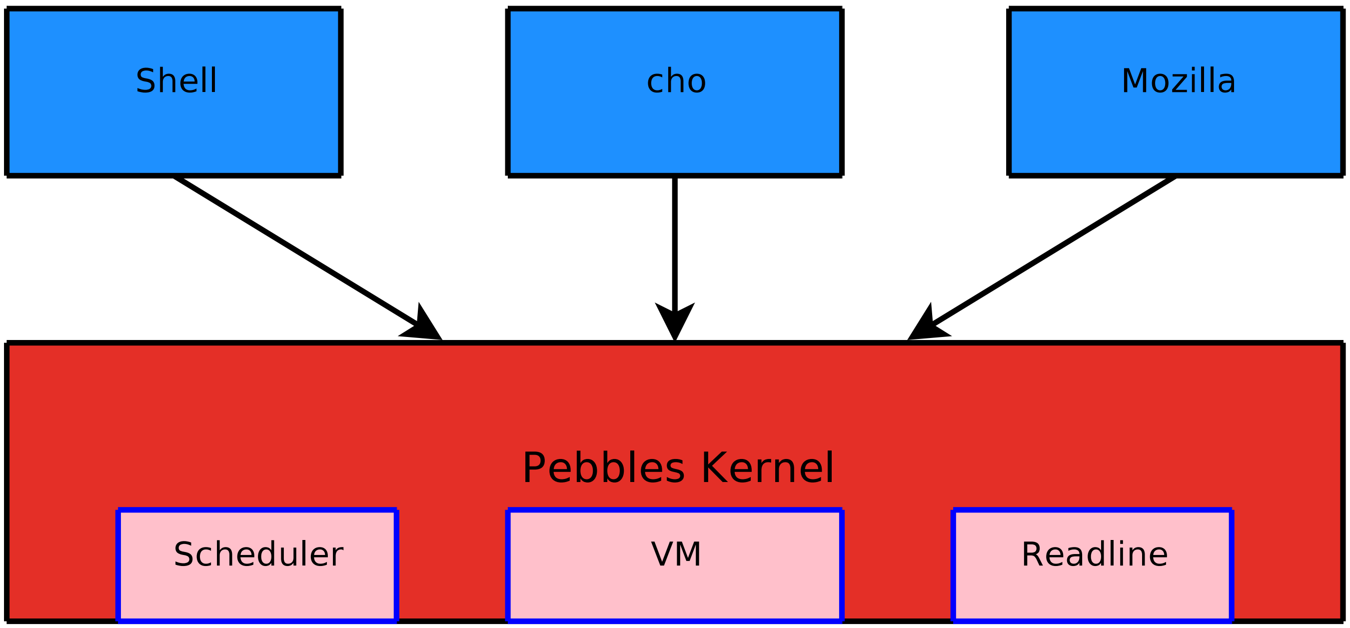
- Abstraction Layer
  - Presents “simple”, “uniform” interface to hardware
  - Applications see a well defined interface (system calls)
    - * Block Device (hard drive, flash card, network mount, USB drive)
    - * CD drive (SCSI, IDE)
    - * tty (teletype, serial terminal, virtual terminal)
    - * filesystem (ext2-4, reiserfs, UFS, FFS, NFS, AFS, JFFS2, CRAMFS)
    - * network stack (TCP/IP abstraction)

Motivations

- Protection Boundaries
  - Protect processes from each other
  - Protect crucial services (like the kernel) from process
  - Note: Everyone trusts the kernel
- Complicated
  - See Project 3 :)
  - Full OS is hundreds of thousands of lines
  - Very Roughly: correctness $\propto$ 1/code_size

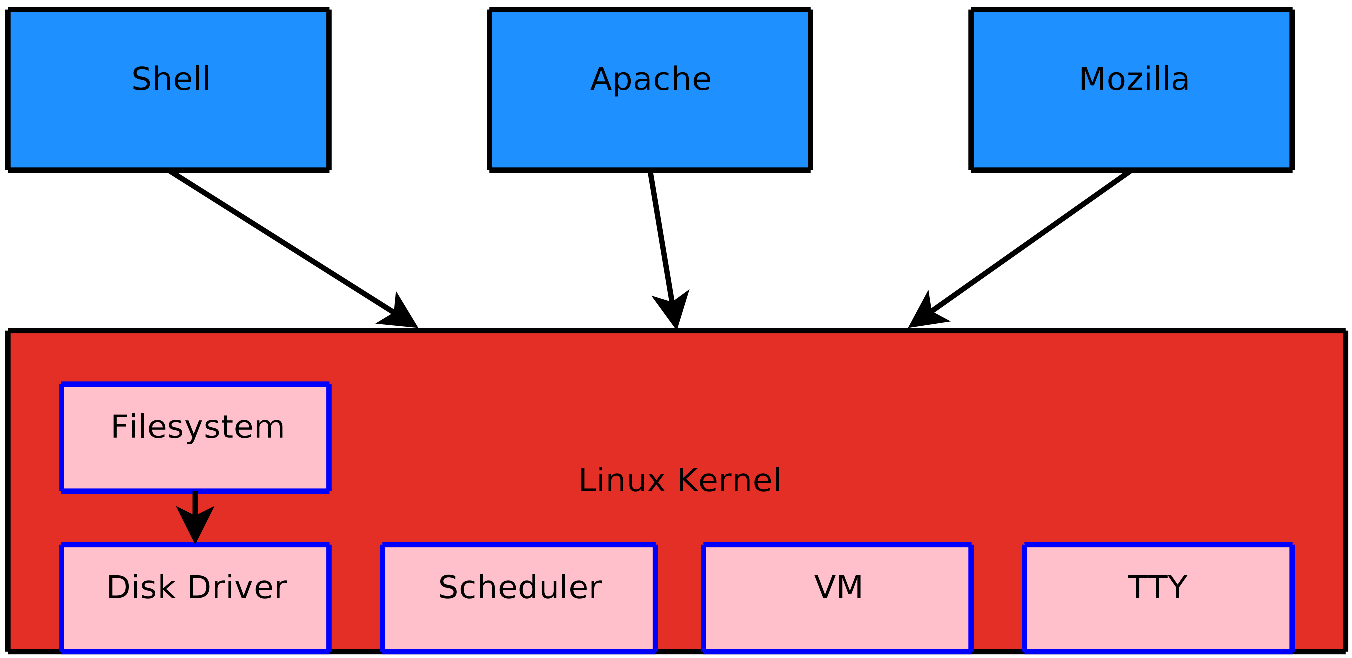
Monolithic Kernels

- Pebbles Kernel



Monolithic Kernels

- Linux Kernel... similar?



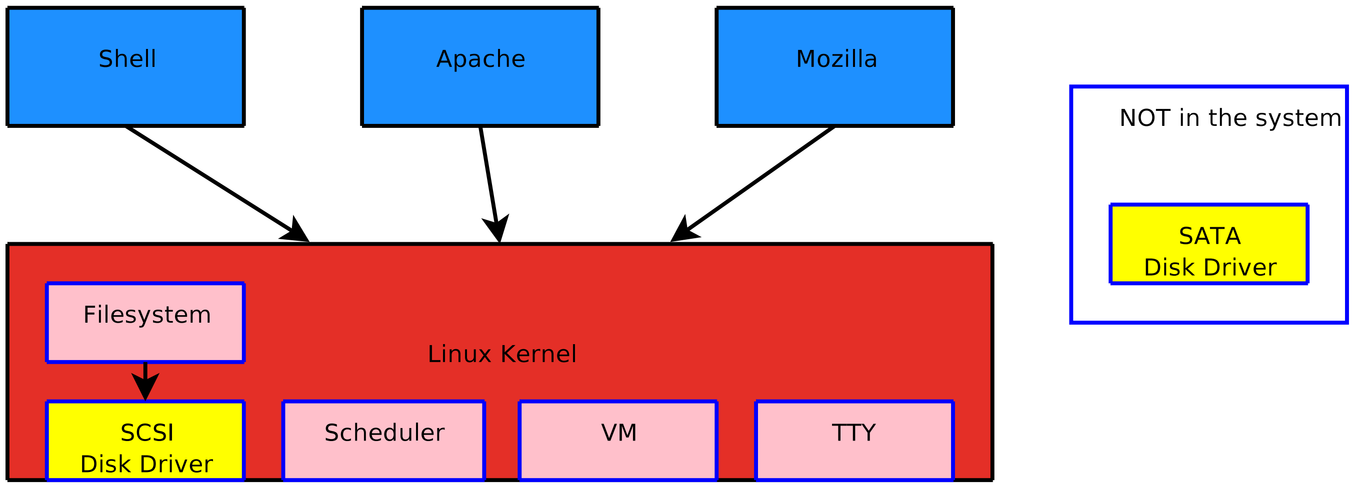
Monolithic Kernels

- Advantages:
  - + Well understood
  - + Good performance
  - + High level of protection between applications
- Disadvantages:
  - – No protection between kernel components
  - – LOTS of code is in kernel
  - – Not (very) extensible
- Examples: UNIX, Mac OS X, Windows NT/XP, Linux, BSD, i.e., common

Kernel Extensions

- Problem - I have a SCSI disk, he has a SATA disk
- I don't want a (possibly unstable, large) SATA driver muddying my kernel
- Solution - kernel modules!
  - Special binaries compiled with kernel
  - Can be loaded at run-time - so we can have LOTS of them
  - Can break kernel, so loadable only by root
- done in: VMS, Windows NT, Linux, BSD, OS X

Kernel Extensions



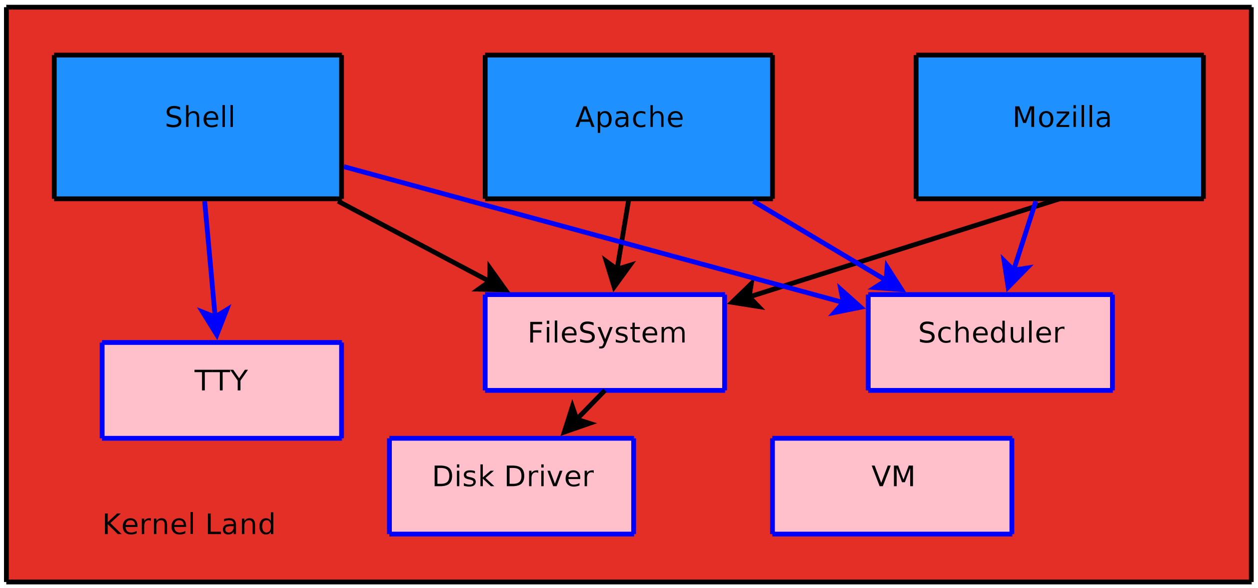
Kernel Extensions

- Advantages
  - Can extend kernel
  - Code runs FAST
- Disadvantages
  - Adding things to kernel can break it
  - Have to ask sysadmin nicely

Open Systems

- Monolithic kernels run reasonably fast, and can be extended (at least by root)
- System calls and address space separation is overhead,
  - X86 processor - minimum of 90 cycles to trap to higher PL
  - Context switch must dump TLB, this costs more every day
- So, do we need protection?

Open Systems



Open Systems

- Applications, libraries, and kernel all sit in the *same address space*

- Does anyone actually do this craziness?
  - MS-DOS
  - Mac OS 9 and prior
  - Windows ME, 98, 95, 3.1, etc.
  - Palm OS
  - Some embedded systems

- Used to be *very* common

Open Systems

- Advantages:
  - + *Very* good performance
  - + Very extensible
    - * Undocumented Windows, Schulman et al. 1992
    - * In the case of Mac OS and Palm OS there's an extensions *industry*
  - + Can work well in practice
  - + Lack of abstractions makes realtime systems easier
- Disadvantages:
  - – No protection between kernel and/or applications
  - – Not particularly stable
  - – Composing extensions can result in unpredictable behavior

Microkernels

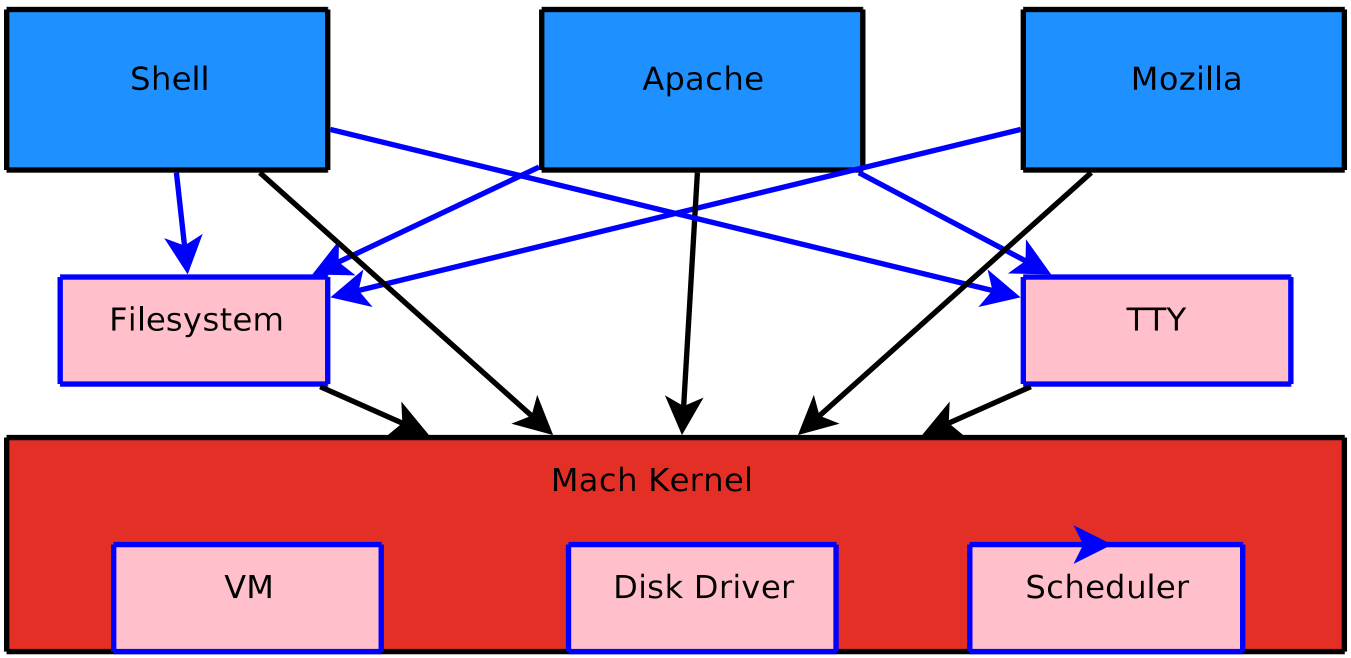
- Monolithic Kernels
  - Extensible (by root)
  - User protection
  - No internal protection - makes debugging hard, bugs CRASH
- Open Systems
  - Extensible by everyone
  - No protection at all - same_deal++ AND can't be multi-user
- ... Can we have user extensibility, and internal protection?

Microkernels

- Replace the monolithic kernel with a “small, clean, logical” set of abstractions
  - Tasks
  - Threads
  - Virtual Memory
  - Interprocess Communication
- Move the rest of the OS into *server processes*

Microkernels (Mach)

multi-server



Microkernels (Mach)

- Started as a project at CMU (based on RIG project from Rochester)
- Plan

1. Mach 2: Take BSD 4.1 add VM API,IPC,SMP support
2. Mach 3: saw kernel in half and run as “single-server”
3. Mach 3 continued: decompose single server into smaller servers

Microkernels (Mach)

- Results
  - Mach 2 completed in 1989
    - Unix: SMP, kernel threads, 5 architectures
    - Used for Encore, Convex, NeXT, and subsequently OS X
    - success!
  - Mach 3 Finished(ish)
    - Mach 2 split in 2 (and then more)
    - Ran on a few systems at CMU, and a few outside
    - Multi-server systems: Lites, Mach-US, OSF

Microkernels (Mach 3)

- Now that we have a microkernel, look what we can do!
- IBM Workplace OS (Mach 3.0)
  * one kernel for OS/2, OS/400, and AIX
  * failure
- Called a “hypervisor” - idea is getting popular again
  * Xen, L4Linux

Microkernels (Mach 3)

- Advantages (Mach 3):
  - + Strong protection, the operating system is protected even from itself
  - + Can run untrusted system services (user-space filesystem... see Hurd)
  - + Naturally extends to distributed/parallel systems

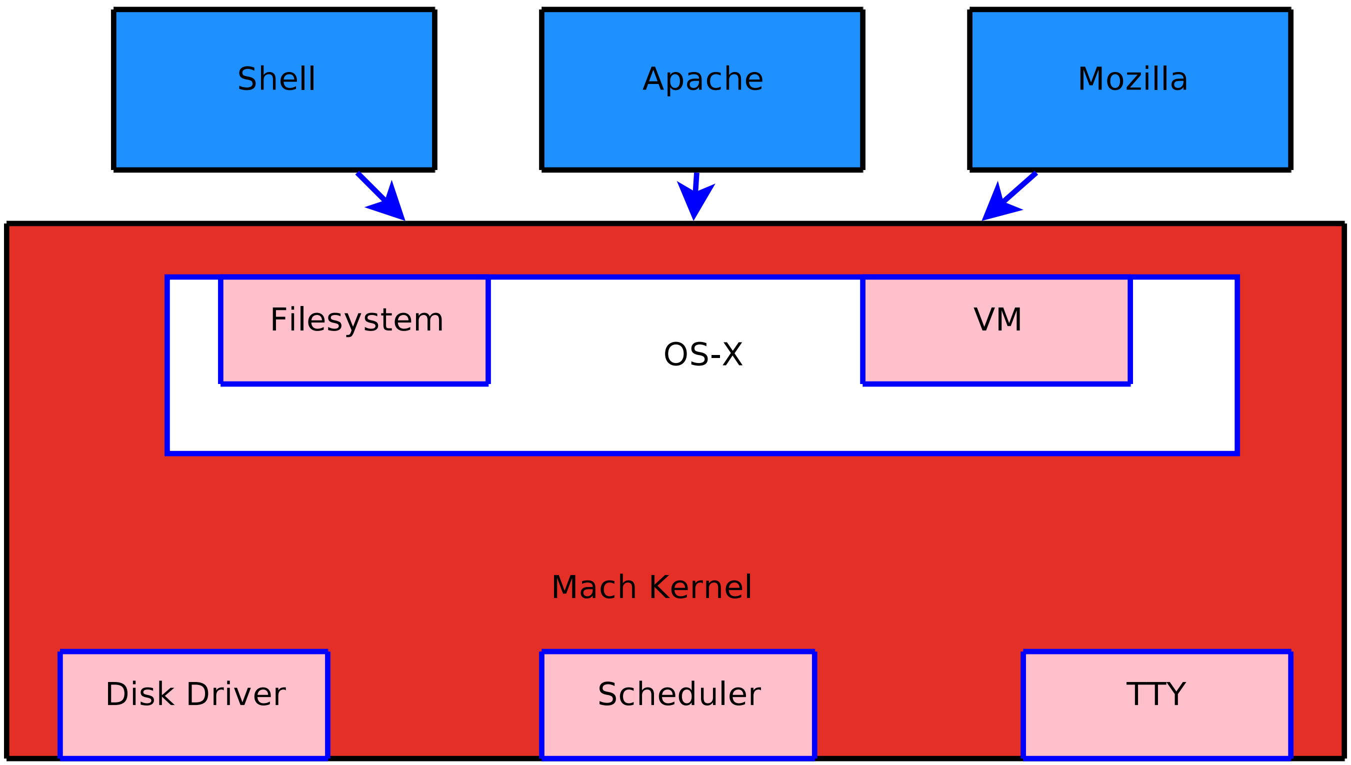
- Disadvantages:
  - – Performance
    - ∗ It looks like extra context switches and copying would be expensive
    - ∗ Mach 3 (untuned) ran slow in experiments
    - ∗ Kernel code still enormous due to IPC, but now doesn't do much
    - ∗ Still hasn't REALLY been tried

Microkernels (Mach)

- What else can we do with our microkernel?
- Remember the Mach development process
  - Mach 2) Microkernel with server in kernel address space
  - Mach 3) Microkernel plus multi-server OS
- OS X) Mach 2 - windowing system uses external server (similar to unix)

Microkernels (Mach/OSX)

So why bother with the microkernel?



Microkernels (Mach/OSX)

- Advantages:
  - \+ Mach provides nice API for kernel development
  - \+ Can restart crucial system services on a crash (maybe)
  - \+ Step towards pushing more servers into userland
  - \+ To extend OS just add a new server (read, monolithic kernel)

- Disadvantages:
  - – Mach is large, so kernel is large before you write your OS
  - – Slow at first... though Apple is fixing this

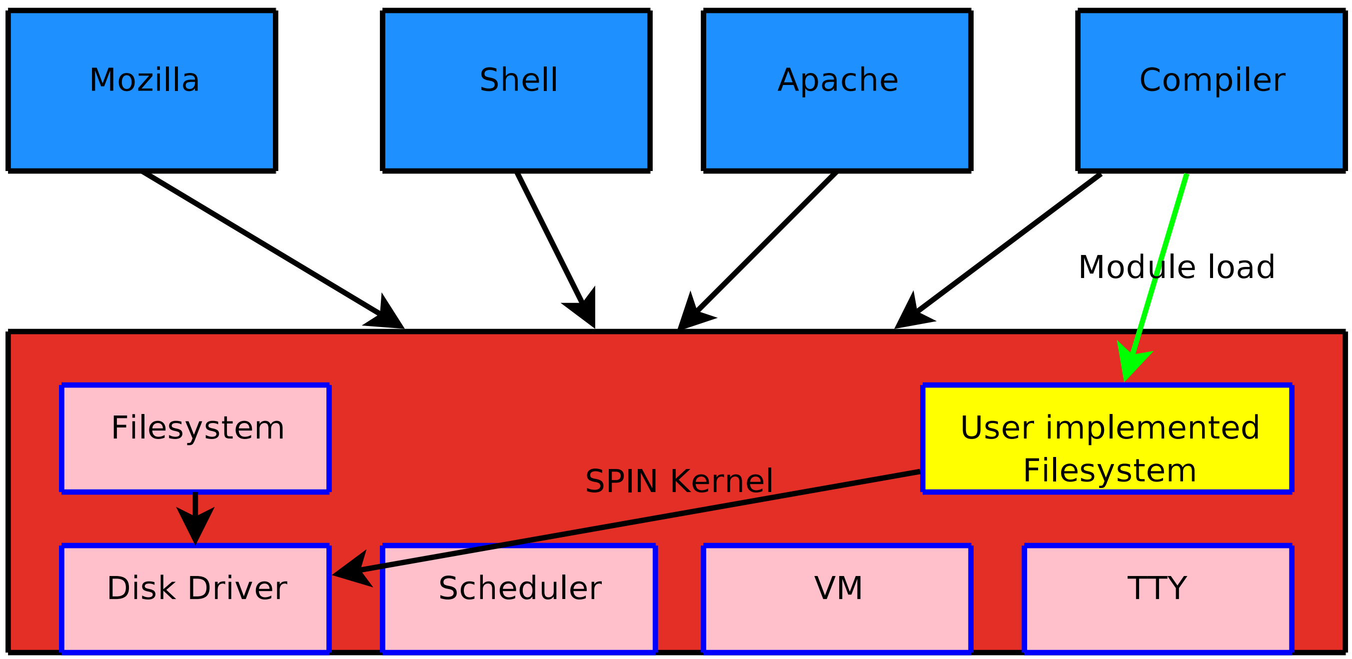
Microkernels (Mach)

- Things to remember about Mach 3
  - Mach 3 == microkernel, Mach 2 not so much
  - Code ran slow at first, was never tuned
  - Then everyone graduated
  - Proved microkernel is feasible, proved nothing about performance
- Other interesting points
  - Other microkernels from Mach period: ChorusOS, QNX
  - QNX competes with VxWorks as a realtime OS
  - ChorusOS is a realtime kernel out of Sun, now open sourced
  - More later

Provable Kernel Extensions

- We want an extensible OS
- We want extensions to run fast, but be safe for addition by users
- Assume we don't like microkernels (slow, more code, whatever)
- So... other ideas?

Provable Kernel Extensions

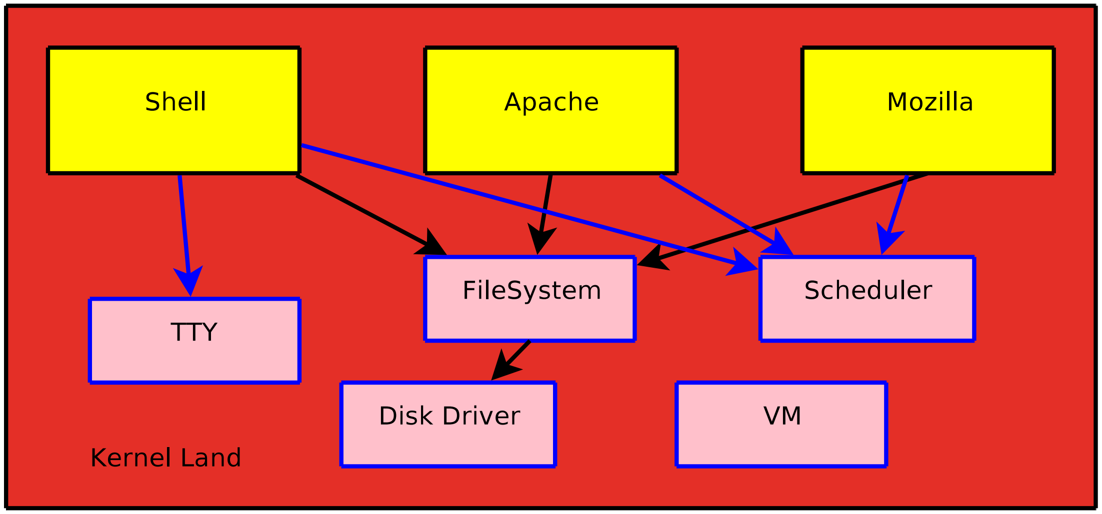


Provable Kernel Extensions

- PROVE the code does what we want
- Allow trusted “theorem checker” (maybe a whole compiler) to load modules
- Submit code to compiler, if code compiles it’s loaded into kernel
- Checker can be EXTREMELY conservative and careful about what it lets in
  - Compiler-checked source safety (UW: Spin: Modula-3)
  - Kernel-verified binary safety (CMU: Proof-carrying code)
    - More language agnostic - *just* need a compiler that compiles to PCC
- Safe? Guaranteed (if compiler is correct... same deal as a kernel)

Provable Kernel Extensions

This should look really attractive, though requires a leap of faith.



Provable Kernel Extensions

- What if ALL code was loaded into the "kernel" and just proved to do the "right" thing?... Is this silly, or a good idea?
  - Looks a lot like Open Systems
  - Except compiler can enforce more stability

- Effectiveness strongly dependent on quality of proofs

- Some proofs are HARD, some proofs are IMPOSSIBLE!

- Smart people here, and at Microsoft are working on it
  - take this as you will

Provable Kernel Extensions

- Advantages:
  - + Extensible even by users, just add a new extension
  - + Safe, provably so
  - + Good performance because everything is in the kernel
- Disadvantages:
  - – Proofs are hard - and checking can be slow
  - – We can’t actually DO this for interesting code (yet?)
  - – Constrained implementation language
  - – Constraints may cause things to run slower than protection boundaries
  - – Still very limited in scope, not used widely

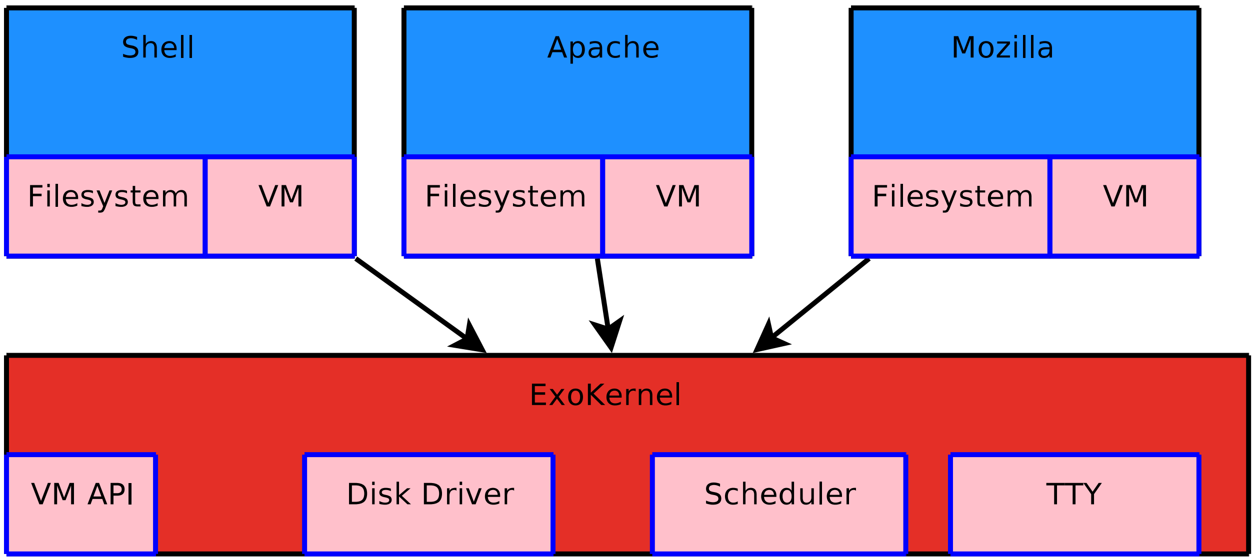
Exokernels

- Monolithic kernel
  - Too many abstractions get in the way
  - Not easily extensible for every application (special kernel mods)
- Microkernel
  - “It’s not micro in size, it’s micro in functionality”
  - Too heavy an abstraction, too portable, just too much
- If applications control system, can optimize for their usage cases
- So maybe Mach is still too much kernel?

Exokernels

- Basic idea: Take the operating system out of the kernel and put it into libraries
- Why? Applications know better how to manage active hardware resources than kernel writers do
- Safe? Exokernel is simply a hardware multiplexer, and thus a permissions boundary.
- Separates the security and protection from the management of resources

Exokernels


Shell
Filesystem
VM
Apache
Filesystem
VM
Mozilla
Filesystem
VM
ExoKernel
VM API
Disk Driver
Scheduler
TTY

Exokernels: VM Example

- There is no fork()
- There is no exec()
- There is no automatic stack growth
- Exokernel keeps track of physical memory pages and assigns them to an application on request
- Application makes a call into the Exokernel and asks for a physical memory page
- Exokernel manages hardware level of virtual memory

Exokernels: simple fork()

- fork():
  - Acquire a new, blank address space
  - Allocate some physical frames
  - Map physical pages into blank address space
  - Copy bits (from us) to the target, blank address space
  - Allocate a new thread and bind it to the address space
  - Fill in new thread's registers and start it running
- The point is that the kernel doesn't provide this service

Exokernels: COW fork()

- fork(), advanced:
  - Acquire a new, blank address space
  - Ask kernel to set current space's mappings to R/O
  - Map current space's physical pages R/O into blank space
  - Update copy-on-write table in each address space
  - Application's page-fault handler (like a signal handler) copies/re-maps
- Each process can have it's own fork() optomized for it – or none at all

Exokernels: Web Server Example

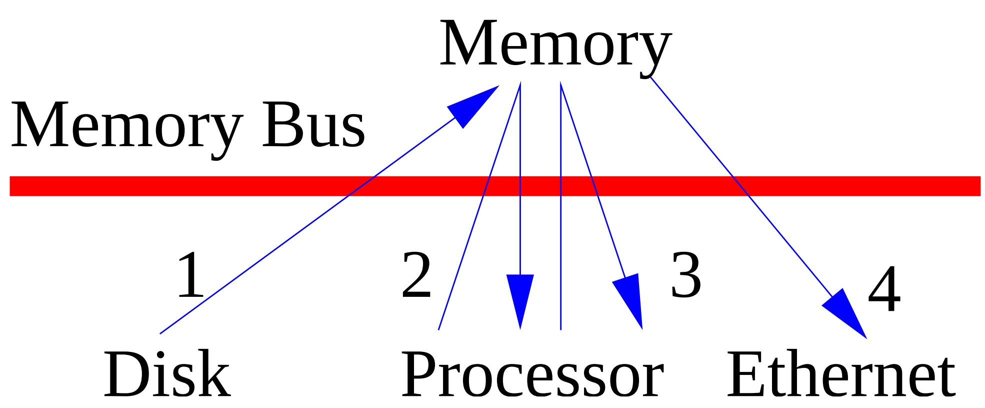
- In a typical web server the data must go from:
  1. the disk to kernel memory
  2. kernel memory to user memory
  3. user memory back to kernel memory
  4. kernel memory to the network device
- In an exokernel, the application can have the data go straight from disk to the network interface

Exokernels: Web Server Example

- Traditional kernel and web server:

1. read() − copy from disk to kernel buffer
2. read() − copy from kernel to user buffer
3. send() − user buffer to kernel buffer

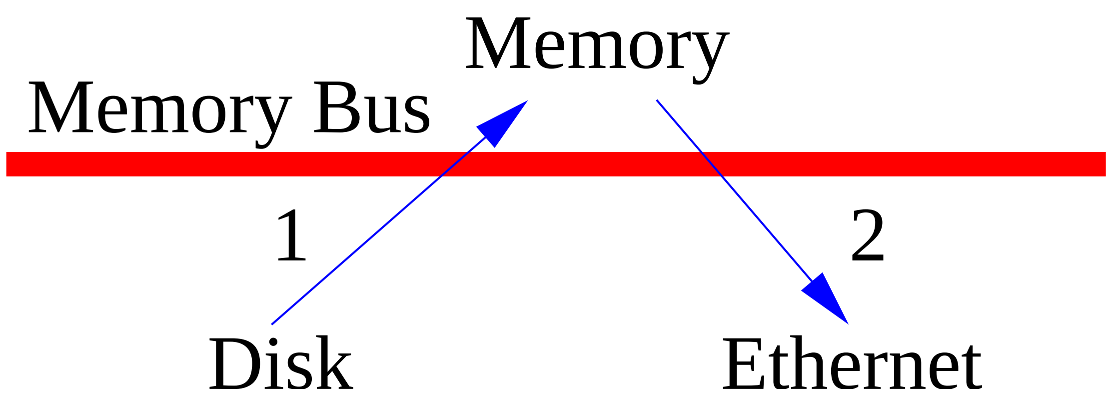
   −− data is check−summed
4. send() − kernel buffer to device memory



Exokernels: Web Server Example

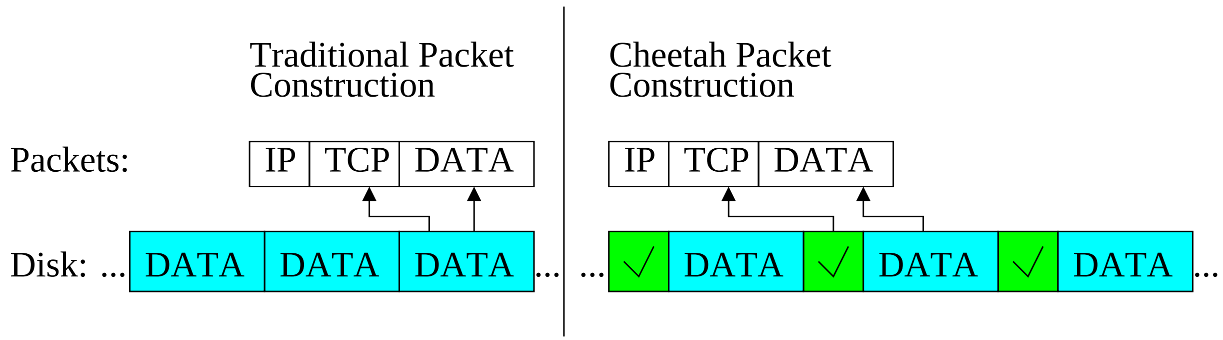
- Exokernel and Cheetah:

  1. Copy from disk to memory
  2. Copy from memory to network device

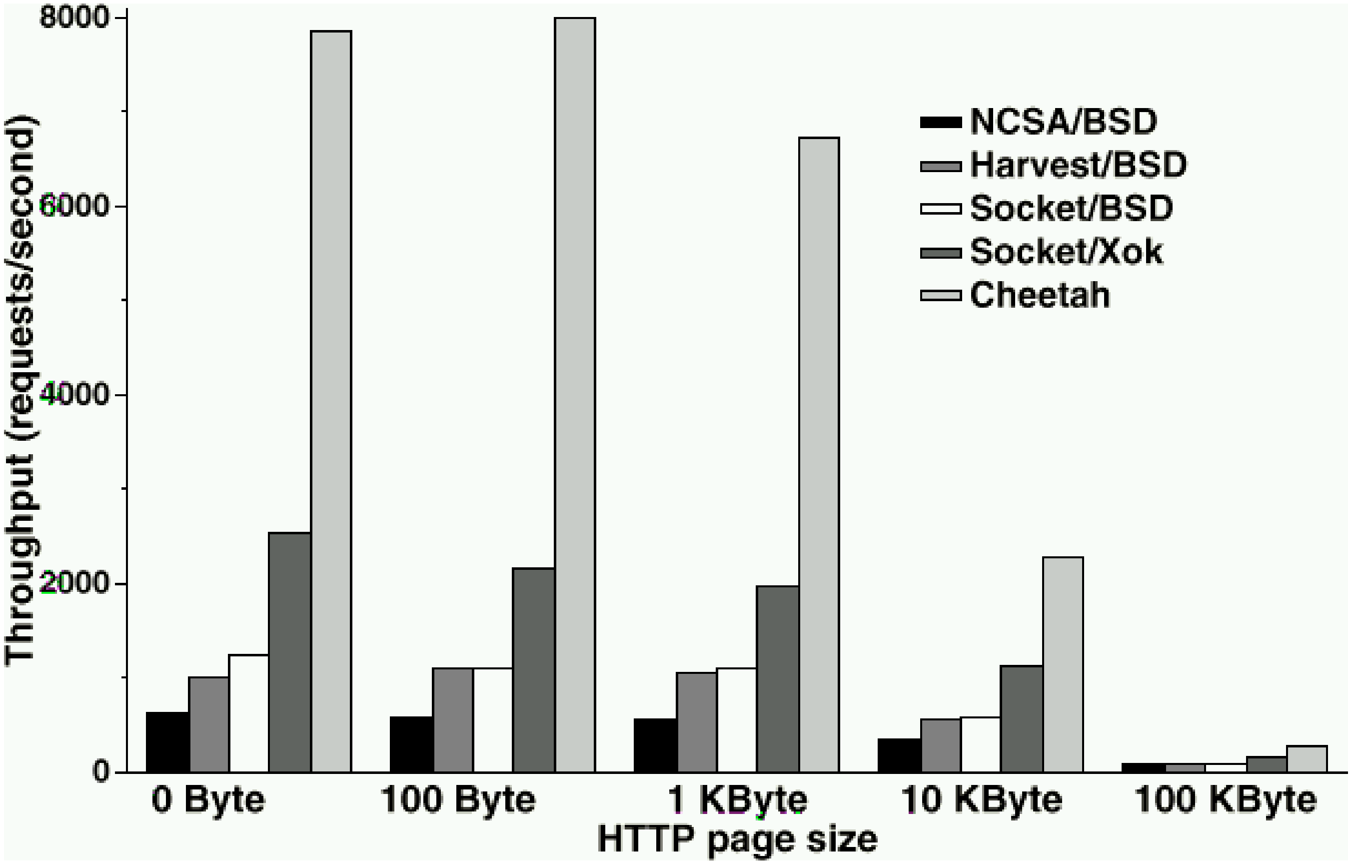


Exokernels: Web Server Example

- Exokernel and Cheetah:
  - "File system" doesn't store files, stores packet-body streams
    - ∗ Data blocks are collocated with pre-computed data check-sums
  - Header is finished when the data is sent out, taking advantage of the ability of TCP check-sums to be "patched"
  - This saves the system from recomputing a check-sum, saves processing power



Exokernels: Cheetah Performance



Exokernels

- Advantages:
  - + Extensible: just add a new libOS
  - + Fast?: Applications directly access hardware, no obstruction layers
  - + Safe: Exokernel allows safe sharing of resources
- Disadvantages:
  - – To take advantage of Exo, basically writing an OS for each app
  - – Nothing about moving an OS into libraries makes it easier to write
  - – Slow?: Many many small syscalls instead of one big syscall
  - – send_file(2) - Why change when you can steal?
  - – Requires policy: despite assertions to the contrary

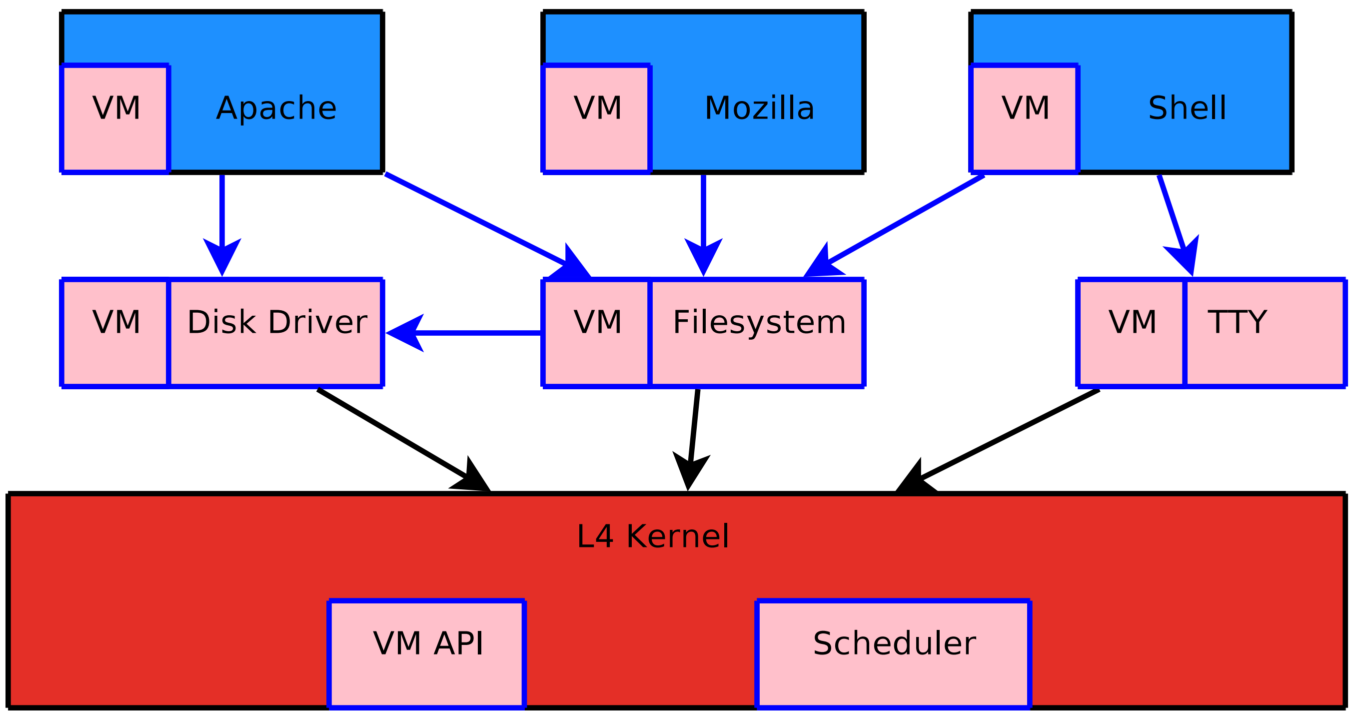
Exokernels

- Xok development is mostly over
- Torch has been passed to L4

more Microkernels (L4)

- In practice Exokernels still has some abstractions
- Exokernel still missing some abstractions that seem necessary
- But we like small: correctness $\propto$ 1/code_size
- Then what do we need?
- More processes! (and some IPC, and VM API)

more Microkernels (L4)



more Microkernels (L4)

- Idea:
  - Kernel provides synchronous IPC (not Mach IPC™)
  - Kernel provides some VM abstraction
  - Kernel Doesn't provide device drivers, so we can have untrusted ones
  - like Exo: implement OS in libraries for mere abstractions
    * Fork, Exec, Filesystem Interface, VM interface
  - new: Implement OS in processes for required protection
    * Filesystem, Global Namespace, Device Drivers
  - For fun and profit: `http://os.inf.tu-dresden.de/L4/`

More Microkernels (L4)

- Advantages:
  - + Fast as hypervisor, similar to Mach (L4Linux 4% slower than Linux)
  - + VERY Good separation (if we want it)
  - + Supports multiple OS personalities
  - + Soft realtime
- Disadvantages:
  - – Recreated much of Mach, but smaller, entails same problems
  - – Still notable missing abstraction: capabilities (more on this shortly)
  - – No Micro-OS written for it with protection boundaries
  - – Still untested with a multiserver topology

Microkernel OS'n (GNU Hurd Project)

- GNU Hurd Project:
  - Hurd stands for 'Hird of Unix-Replacing Daemons' and Hird stands for 'Hurd of Interfaces Representing Depth'
  - GNU Hurd is the FSF's kernel (Richard M Stallman)
  - Work began in 1990 on the kernel, has run on 10's of machines
  - Hurd/Mach vaguely runs, so abandoned in favor of Hurd/L4
  - Hurd/L4 abandoned after a particular OS TA (and a former OS TA) tried to write their IPC layer.
  - Ready for mass deployment Real Soon Now™

Microkernel OS'n

- The literature has between 5 and 50 percent overhead for microkernels
  - See *The Performance of μ-Kernel-Based Systems*
    - http://os.inf.tu-dresden.de/pubs/sosp97/

Summing Up

- Goodness (looks_nice metric)
  - Monolithic kernel: easy to implement, some protection
  - Open System: easy to implement, no protection
  - Microkernel + kernel land tasks: Can add more to run multiple OS'n
  - Microkernel + multiserver: nice separation, speed unknown
  - Proven extension: looks really good, but we can't do it (yet?)
  - Exokernel: why not just write an OS from scratch for each app?
  - L4 type microkernel + multiserver: nice separation, realities unknown

Summing Up

- Goodness (usage metric)
  - Monolithic kernels: widely used (Linux, BSD, Windows, etc.)
  - Open systems: widely used (MacOS 9, Palm OS)
  - Microkernel + kernel land tasks: widely used (OS-X)
  - Microkernel + multiserver: Used in a few places (QNX, Symbian, BeOS)
  - Proven extensions: not used, demo only
  - Exokernels: pretty much dead, but inspired some thought
  - L4 type microkernel + multiserver: not even implemented

Summing Up

- So why don't we use microkernels or something similar?
- Say we have a micro-(or exo)-kernel, and make it run fast
  - We describe things we can do in userspace faster (like Cheetah)
  - Monolithic developer listens intently
  - Monolithic developer adds functionality to his/her kernel (send_file(2))
  - Monolithic kernel again runs as fast or faster than our microkernel
- So, if monolithic kernel runs as fast, why bother porting to new OS?
  - Stability - new device drivers break Linux often, we use them anyway
  - No single abstraction seems to be right, so allow everything at once

Further Reading

- Jochen Liedtke, On Micro-Kernel Construction
- Willy Zwaenepoel, Extensible Systems are Leading OS Research Astray
- Michael Swift, Improving the Reliability of Commodity Operating Systems
- An Overview of the Singularity Project, Microsoft Research MSR-TR-2005-135
- Harmen Hartig, *The Performance of μ-Kernel-Based Systems*
- CODE: (recommend new_OS, L4 pistachio, Plan 9, maybe NetBSD)