Operating System Structure

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Overview

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

Motivations

- Operating systems have a hard job.
- Operating systems are:
  - Abstraction layers
  - Resource allocators
  - Protection boundaries
  - Resource Schedulers
  - Complicated

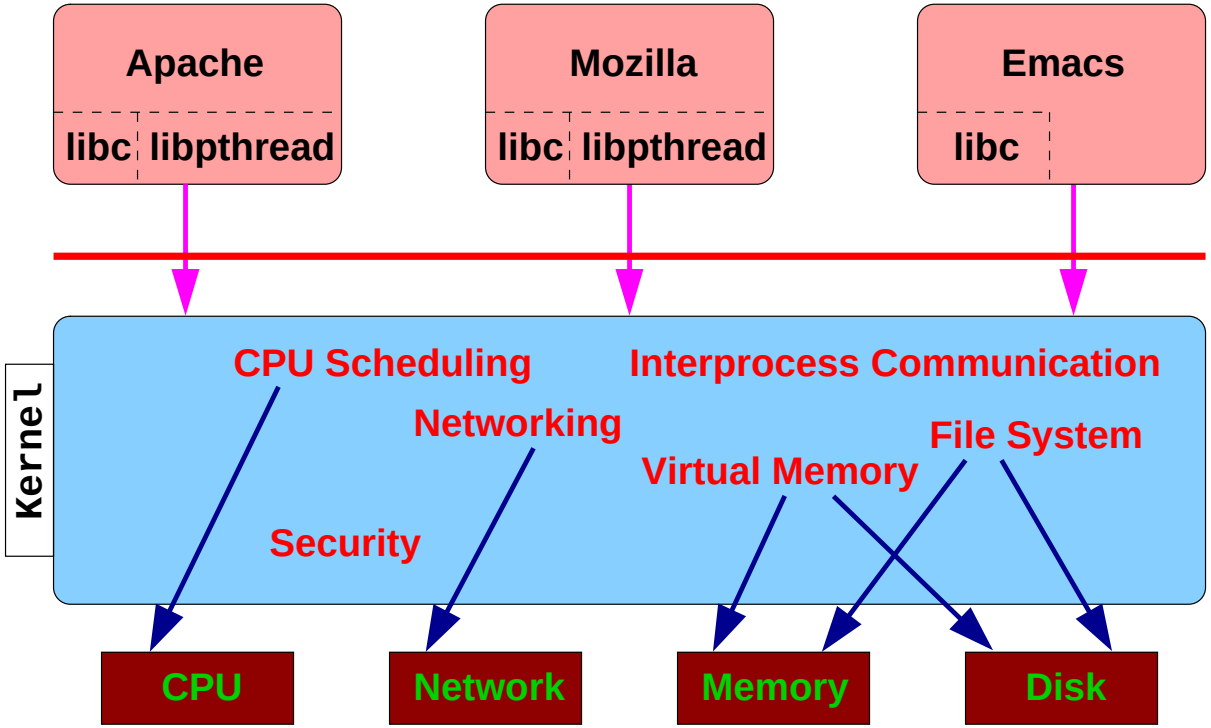
Motivations

- Abstraction Layer
  - Operating systems present a simplified view of hardware
  - Applications see a well defined interface (system calls)
- Resource Allocator
  - Operating systems allocate hardware resources to processes
    - memory
    - network
    - disk space
    - CPU time
    - I/O devices

Motivations

- Protection Boundaries
  - Operating systems protect processes from each other and itself from process.
  - Note: Everyone trusts the kernel.
- Resource Schedulers
  - Operating systems schedule access to resources.
  - e.g., process scheduling, disk scheduling, etc.
- Complicated
  - See Project 3 :)

Monolithic Kernels



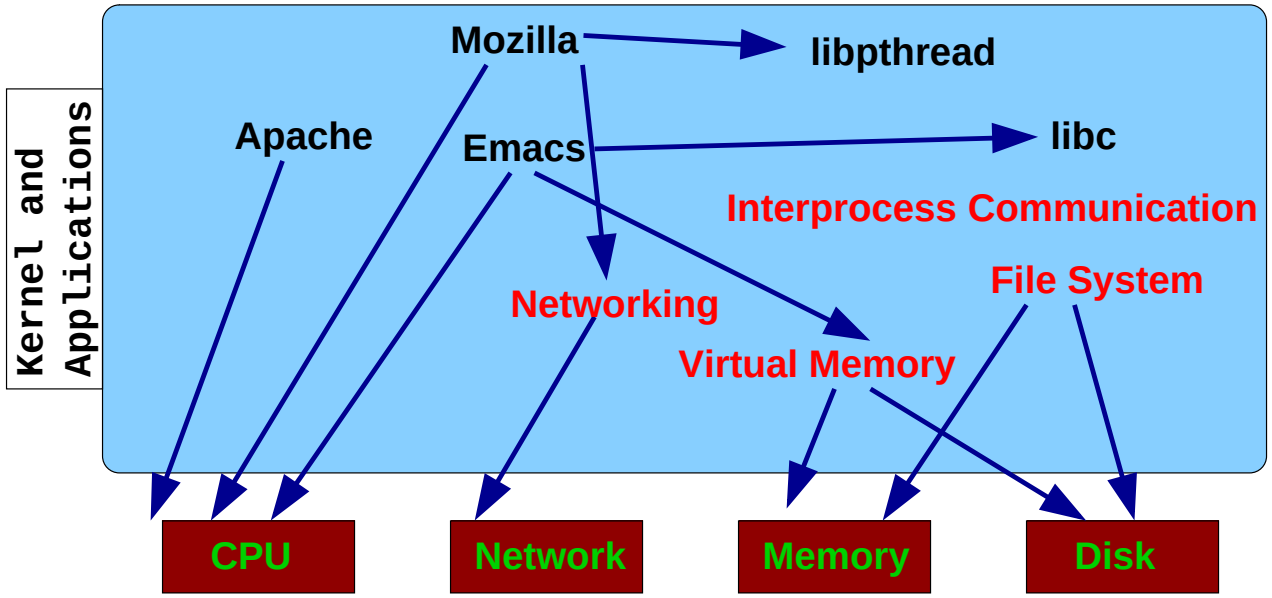
Monolithic Kernels

- You've seen this before.
- The kernel is all in one place with no protection between components.
  - See Project 3 :)
- Applications use a well-defined system call interface to interact with the kernel.
- Examples: UNIX, Mac OS X, Windows NT/XP, Linux, BSD, i.e., common

Monolithic Kernels

- Advantages:
  - Well understood
  - Good performance
  - High level of protection between applications
- Disadvantages:
  - No protection between kernel components
  - Not extensible
  - Overall structure is complicated
    - Everything is intermixed
    - There aren't clear boundaries between modules

Open Systems



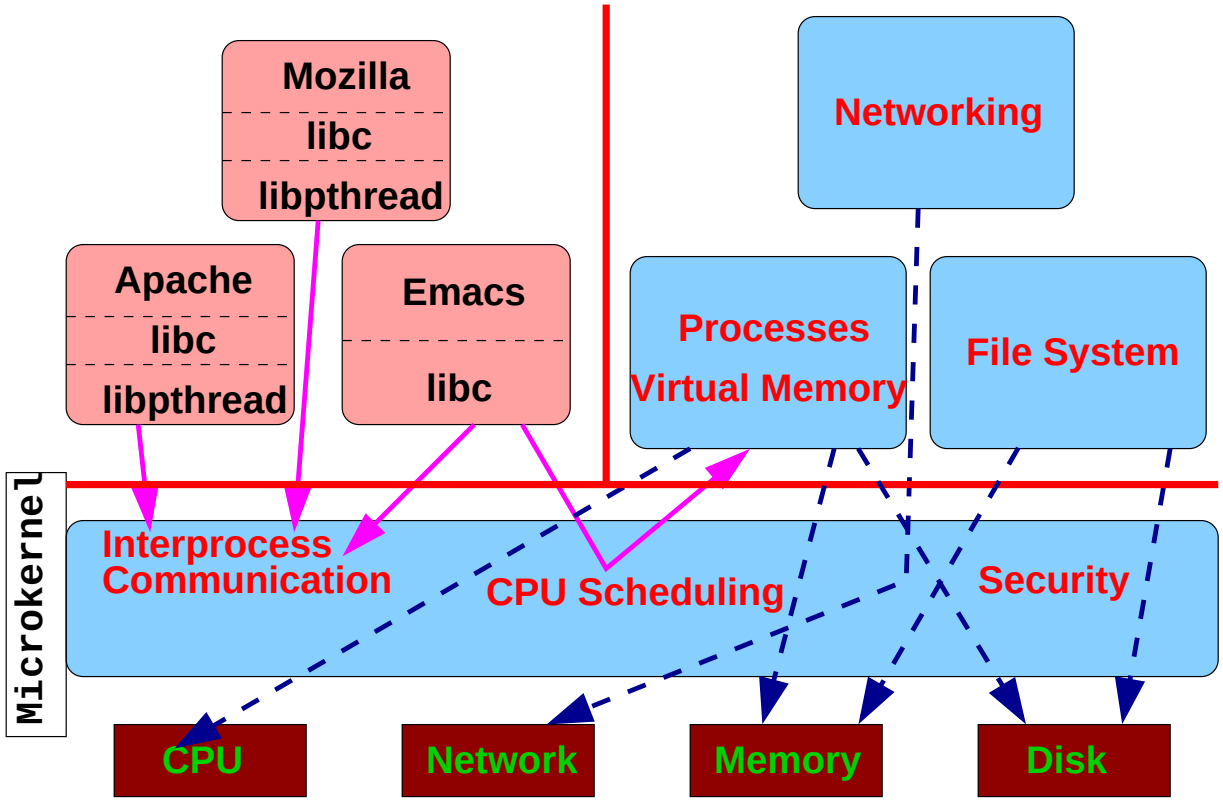
Open Systems

- 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
- Disadvantages:
  - No protection between kernel and/or applications
  - Not particularly stable
  - Composing extensions can result in unpredictable results

Microkernels



Microkernels

- Replace the monolithic kernel with a “small, clean, logical” set of abstractions.
  - Tasks and Threads
  - Virtual Memory
  - Interprocess Communication
- Move the rest of the OS into *server* processes
- Examples: Mach, Chorus, QNX, GNU/Hurd
- Mixed results: QNX commercially successful in the embedded space, microkernels are mostly nonexistent elsewhere

Microkernels

- Advantages:
  - Extensible: just add a new server to extend the OS
  - "Operating system" agnostic:
    - Support of operating system *personalities*
    - Have a server for each system (Mac, Windows, UNIX)
    - All applications can run on the same kernel
    - IBM Workplace OS
      - one kernel for OS/2, OS/400, and AIX
      - based on Mach 3.0
      - failure

Microkernels

- Advantages:
  - Mostly hardware agnostic
    - Threads and IPC don't care about the details of the underlying hardware.
  - Strong security, the operating system is protected even from itself.
  - Naturally extended to distributed systems.

Microkernels

- Disadvantages:
  - Performance
    - System calls can require a large number of protection mode changes.
    - Mach frequently criticized for its performance.
    - Is this really an issue?
  - Expensive to re-implement everything using a new model

Mach

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

- Plan

  1. Proof of concept
     - Take BSD 4.1, fix parts like VM, user visible kernel threads, IPC
  2. Microkernel and a single-server
     - Take the kernel and saw in half
  3. Microkernel and multiple servers (FS, paging, network, etc.)
     - Servers glued together by OS *personality modules* which catch syscalls

Mach

- What actually happened:

1. Proof of concept
   - Completed in 1989
   - Unix: SMP, kernel threads, 5 architectures
   - Commercial deployment: Encore Multimax, Convex Exemplar (SPP-UX), OSF/1
   - Avie Tevanian took this to NeXT: NeXTStep $\rightarrow$ OS X
2. Microkernel and a single-server
   - Completed, deployed to 10's of machines (everybody graduated)
3. Microkernel and multiple servers (FS, paging, network, etc.)
   - Never really completed (everybody graduated)

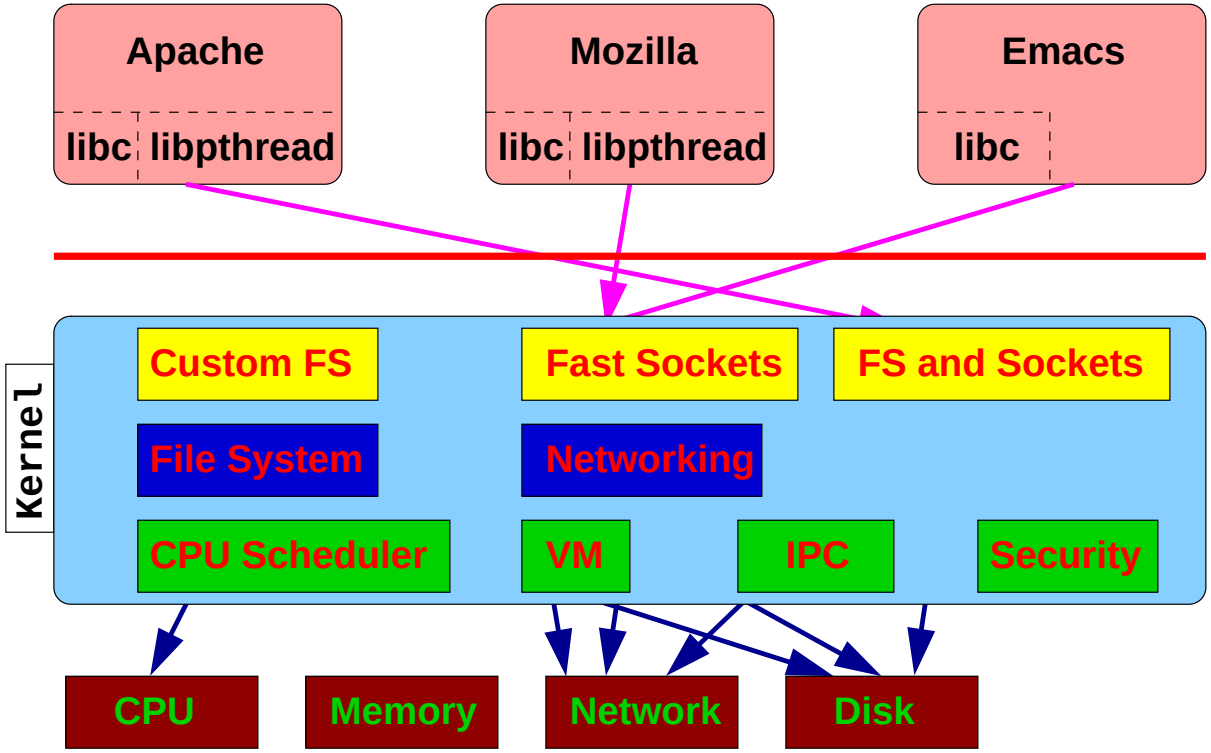
Microkernel Performance

- Mach was never aggressively tuned in the desktop/server context.
  - Is it fair to compare Mach to monolithic kernels?
- QNX is at least strong enough to be competitive with other real-time operating systems, such as VxWorks.
- The literature has between 5 and 50 percent performance overhead for microkernels.
- Summary: Still up in the air.

GNU Hurd

- Hurd stands for ’Hird of Unix-Replacing Daemons’ and Hird stands for ’Hurd of Interfaces Representing Depth’
- GNU Hurd is the FSF’s kernel
- Work began in 1990 on the kernel, has run on 10’s of machines
- Ready for mass deployment Real Soon Now™

Kernel Extensions



User Kernel Extensions

Default Services

Core Services

Kernel Extensions

- Two related ideas: old way and new way
- Old way:
  - System administrator adds a new module to an existing kernel
  - This can be hot or may require a reboot: no compiling
  - VMS, Windows NT, Linux, BSD, Mac OS X
  - Safe? “of course”

Kernel Extensions

- New way:
  - Allow *users* to download enhancements into the kernel
  - This can be done with compiler safety (Spin: Modula-3) or proof-carrying code (PCC)
  - Spin (University of Washington), Proof-carrying code (CMU)
  - Safe? Guaranteed

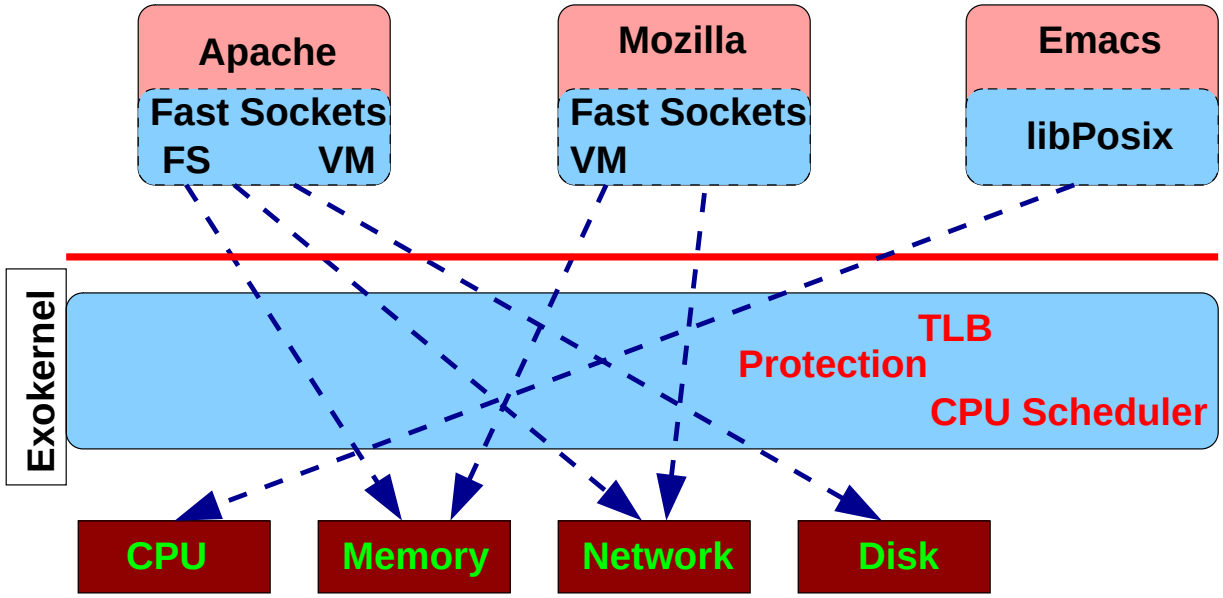
Kernel Extensions

- Advantages:
  - Extensible, just add a new extension.
  - Safe (New way)
  - Good performance because everything is in the kernel.
- Disadvantages:
  - Rely on compilers, PCC proof checker, head of project, etc., for safety.
  - Constrained implementation language on systems like Spin
  - The old way doesn't give safety, but does give extensibility

Pause

- So far we've really just moved things around
- There is still a VM system, file system, IPC, etc.
- Why should I trust the kernel to give me a filesystem that is good for me?
  - Best performance for small, big, mutable, and static files.
  - The right ACL model.
- Let's try something different.

Exokernels


Apache
Fast Sockets
FS
VM
Mozilla
Fast Sockets
VM
Emacs
libPosix
Exokernel
TLB
Protection
CPU Scheduler
CPU
Memory
Network
Disk

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.
- Is this safe? Sure, the Exokernel's job is to provide *safe*, *multiplexed* access to the hardware.
- This separates the security and protection from the management of resources.

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: VM Example

- fork():
  - Application asks the kernel for a bunch of pages
  - Application copies its pages into the new ones
  - The point is that the kernel doesn't provide this service
  - Alternative: mark pages copy on write except for the pages that fork() is using.
  - Basically, the fork() implementation can choose how to handle these details.

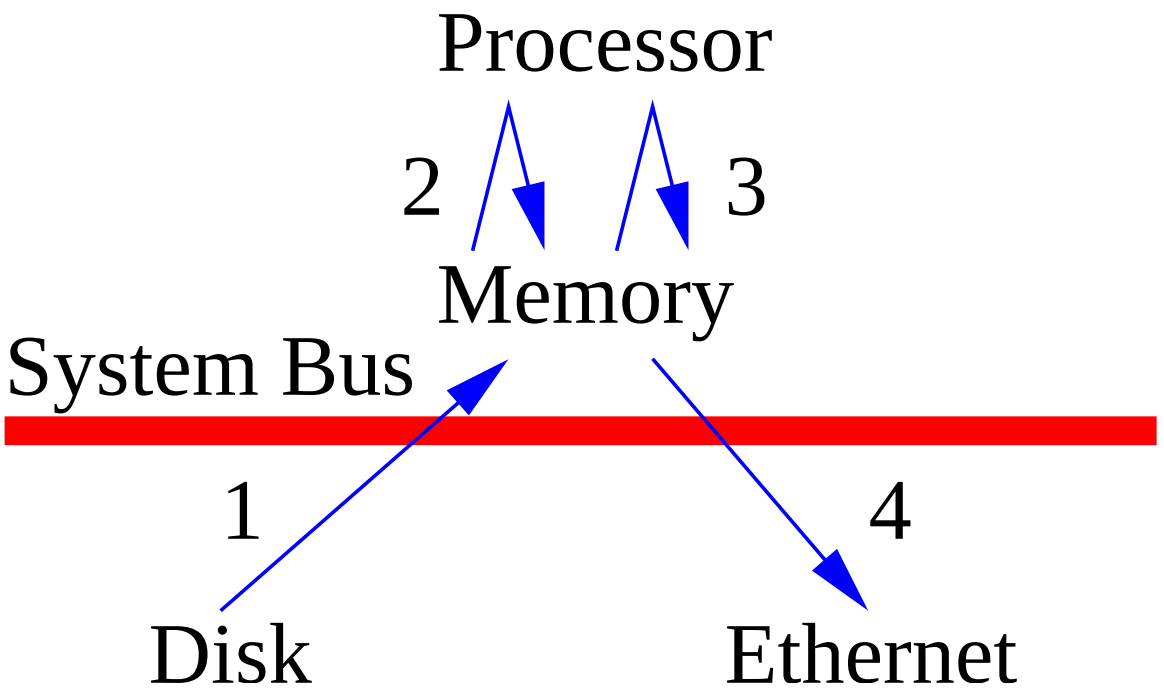
Exokernels: VM Example

- To revoke a virtual to physical mapping, the Exokernel asks for a physical page victim
- If an application does not cooperate, the Exokernel can take a physical page by force, writing it out to disk
- The application is free to manage its virtual to physical mappings using any data structure it wants.

Exokernels

- Example: Cheetah Web Server
  - Web server uses custom, mutually-optimized FS and protocol stack.
  - In a typical web server the data has to 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



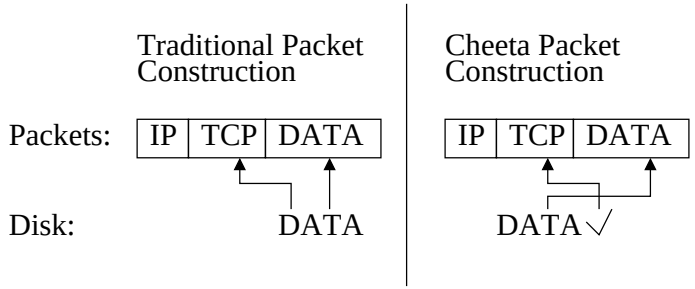
Exokernels

- Traditional kernel and web server:

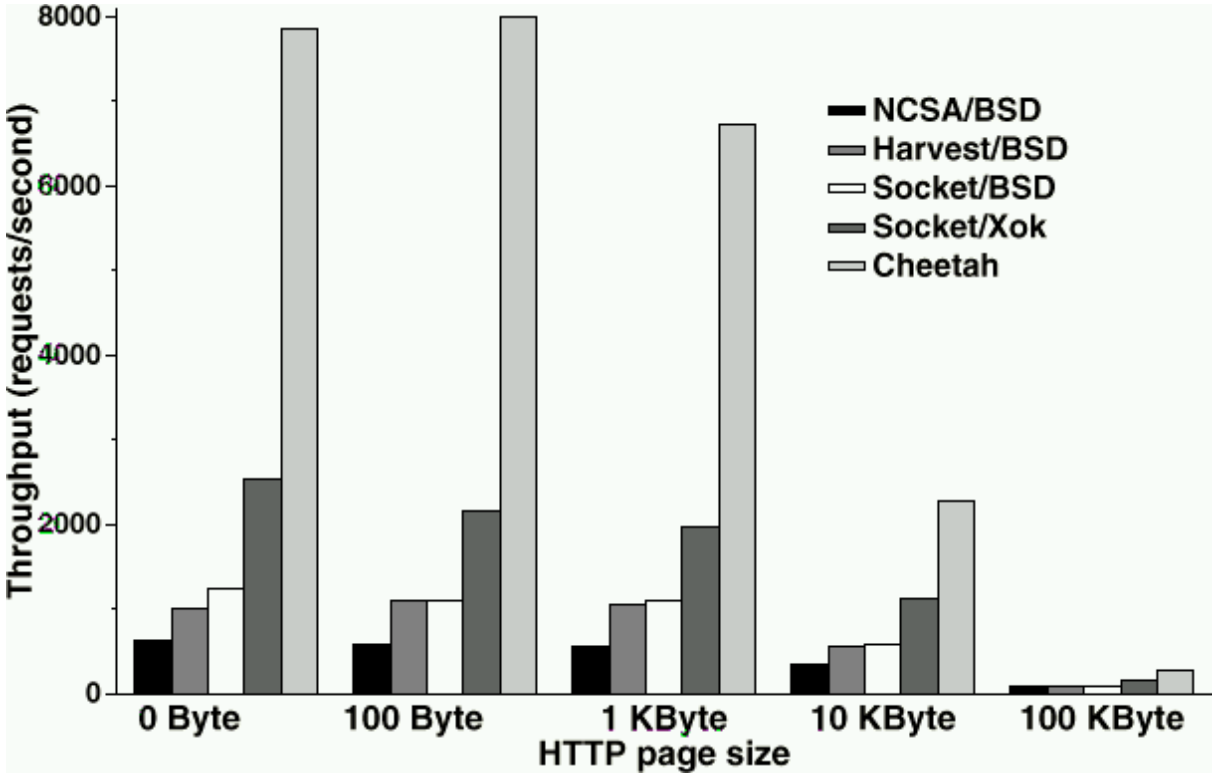
1. read() - copy from disk to kernel buffer
2. read() - copy from kernel buffer to user buffer
3. send() - user buffer to kernel buffer
   - send() - data is check-summed
4. send() - kernel buffer to device memory

Exokernels

- Exokernel and Cheetah:
  - Copy from disk to memory
  - Copy from memory to network
  - “File system” doesn’t store files, stores packet-body streams
  - Header is finished when the data is sent out
  - This saves the system from recomputing a checksum, saves processing power



Exokernels


8000
6000
4000
2000
0
Throughput (requests/second)
NCSA/BSD
Harvest/BSD
Socket/BSD
Socket/Xok
Cheetah
0 Byte
100 Byte
1 KByte
10 KByte
100 KByte
HTTP page size

Exokernels

- Advantages:
  - Extensible: just add a new libOS
  - Fast: Applications get direct access to hardware
  - Safe: Exokernel allows safe sharing of resources
- Disadvantages:
  - Still complicated, just moving it up into user space libraries
  - Extensible in theory, in practice need to change libPosix which is a lot like changing a monolithic kernel.
  - Expensive to rewrite existing kernels
  - send_file(2) - Why change when you can steal?
  - Requires policy, despite assertions to the contrary

Final Thoughts

- Operating systems are complicated.
- Structure *does* matter.
- Many alternatives, but monolithic with a little bit of kernel extensions thrown in are the most common.
- Why did none of the other structures win?
- Why should I re-implement my kernel when I can just add the functionality that gave you better performance numbers? (see send_file(2)).