Operating System Kernels

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(borrowing some content from
Peter Sirokman)

A short history of kernels

- Early kernel: a library of device drivers, support for threads (QNX)
- Monolithic kernels: Unix, VMS, OS 360…
  - Unstructured but fast…
  - Over time, became very large
  - Eventually, DLLs helped on size
- Pure microkernels: Mach, Amoeba, Chorus…
  - OS as a kind of application
- Impure microkernels: Modern Windows OS
  - Microkernel optimized to support a single OS
  - VMM support for Unix on Windows and vice versa

The great μ-kernel debate

- How big does it need to be?
  - With a μ-kernel protection-boundary crossing forces us to
    - Change memory -map
    - Flush TLB (unless tagged)
  - With a macro-kernel we lose structural protection benefits and fault-containment
- Debate raged during early 1980's

Summary of First Paper

- The Performance of μ-Kernel-Based Systems (Hartig et al. 16th SOSP, Oct 1997)
  - Evaluates the L4 microkernel as a basis for a full operating system
  - Ports Linux to run on top of L4 and compares performance to native Linux and Linux running on the Mach microkernel
  - Explores the extensibility of the L4 microkernel

Summary of Second Paper

- The Flux OSKit: A Substrate for Kernel and Language Research (Ford et al. 16th SOSP, 1997)
  - Describes a set of OS components designed to be used to build custom operating systems
  - Includes existing code simply using "glue code"
  - Describes projects that have successfully used the OSKit

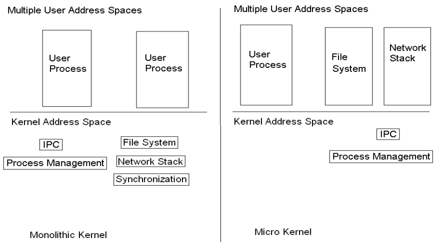
In perspective?

- L4 seeks to validate idea that a μ-kernel can support a full OS without terrible cost penalty
  - Opened the door to architectures like the Windows one
- Flux argues that we can get desired structural benefit in a toolkit and that *runtime* μ-kernel structure isn't needed

Microkernels

- An operating system kernel that provides minimal services
- Usually has some concept of threads or processes, address spaces, and interprocess communication (IPC)
- Might not have a file system, device drivers, or network stack

Monolithic and Micro-kernels



Multiple User Address Spaces

User Process

User Process

Kernel Address Space

IPC

File System

Process Management

Network Stack

Synchronization

Monolithic Kernel

Multiple User Address Spaces

User Process

File System

Network Stack

Kernel Address Space

IPC

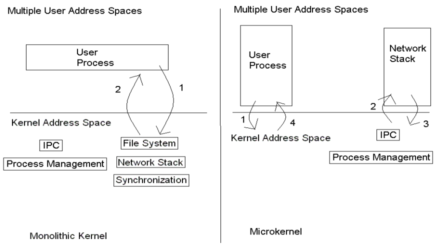
Process Management

Micro Kernel

Microkernels: Pro

- Flexibility: allows multiple choices for any service not implemented in the microkernel
- Modular design, easier to change
- Stability:
  - Smaller kernel means it is easier to debug
  - User level services can be restarted if they fail
- More memory protection

Context Switches



Multiple User Address Spaces

User Process

2

1

Kernel Address Space

IPC

File System

Process Management

Network Stack

Synchronization

Monolithic Kernel

Multiple User Address Spaces

User Process

Network Stack

1

4

2

3

Kernel Address Space

IPC

Process Management

Microkernel

Microkernel: Con

- Performance
  - Requires more context switches
    - Each “system call” must switch to the kernel and then to another user level process
    - Context switches are expensive
    - State must be saved and restored
    - TLB is flushed

Paper Goals

- Is it possible to build an OS on a Microkernel that performs well?
  - Goal is to prove that it is
  - Port Linux to run on top of L4 (a microkernel)
  - Compare performance of L4Linux to native Linux
  - Since L4Linux is a “complete” operating system, it is representative of microkernel operating systems

More Paper Goals

- Is this actually useful? Is the microkernel extensible?
  - Implemented a second memory manager optimized for real-time applications to run alongside Linux on L4
  - Implemented an alternative IPC for applications that used L4 directly (requires modifying the application)

The L4 Microkernel

- Operations:
  - The kernel starts with one address space, which is essentially physical memory
  - A process can *grant*, *map*, or *unmap* pages of size 2^n from its own virtual address space
  - Some user level processes are *pagers* and do memory management (and possibly virtual memory) for other processes using these primitives.

The L4 Microkernel (continued)

- Provides communication between address spaces (inter-process communication or IPC)
- Page faults and interrupts are forwarded by the kernel to the user process responsible for them (i.e. pagers and device drivers)
- On an exception, the kernel transfers control back to the thread's own exception handler

L4Linux

- Linux source has two cleanly separated parts
  - Architecture dependent
  - Architecture independent
- In L4Linux
  - Architecture dependent code is replaced by L4
  - Architecture independent part is unchanged
  - L4 not specifically modified to support Linux

L4Linux (continued)

- Linux kernel as L4 user service
  - Runs as an L4 thread in a single L4 address space
  - Creates L4 threads for its user processes
  - Maps parts of its address space to user process threads (using L4 primitives)
  - Acts as pager thread for its user threads
  - Has its own logical page table
  - Multiplexes its own single thread (to avoid having to change Linux source code)

L4Linux – System Calls

- The statically linked and the shared C libraries are modified
  - System calls in the library call the kernel using L4 IPC
- For unmodified native Linux applications there is a "trampoline"
  - The application traps to the kernel as normal
  - The kernel bounces control to a user-level exception handler
  - The handler calls the modified shared library

A note on TLBs

- Translation Lookaside Buffer (TLB) caches page table lookups
- On context switch, TLB needs to be flushed
- A tagged TLB tags each entry with an address space label, avoiding flushes
- A Pentium CPU can emulate a tagged TLB for small address spaces

Microkernel Cons Revisited

- A significant portion of the performance penalty of using a microkernel comes from the added work to reload the page table into the TLB on every context switch
- Since L4 runs in a small address space, it runs with a simulated tagged TLB
- Thus, the TLB is not flushed on every context switch
- Note that some pages will still be evicted – but not as many

Performance – Compatibility

- L4Linux is binary compatible with native Linux from the applications point of view.

Performance – The Competitors

- Mach 3.0
  - A “first generation” microkernel
  - Developed at CMU
  - Originally had the BSD kernel inside it
- L4
  - A “second generation” microkernel
  - Designed from scratch

Performance – Benchmarks

- Compared the following systems
  - Native Linux
  - L4Linux
  - MkLinux (in-kernel)
    - Linux ported to run inside the Mach microkernel
  - MkLinux (user)
    - Linux ported to run as a user process on top of the Mach microkernel

Performance - Microbenchmarks

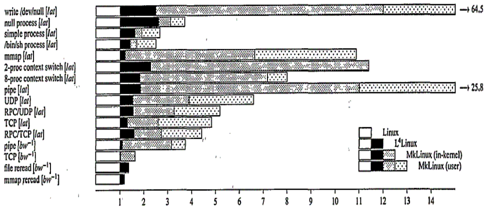


Figure 6: *lmbench results, normalized to native Linux.* These are presented as slowdowns: a shorter bar is a better result. [*lat*] is a latency measurement, [*bw*$^{-1}$] the inverse of a bandwidth one. Hardware is a 133 MHz Pentium.

Performance - Macrobenchmarks

- AIM Benchmark Suite VII simulates “different application loads” using “Load Mix Modeling”.
  - This benchmark has fallen out of favor but included various compilation tasks
  - Tasks are more representative of development in a systems lab than production OS in a web farm or data center

Performance - Macrobenchmarks

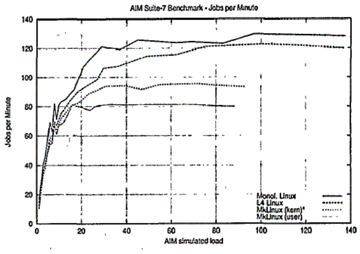


Figure 9: *AIM Multiuser Benchmark Suite VII.* Jobs completed per minute depending on AIM load units. (133 MHz Pentium)

Performance – Analysis

- L4Linux is 5% - 10% slower than native for macrobenchmarks
- User mode MkLinux is 49% slower (averaged over all loads)
- In-kernel MkLinux is 29% slower (averaged over all loads)
- Co-location of kernel is not enough for good performance

So What?

- If performance suffers, there must be other benefits – Extensibility
  - While Linux pipes in L4Linux are slower than in native Linux, pipes implemented using the bare L4 interface are faster
  - Certain primitive virtual-memory options are faster using the L4 interface than in native Linux
  - Cache partitioning allows L4Linux to run concurrently with a real-time system with better timing predictability than native Linux

Microkernel Con: Revisited Again

- The Linux kernel was essentially unmodified
- Results from “extensibility” show that improvements can be made (e.g. pipes)
- If the entire OS were optimized to take advantage of L4, performance would probably improve
- Goal Demonstrated

Flux OS

- Research group wanted to experiment with microkernel designs
- Decided that existing microkernels (Mach) were too inflexible to be modified
- Decided to write their own from scratch
- In order to avoid having it become inflexible, built it in modules
- Invented an operating system building kit!

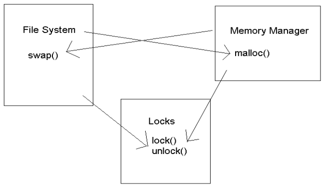
The Flux OSKit

- Writing Operating Systems is hard:
  - Relevant OSs have lots of functionality:
    - File system
    - Network Stack
    - Debugging
  - Large parts of OS not relevant to specific research
  - Not cost effective for small groups

Adapting Existing Code

- Many OS projects attempt to leverage existing code
- Difficult
  - Many parts of operating systems are interdependent
  - E.g. File system depends on a specific memory management technique
  - E.g. Virtual memory depends on the file system
  - Hard to separate components

Separating OS Components



File System

swap()

Memory Manager

malloc()

Locks

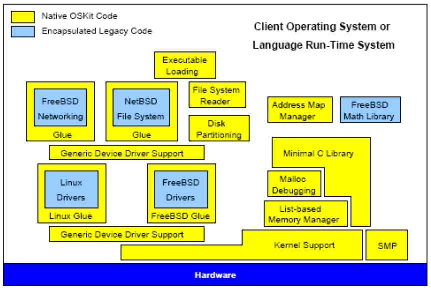
lock()

unlock()

OSKit

- OSKit is not an operating system
- OSKit is a set of operating system components
- OSKit components are designed to be as self-sufficient as possible
- OSKit components can be used to build a custom operating system – pick and choose the parts you want – customize the parts you want

Diagram of OSKit



🟨 Native OSKit Code

🟦 Encapsulated Legacy Code

Client Operating System or

Language Run-Time System

Executable Loading

FreeBSD Networking

Glue

NetBSD File System

Glue

File System Reader

Disk Partitioning

Address Map Manager

FreeBSD Math Library

Generic Device Driver Support

Minimal C Library

Linux Drivers

Linux Glue

FreeBSD Drivers

FreeBSD Glue

Malloc Debugging

List-based Memory Manager

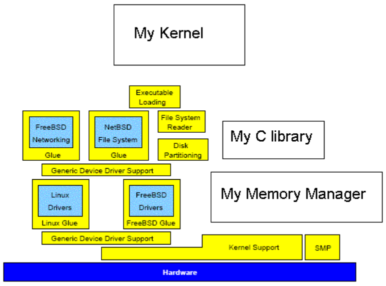
Generic Device Driver Support

Kernel Support

SMP

Hardware

Example OS using OSKit



My Kernel

Executable Loading

FreeBSD Networking

Glue

NetBSD File System

Glue

File System Reader

Disk Partitioning

My C library

Generic Device Driver Support

Linux Drivers

Linux Glue

FreeBSD Drivers

FreeBSD Glue

My Memory Manager

Generic Device Driver Support

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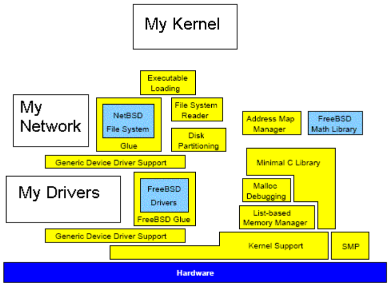
Hardware

Another Example OS


My Kernel

Executable Loading

My Network

NetBSD File System

Glue

File System Reader

Disk Partitioning

Address Map Manager

FreeBSD Math Library

Generic Device Driver Support

Minimal C Library

My Drivers

FreeBSD Drivers

FreeBSD Glue

Malloc Debugging

List-based Memory Manager

Generic Device Driver Support

Kernel Support

SMP

Hardware

OSKit Components

- Bootstrapping
  - Provides a standard for boot loaders and operating systems
- Kernel support library
  - Make accessing hardware easier
  - Architecture specific
  - E.g. on x86, helps initialize page translation tables, set up interrupt vector table, and interrupt handlers

More OSKit Components

- Memory Management Library
  - Supports low level features
  - Allows tracking of memory by various traits, such as alignment or size
- Minimal C Library
  - Designed to minimize dependencies
  - Results in lower functionality and performance
  - E.g. standard I/O functions don't use buffering

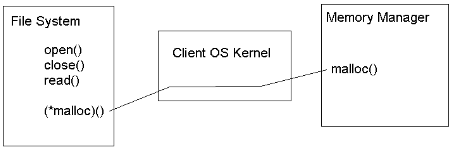
Even More OSKit Components

- Debugging Support
  - Can be debugged using GDB over the serial port
  - Debugging memory allocation library
- Device Drivers
  - Taken from existing systems (Linux, FreeBSD)
  - Mostly unmodified, but encapsulated by “glue” code – this makes it easy to port updates

Two more OSKit Components

- Network Stack
  - Taken from FreeBSD and “encapsulated” using glue code
- File System
  - Taken from NetBSD and “encapsulated” using glue code

OSKit Component Interfaces


File System

open()
close()
read()

(*malloc)()

Client OS Kernel

Memory Manager

malloc()

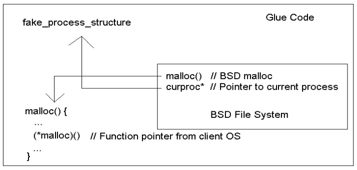
OSKit Implementation

- Libraries
  - To the developer, the OSKit appears as a set of libraries that can be linked to programs
  - Therefore, easy to use

Providing Separability

- Most operating systems are modular, but this does not make them separable into components
- Modules will assume and depend on the implementation specifics of other modules
- In OSKit components are wrapped in “glue code” to make them independent of other components

Glue Code



```
malloc()   // BSD malloc
curproc*   // Pointer to current process
```

```
malloc() {
  ...
  (*malloc)()   // Function pointer from client OS
  ...
}
```

What is this “glue code”?

- Overridable functions
  - E.g. all device drivers use a function fdev_mem_alloc to allocate memory
  - The client OS (the OSKit user) must provide an implementation of this depending on the memory manager used by the OS being built
  - The default implementation uses the OSKit memory manager

More “glue code”

- The file system must use block device drivers
- Yet the file system can’t know what the block device driver code will be
- Device drivers can return pointers to interfaces, which can be passed to the file system
- The file system is bound to a block device driver at run time

Interfaces

- Interfaces use the COM standard
- Like a Java object, a COM interface has known methods that can be invoked
- The internal state is hidden
- Each block device driver can implement a common COM interface, allowing all drivers to look the same to the file system

Execution Environment

- It is impossible to turn all components into black boxes that will automatically work in all environments
- The absolute basic needs of a component, a file system for example, is abstracted as specified execution environment that the developer must follow

Execution Environment

- The execution environment specifies limitations on the use of the component
  - Is the component reentrant?
  - Must certain functions in the interface be synchronized?
  - Can the execution of the component be interrupted?
- Example: While the file system is not designed to be used on a multiprocessor system, the execution environment can be satisfied using locks to synchronize its use

Exposing the Implementation

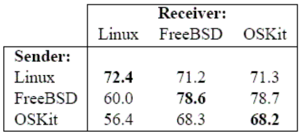
- The OSKit provides abstract interfaces to its components
- The OSKit also provides implementation specific interfaces to allow the user to have more control over the component
- Key: these specialized interfaces are optional
- E.g. the memory manager can be used as a simple malloc, or it can manipulate physical memory and the free list directly
- Components can offer multiple COM interfaces to do this

Encapsulating Legacy Code

- Interfaces presented by the OSKit are implemented as “glue code”
- This glue code makes calls to the imported legacy code, and makes modifications as needed to emulate the legacy code’s original environment
- The glue code also accepts calls from the legacy code and translates them back to the interface offered
- Thus once two components are encapsulated, their interfaces can be joined together seamlessly

The Obligatory Benchmark

- Measured TCP bandwidth and latency



	Receiver:		
	Linux	FreeBSD	OSKit
Sender:			
Linux	**72.4**	71.2	71.3
FreeBSD	60.0	**78.6**	78.7
OSKit	56.4	68.3	**68.2**

Table 1: TCP bandwidth in MBit/s measured with `ttcp` between two Pentium Pro 200MHz PCs connected by 100Mbps Ethernet.

Bandwidth Analysis

- FreeBSD can use discontinuous buffers,

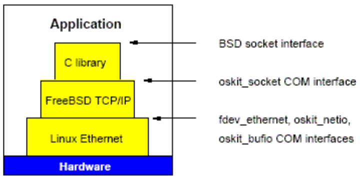
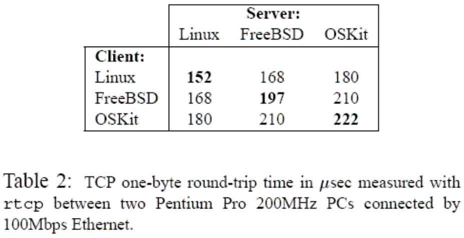


Figure 3: Structure of the `ttcp` and `rtcp` example kernels.

Latency



	Server: Linux	FreeBSD	OSKit
Client:			
Linux	**152**	168	180
FreeBSD	168	**197**	210
OSKit	180	210	**222**

Table 2: TCP one-byte round-trip time in μsec measured with `rtcp` between two Pentium Pro 200MHz PCs connected by 100Mbps Ethernet.

Case Study 2: Standard ML

- SML is a functional programming language
- Goal: to model concurrency as continuations in high level programming languages
- This requires ML and its compiler to be able to manipulate context switching – difficult if not impossible on a standard OS
- ML/OS constructed by 2 people over a semester using OSKit
- Other projects with similar goals have not succeeded (at the time)
  - Fox project at CMU
  - Programming Principles group at Bell Labs

Other language based OSs

- SR – a language for writing concurrent programs
  - Other attempts abandoned
- Java/PC
  - Given a Java Virtual Machine and OSKit, took three weeks
  - Sun’s version took much longer to build since it was written mostly from scratch in Java

OSKit vs. Microkernel

- A Microkernel is an architecture for operating systems designed to be flexible
- OSKit is a tool for making operating systems
- OS-s built with OSKit may or may not be microkernel
- OSKit gives greater flexibility than a microkernel, since even microkernels force some concepts (threads, IPC) onto the overall system