# Microkernels: From Mach to seL4 (Lecture 8, cs262a)

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September 21, 2016

# Project Proposals

We'll give you feedback on the projects by next Monday, 9/28

Please make sure you are enabling comments

# Papers

"Microkernel Operating System Architecure and Mach", D. Black, D. Golub, D. Julin, R. Rashid, R. Draves, R. Dean, A. Forin, J. Barrera, H. Tokuda, G. Malan, and D. Bohman (https://amplab.github.io/cs262a-fall2016/notes/Mach.pdf)

From L3 to seL4 What Have We Learnt in 20 Years of L4 Microkernels?", K. Elphinstone and G. Heiser, Proceedings of SOSP'13, Farmington, Pennsylvania, USA (http://sigops.org/sosp/sosp13/papers/p133-elphinstone.pdf)

# Key Observation (~1985)

Modern OSes systems (e.g., Unix, OS/2) primarily distinguished by the programming environment they provide and not by the way they manage resources

Opportunity:

- Factor out the common part
- Make it easier to build new OSes

# Microkernels separates OS in two parts

Part of OS that control basic hardware resources (i.e.. microkernel)

Part of OS that determine unique characteristics of application environment (e.g., file system)

# What problem do they try to solve?

Portability:

- Environment mostly independent on the instruction set architecture

Extensibility & customization:

- Can easily add new versions of environments
- Enable environments to evolve faster (decouples them from microkernel)
- Can simultaneously provide environments emulating interfaces

Sounds familiar?

- Microkernel as a narrow waist (anchor point) of OSes
- Provide hardware independence, similar to data independence in relational data models

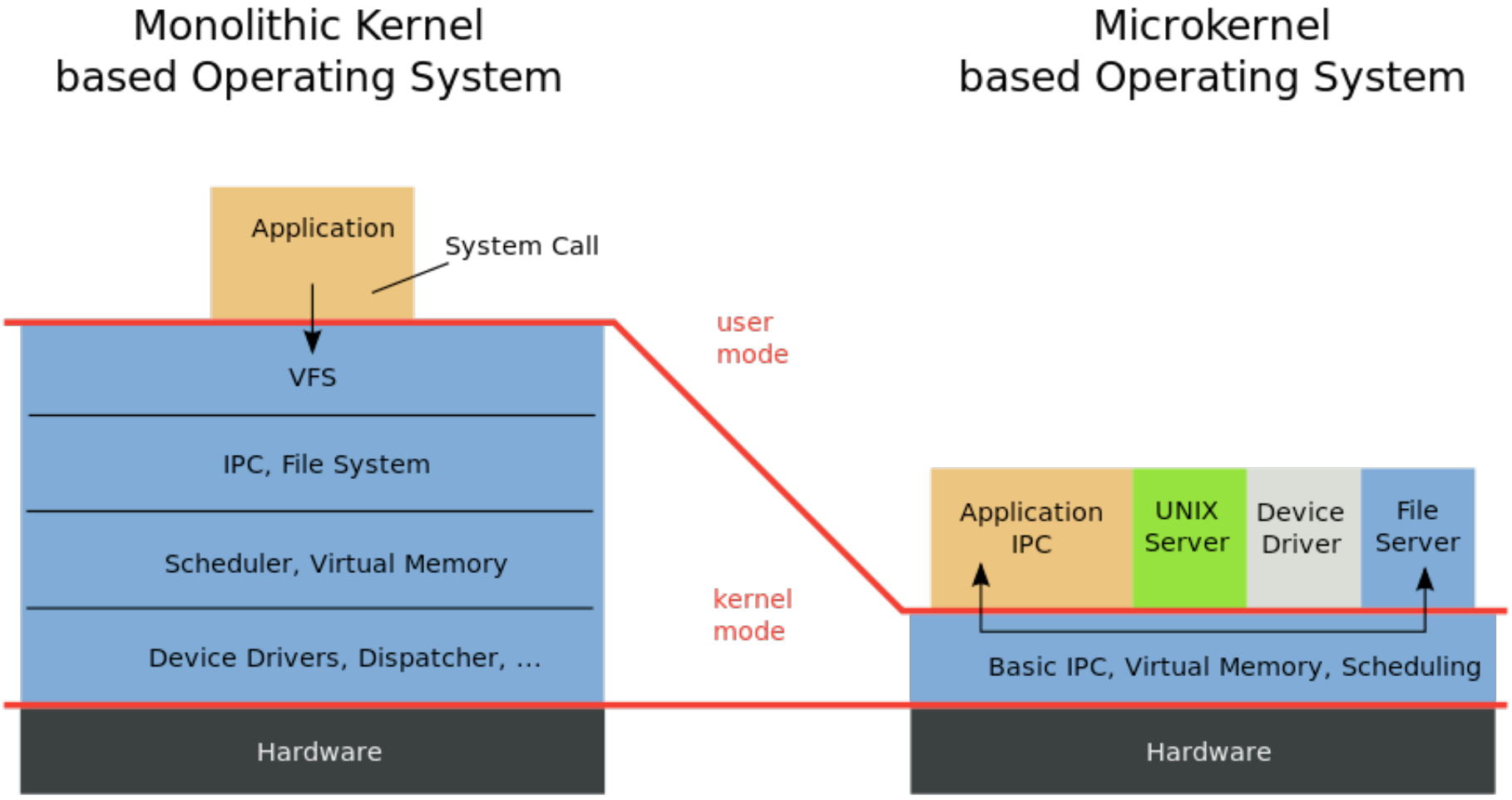
# What problem do they try to solve?

Easier to provide better functionality and performance for kernel:

- Real-time: no need to maintain lock for extended periods of time; environments are preemptable
- Multiprocessor support: simpler functionality → easier to parallelize
- Multicomputer support: simpler functionality → easier to distribute
- Security: simpler functionality → easier to secure

Flexibility (network accessibility):

- System environment can run remotely




(https://en.wikipedia.org/wiki/Microkernel)

# Mach

Goal: show that microkernels can be as efficient as monolithic operating systems:

- "… achieving the levels of functionality and performance expected and required of commercial products"

Sounds familiar?

- Similar goals as System R and Ingress: Show that a conceptually superior solution (i.e., relational model) admit efficient implementations that can match the performance of existing solutions (i.e., network and hierarchical models)

# Mach

Developed at CMU

Led by Rick Rashid

- Now VP of research at Microsoft

Initial release: 1985

Big impact (as we will see)

Rick Rashid

# What does a microkernel (Mach) do?

Task and thread management:

- Task (process) unit of allocation
- Thread, unit of execution
- Implements CPU scheduling: exposed to apps
  - Applications/environments can implement their own scheduling policies

Interprocess communication (IPC)

- Between threads via ports
- Secured by capabilities

# What does a microkernel (Mach) do?

Memory object management:

- Essentially virtual memory
- Persistent store accessed via IPC

System call redirection:

- Enable to trap system calls and transfer control to user mode
- Essentially enable applications to modify/extend the behavior and functionality of system calls, e.g.,
  - Enable binary emulation of environments, tracing, debugging

# What else does a microkernel (Mach) do?

Device support:

- Implemented using IPC (devices are contacted via ports)
- Support both synchronous and asynchronous devices

User multiprocessing:

- Essentially a user level thread package, with wait()/signal() primitives
- One or more user threads can map to same kernel thread

Multicomputer support:

- Can map transparently tasks/resources on different nodes in a cluster

# Mach 2.5

Contains BSD code compatibility code, e.g., one-to-one mapping between tasks and processes

Some commercial success:

- NeXT
  - Steve Jobs' company after he left Apple
  - Used by Tim Berners-Lee to develop WWW
- Encore, OSF (Open Software Foundation), …

# Mach 3

Eliminate BSD code

Rewrite IPC to improve performance

- RPC on (then) contemporary workstations: 95 usec

Expose device interface

Provide more control to user applications via continuation:

- Address of an user function to be called when thread is rescheduled plus some data: essentially a callback
- Enable application to save restore state, so that the microkernel doesn't need to do it, e.g., saving and restoring register state

# OSes and Application Programs

Mach allows application to implement:

- Paging
- Control data cached by virtual memory
- …

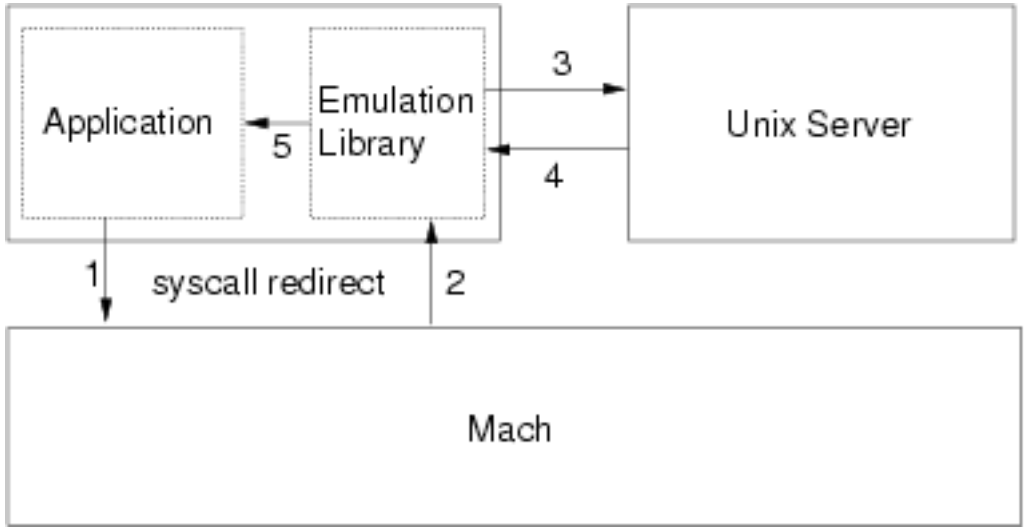
Redirection allows call traps to link directly to executable binaries without modifying he kernel!

- Just need an emulation library

# Emulation Libraries

Translator for system services and a cache for their results

- Converts app calls to Mach calls
- Invoke functionality of the environment (e.g., OS) and reply to app
- Typically linked to app to avoid another context switching



# OSes Environment Architectures

Fully implemented in the emulation library

- Simple, single user systems (e.g., MS-DoS)

As a server (see previous slide)

Native OSes: use the code of the original systems

- Used to implement both MacOS, and DOS
- Emulation library also virtualizes the physical resources

# Performance: Mach 2.5 vs 3.0

Virtually the same as Mach 2.5, and commercial Unix systems of that time

- SunOS 4.1 and Ultrix 4.1

Why?

- I/O dominated tasks (read, write, compile)

Microbenchmarks would have been nice, e.g.:

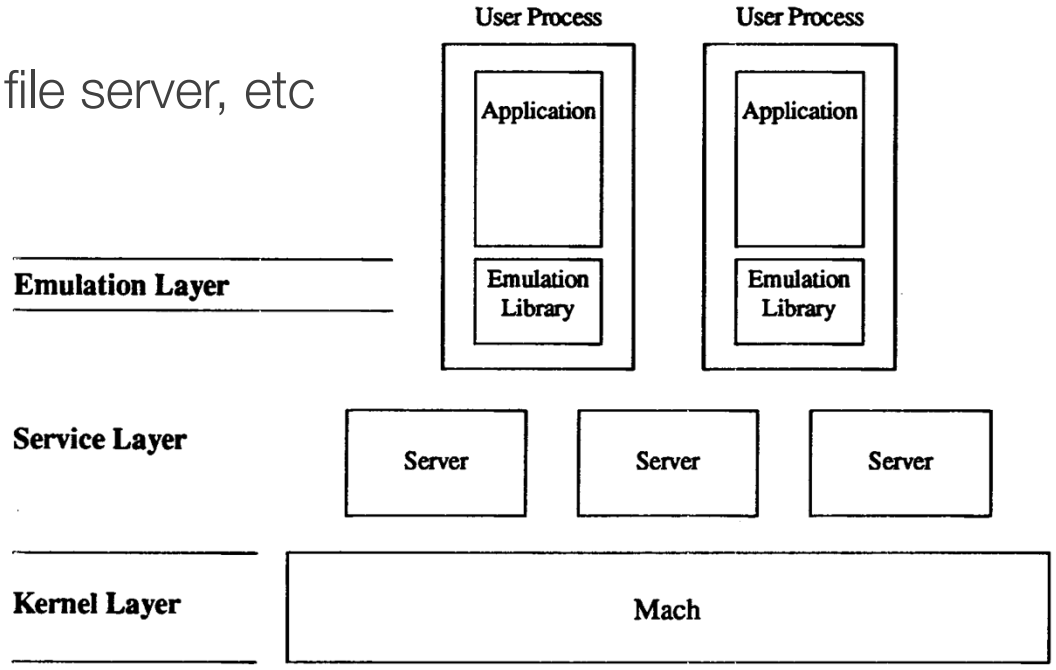
- IPC
- Cost of a page fault

# OSF/1 Unix Server

Even more modularity: different OS functionalities implemented as different servers, e.g.,

- IPC, process management, file server, etc

Server proxies on client side for optimization



L3 → seL4

# How it started? (1993)

Microkernels (e.g., Mach) still too slow

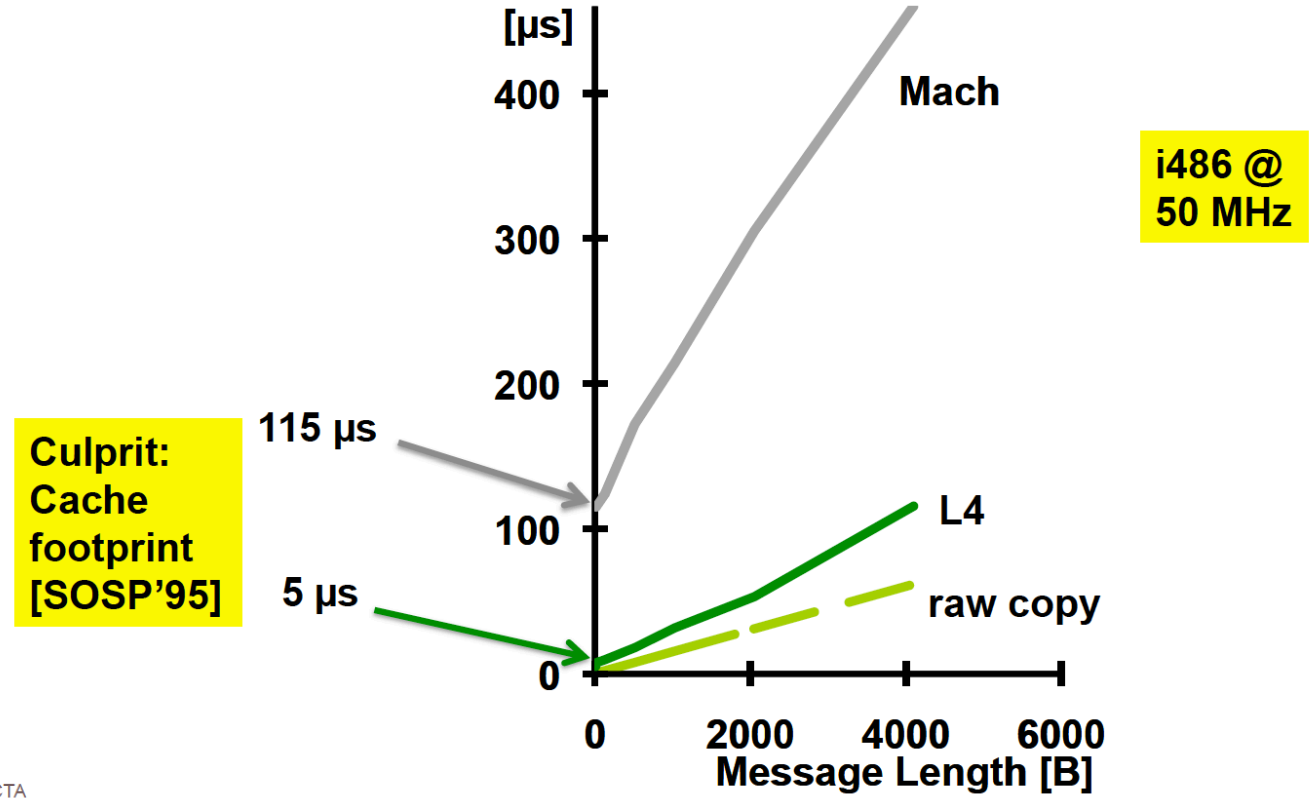
- Mostly because IPCs

Tide was turning towards monolithic kernels

**Jochen Liedtke** (GMD – Society for Mathematics and Information technology) aimed to show that IPC can be supper-fast

Jochen Liedtke

# How fast?

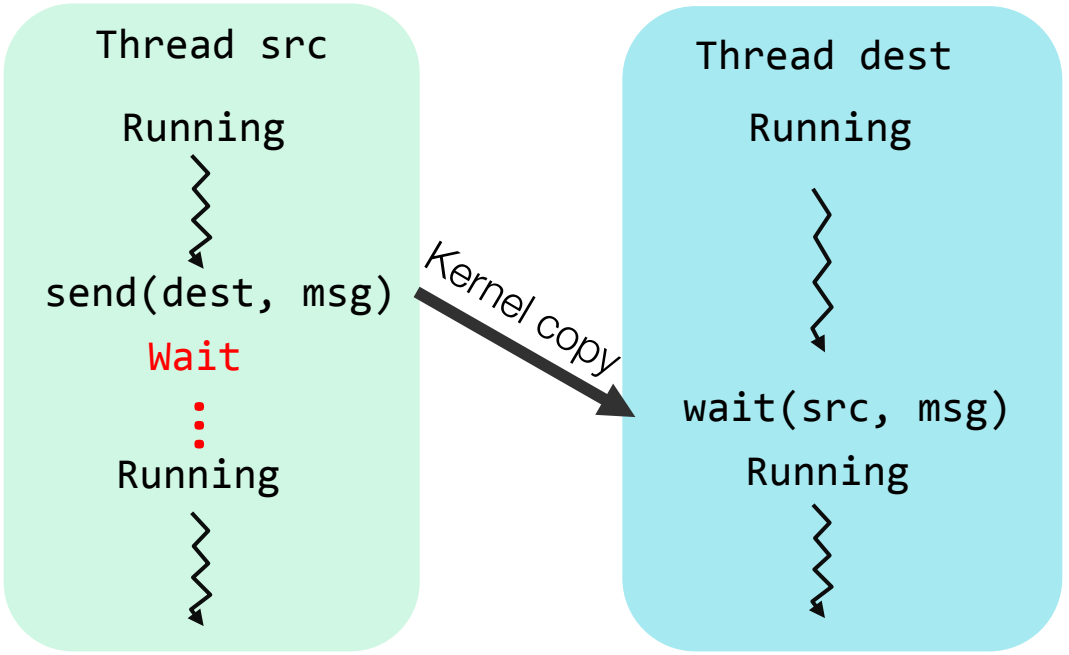


# How did he do it?

## Synchronous IPC → Rendezvous model

Kernel executes in sender's context

- copies memory data directly to receiver (**single-copy**)
- leaves message registers unchanged during context switch (**zero copy**)



# One-way IPC cost over years

| Name | Year | Processor | MHz | Cycles | $\mu$s |
|---|---|---|---|---|---|
| Original | 1993 | i486 | 50 | 250 | 5.00 |
| Original | 1997 | Pentium | 160 | 121 | 0.75 |
| L4/MIPS | 1997 | R4700 | 100 | 86 | 0.86 |
| L4/Alpha | 1997 | 21064 | 433 | 45 | 0.10 |
| Hazelnut | 2002 | Pentium 4 | 1,400 | 2,000 | 1.38 |
| Pistachio | 2005 | Itanium 2 | 1,500 | 36 | 0.02 |
| OKL4 | 2007 | XScale 255 | 400 | 151 | 0.64 |
| NOVA | 2010 | Core i7 (Bloomfield) 32-bit | 2,660 | 288 | 0.11 |
| seL4 | 2013 | Core i7 4770 (Haswell) 32-bit | 3,400 | 301 | 0.09 |
| seL4 | 2013 | ARM11 | 532 | 188 | 0.35 |
| seL4 | 2013 | Cortex A9 | 1,000 | 316 | 0.32 |

# Minimalist design

“A concept is tolerated inside the microkernel only if moving it outside the kernel, i.e. permitting competing implementations, would prevent the implementation of the system’s required functionality”

Sounds familiar?

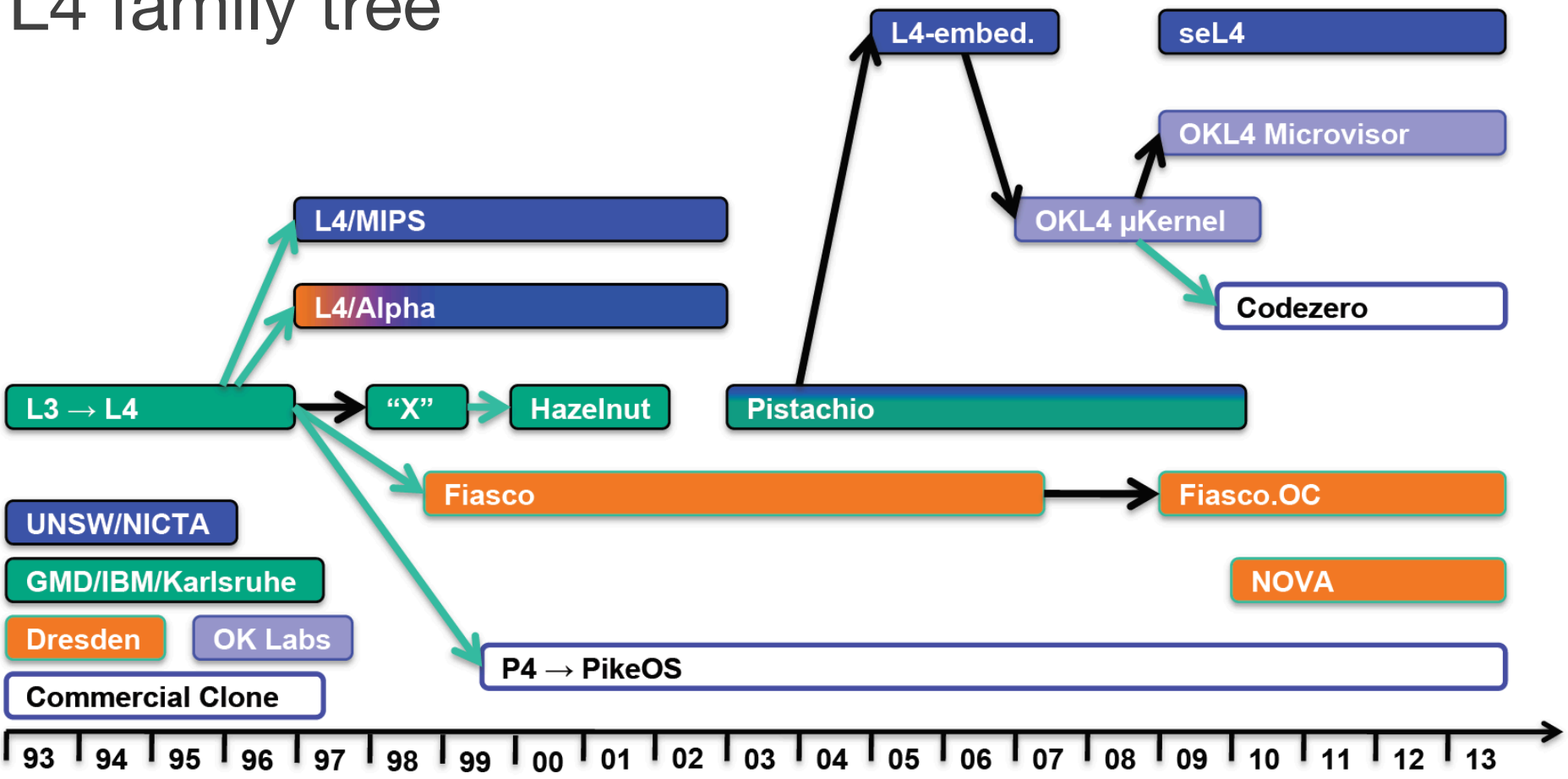
“Don’t implement anything in the network that can be implemented correctly by the hosts”

-- radical interpretation of the e2e argument!

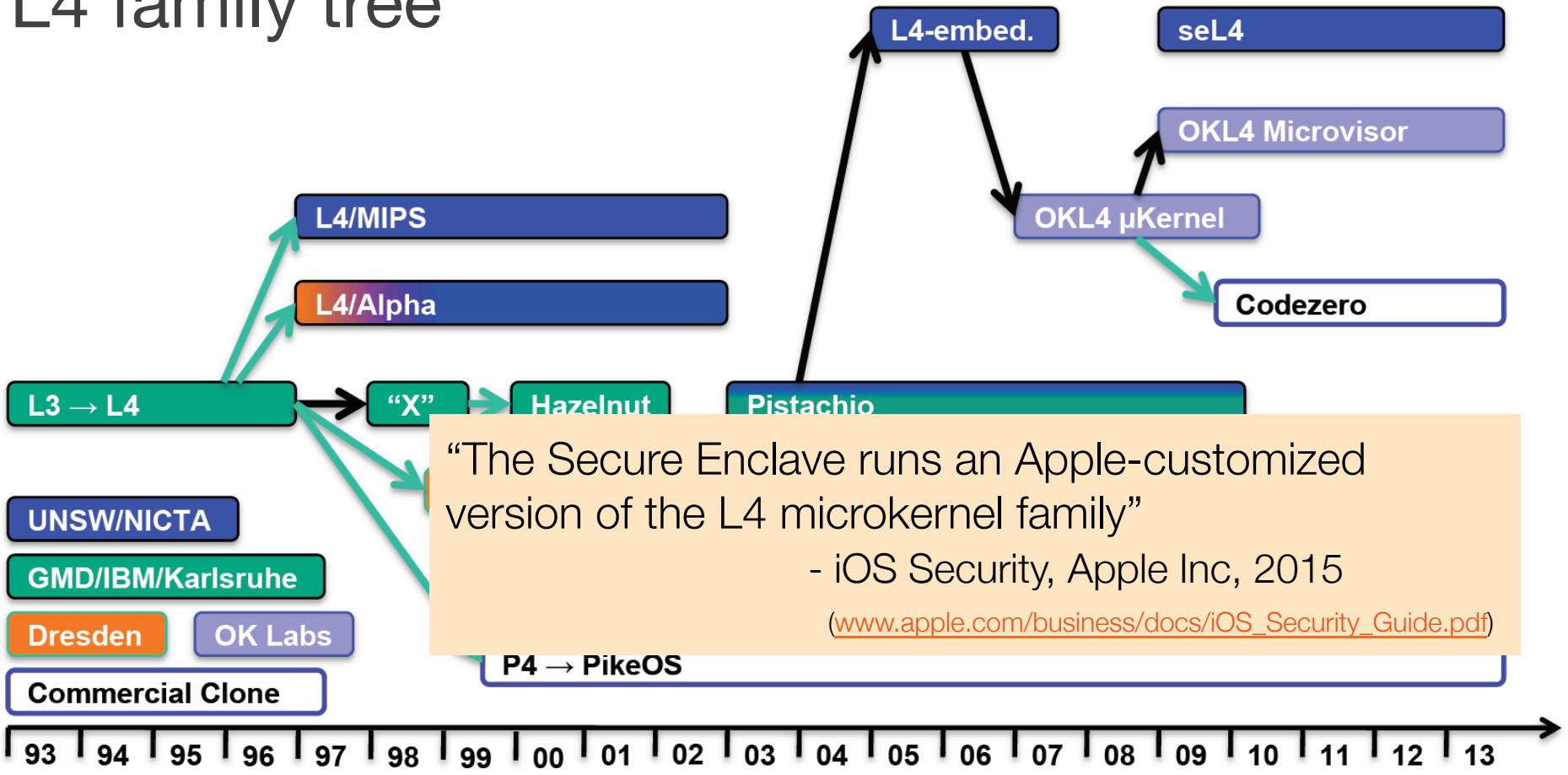
# Source Lines of Code

| Name | Archi-tecture | Size (kLOC) | | |
|---|---|---|---|---|
| | | C/C++ | asm | Total |
| Original | 486 | 0 | 6.4 | 6.4 |
| L4/Alpha | Alpha | 0 | 14.2 | 14.2 |
| L4/MIPS | MIPS64 | 6.0 | 4.5 | 10.5 |
| Hazelnut | x86 | 10.0 | 0.8 | 10.8 |
| Pistachio | x86 | 22.4 | 1.4 | 23.0 |
| L4-embedded | ARMv5 | 7.6 | 1.4 | 9.0 |
| OKL4 3.0 | ARMv6 | 15.0 | 0.0 | 15.0 |
| Fiasco.OC | x86 | 36.2 | 1.1 | 37.6 |
| seL4 | ARMv6 | 9.7 | 0.5 | 10.2 |

# L4 family tree



# L4 family tree




"The Secure Enclave runs an Apple-customized version of the L4 microkernel family"

- iOS Security, Apple Inc, 2015

(www.apple.com/business/docs/iOS_Security_Guide.pdf)

# Long IPCs: Transferring large messages

What happens during page faults?

IPC page faults are nested exceptions

- L4 executes with interrupts disabled for performance, no concurrency
- Must invoke untrusted user mode page-fault handlers
  - Potential for DOSing other thread (i.e., page fault handler hangs)
- Can use timeouts to avoid DOS attacks
  - Complex, goes against minimalist design

# Why long IPCs?

POSIX-style APIs

- Use message passing between apps and OS, e.g., write(fd, buf, nbytes)

Linux became de-facto standard

- Communicate via shared memory

Long IPC abandoned

Supporting POSIX not as critical

- Message passing can be emulated anyway via shared memory

# IPC destinations

Initially use thread identifier (why?)

- Wanted to avoid cache an TLB pollution

But

- Poor information hiding (e.g., multi-threaded server has to expose the structure to the clients)
- Large caches and TLBs reduced pollution

Thread IDs *replaced* by port-like endpoints

# Timeouts

Synchronous IPC may lead to thread being blocked indefinitely

- E.g., a thread which waits for another thread that hangs

Solution: timeouts

- No reliable way to pick a timeout; application specific

Timeouts abandoned

Ended up just using two values: 0 and infinity

- Client sends and receives with infinite timeouts
- Servers requests with an infinite timeout but replies with a zero timeout

# Asynchronous IPCs

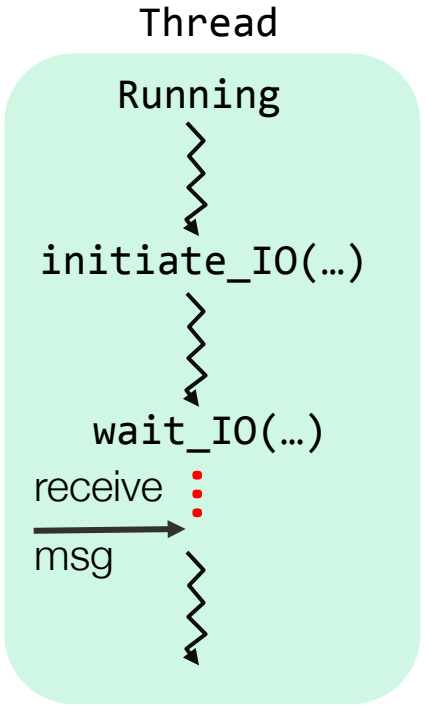
Insufficient (Why?)

Disadvantages of synchronous IPCs

- Have to block on IO operations
- Forces apps to use multithreading
- Poor choice for multicores (no need to block if IO executes on another core!)

Want async IPCs

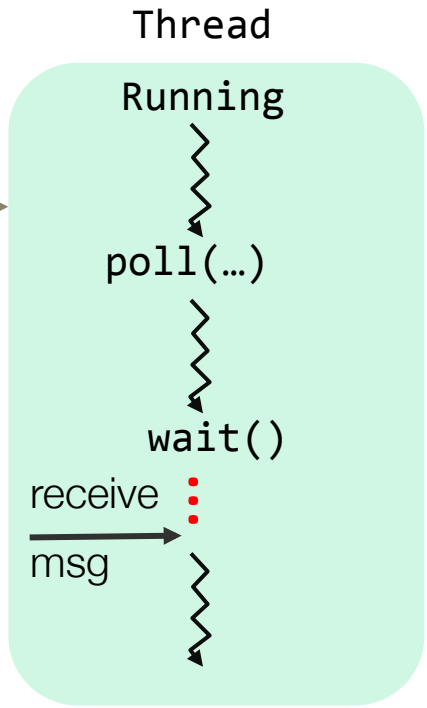
- Want something like select()/poll()/epoll() in Unix



# Async notifications

Sending is non-blocking and asynchronous

Receiver, who can block or poll for message




seL4: Asynchronous Endpoints (AEP)

- Single-word notification field
- Send sets a bit in notification field
- Bits in notification field are ORed → notification
- wait(), effectively select() across notification fields

Added async notifications to complement syn IPCs

# Lazy scheduling

What is the problem?

- Lot's of queue manipulations: threads frequently switch between ready and wait queues due to the rendezvous IPC model

Lazy scheduling:

- When a thread blocks on an IPC operation, leave it in ready queue
- Dequeue all blocked threads at next scheduling event

Why does it work?

- Move work from a high-frequency IPC operation to the less frequently scheduler calls

# Benno scheduling

Lazy scheduling drawback

- Bad when many threads → worst-case proportional with # of threads

Benno scheduling

- Ready queue contains all runnable threads, except current running one
- When a thread is unblocked by an IPC operation, run it without placing in ready queue (as it may block again very soon)
- If running thread is preempted, place it in ready queue
- Still need to maintain wait queues but typically they are in hit cache

Replace lazy scheduling by Benno scheduling

# Summary

| Original design decision | Maintained/ Abandoned | Notes |
|---|---|---|
| Synchronous IPC | ✚ | Added async notifications |
| In-register msg transfer | ✖ | Replaced physical with virtual registers |
| Long IPC | ✖ | |
| IPC timeouts | ✖ | |
| Clans and chiefs | ✖ | |
| User level drivers | ✔ | |
| Process hierarchy | ✖ | |
| Recursive page mapping | ▬ | Some retained it some didn’t |
| Kernel memory control | ✚ | Added user-level control |

# Summary (cont'd)

| Original design decision | Maintained/ Abandoned | Notes |
|---|---|---|
| Scheduling policies | ? | Unresolved: no policy agnostic solution |
| Multicores | ? | Unresolved: cannot be verified |
| Virtual TCP addressing | ✖ | |
| Lazy scheduling | ✖ | Replaced with Benno scheduling |
| Non-preemptable kernel | ✔ | Mostly maintained |
| Non-portability | ✖ | Mostly portable |
| Non-standard calling | ✖ | Replaced by C standard calling convention |
| Language | ✖ | Assembly/C++ mostly replaced by C |

# Discussions: L4 tenets

Minimalist design: strict interpretation of e2e argument

- Only functionality that cannot be implemented completely in the app
- No policies in the microkernel

Obsessive  optimization of IPC

Unlike Mach, didn't care about portability (at least initially)

So what got in besides IPC?

- Scheduling, including scheduling policies
- Some device drivers: timer, interrupt controller
- Minimal memory management

# What drove L4's evolution?

Application domain: embedded devices (natural fit!)

- Small footprint
- Devices ran few applications, didn't need all OS services (e.g., file system)

Embedded devices required:

- Security and resilience → special attention to DoS attacks, formal verification
- Real-time guarantees → non-preemptable kernel

# What drove L4's evolution? (cont'd)

User experience, e.g.,

- New features, e.g., async IPC
- Remove features not useful: timeouts, clans & chiefs

Software evolution:

- E.g., Linux raise and POSIX decline obviate the need for long IPCs

Hardware advances

- Bigger caches, bigger TLBs, better context switching support → obviate the need for some optimizations (e.g., virtual TLBs. Thread IDs as destination IDs)
- Multicores → push for some optimizations (async wait)

# Did microkernels take over the world?

Pretty much…

- MacOS, based on NeXT, based on Mach
- iOS has both bits of Mach and L4
- Windows: hybrid (similar design goals to Mach)

With one notable exception, **Linux!**

# So why didn't take over entire world!

Hardware standardization:

- Intel and ARM dominating
- Less need for portability, one of main goals of Mach

Software standardization:

- Windows, MacOS/iOS, Linux/Android
- Less need to factor out common functionality

Maybe just a fluke?

- Linux could have been very well adopted the microkernel approach
- Philosophical debate between Linus and Andy Tanembaum
  - One of Linus main arguments: there is only i386 I need to write code for! (http://www.oreilly.com/openbook/opensources/book/appa.html)