6410: Microkernels

Presented By: Dan Williams

(some content borrowed from previous years:
Ken Birman (2007) and Saikat Guha (2005))

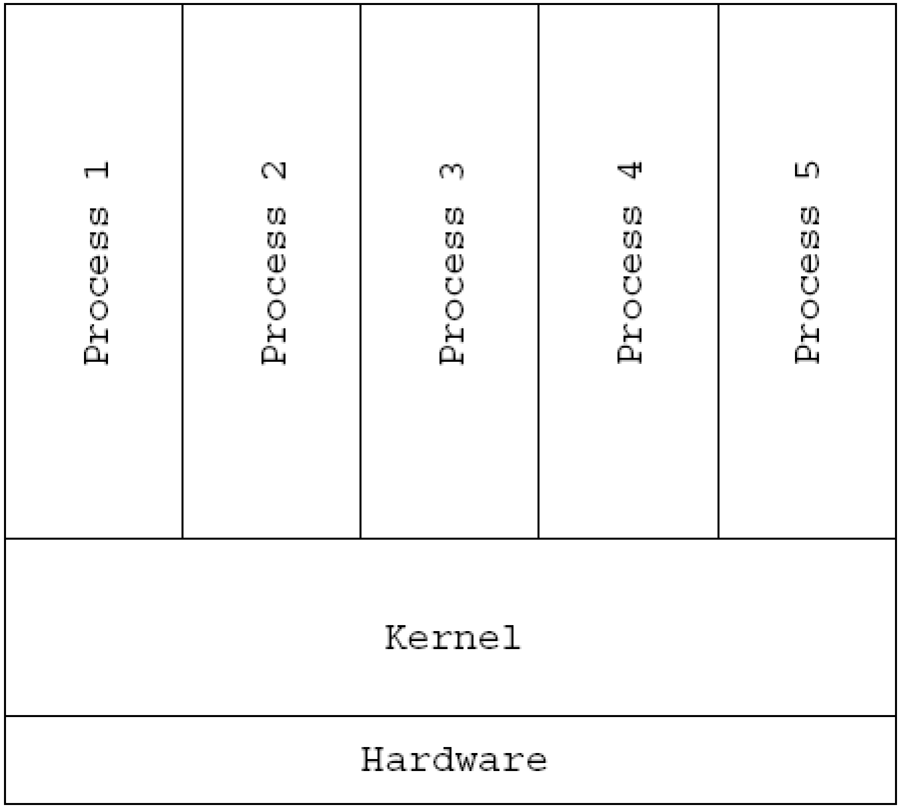
Outline

- Background
- Mach
- L4
- Summary

A short history of kernels

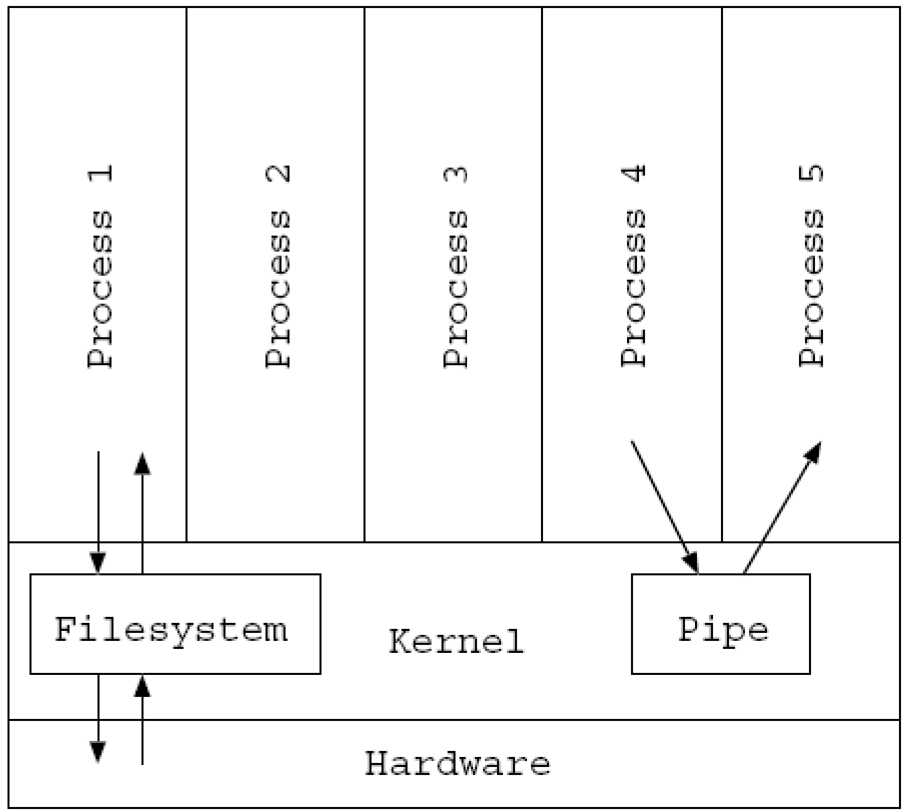
- Early kernel: a library of device drivers, support for threads
- Monolithic kernels: Unix, VMS, OS 360…
  - Unstructured but fast…
  - Over time, became very large
- Pure microkernels: Mach, Amoeba, Chorus…
  - OS as a kind of application
- Impure microkernels: Modern Windows OS
  - Microkernel optimized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

Monolithic Kernels vs Micro Kernels



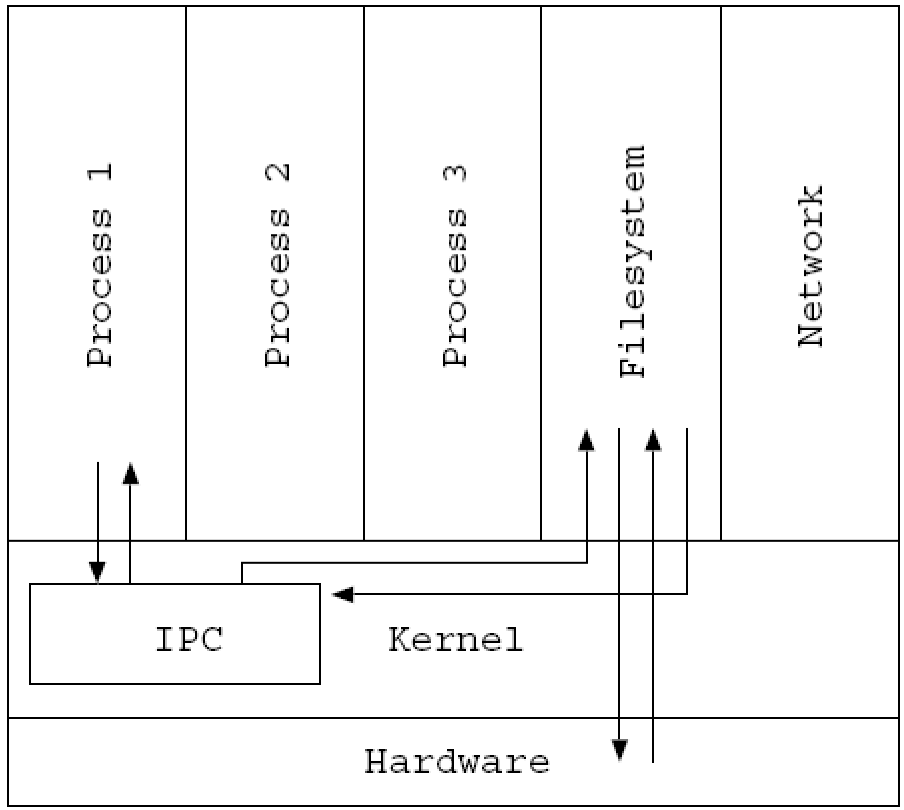
User-Kernel Split

Monolithic Kernels vs Micro Kernels



Monolothic Kernel

Monolithic Kernels vs Micro Kernels



Microkernel

Microkernels

- Minimal services
- Usually threads or processes, address space, and inter-process-communication (IPC)
- User-space filesystem, network, graphics, even device drivers sometimes

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

Monolithic Kernels: Advantages

- Kernel has access to everything
  - All optimizations possible
  - All techniques/mechanisms/concepts can be implemented
- Extended by simply adding more code
  - Linux has millions of lines of code
- Tackle complexity
  - Layered kernels
  - Modular kernels
  - Object oriented kernels. Do C++, Java, C# help?

Microkernels: Advantages

- Minimal
  - Smaller trusted computing base
  - Less error-prone
  - Server malfunction easily isolated
- Elegant
  - Enforces modularity
  - Restartable user-level services
- Extensible
  - Different servers/APIs can exist

Microkernels

- 1st generation
  - Mach, Chorus, Amoeba, L3
- 2nd generation
  - Spin, Exokernel, L4

Papers

- The Duality of Memory and Communication in the Implementation of a Multiprocessor Operating System
  - Young et al.
  - Mach microkernel
  - SOSP 1987
- The Performance of µ-Kernel-based Systems
  - Härtig et al.
  - L4 microkernel
  - SOSP 1997

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Summary of First Paper

- Summary of Mach
- Memory object
  - Manage system services like network paging and filesystem support outside the kernel
  - Kernel acts as cache manager
- Memory via communication
- Performance
  - Does not prohibit caching of physical memory
  - More space for caching without copying

Mach Abstractions

- Task
  - Basic unit of resource allocation
  - Virtual address space, communication capabilities
- Thread
  - Basic unit of computation
- Port
  - Communication channel for IPC
  - Need port capability
- Message
  - May contain port capabilities, pointers
- Memory Object

Messages and Ports

msg_send(message, option, timeout)
Send a message to the destination specified in the message header.

msg_receive(message, option, timeout)
Receive a message from the port specified in the message header, or the default group of ports.

msg_rpc(message, option, rcv_size, send_timeout, receive_timeout)
Send a message, then receive a reply.

port_allocate(task, port)
Allocate a new port.

port_deallocate(task, port)
Deallocate the task's rights to this port.

port_enable(task, port)
Add this port to the task's default group of ports for msg_receive.

port_disable(task, port)
Remove this port from the task's default group of ports for msg_receive.

port_messages(task, ports, ports_count)
Return an array of enabled ports on which messages are currently queued.

port_status(task, port, unrestricted, num_msgs, backlog, receiver, owner)
Return status information about this port.

port_set_backlog(task, port, backlog)
Limit the number of messages that can be waiting on this port.

Virtual Memory

vm_allocate(task, address, size, anywhere)
Allocate new virtual memory at the specified address or anywhere space can be found (filled-zero on demand).

vm_deallocate(task, address, size)
Deallocate a range of addresses, making them no longer valid.

vm_inherit(task, address, size, inheritance)
Specify how this range should be inherited in child tasks.

vm_protect(task, address, size, set_max, protection)
Set the protection attribute of this address range.

vm_read(task, address, size, data, data_count)
Read the contents of this task's address space.

vm_write(task, address, count, data, data_count)
Write the contents of this task's address space.

vm_copy(task, src_addr, count, dst_addr)
Copy a range of memory from one address to another.

vm_regions(task, address, size, elements, elements_count)
Return a description of this task's address space.

vm_statistics(task, vm_stats)
Return statistics about this task's use of virtual memory.

External Memory Management

- No kernel-based filesystem
  - Kernel is just a cache manager
- Memory object
  - Aka “paging object”
- Pager
  - Task that implements memory object

External Memory Management

vm_allocate_with_pager(task, address, size, anywhere, memory_object, offset)
Allocate a region of memory at the specified address. The specified memory object provides the initial data values and receives changes.

- Call by application program to cause a memory object to be mapped into its address space

pager_init(memory_object, pager_request_port, pager_name)
Initialize a memory object.

pager_data_request(memory_object, pager_request_port, offset, length, desired_access)
Requests data from an external data manager.

pager_data_write(memory_object, offset, data, data_count)
Writes data back to a memory object.

pager_data_unlock(memory_object, pager_request_port, offset, length, desired_access)
Requests that data be unlocked.

pager_create(old_memory_object, new_memory_object, new_request_port, new_name)
Accept responsibility for a kernel-created memory object.

- Calls made by kernel on data manager

External Memory Management

pager_data_provided(pager_request_port, offset, data, data_count, lock_value)
Supplies the kernel with the data contents of a region of a memory object.

pager_data_lock(pager_request_port, offset, length, lock_value)
Restricts cache access to the specified data.

pager_flush_request(pager_request_port, offset, length)
Forces cached data to be invalidated.

pager_clean_request(pager_request_port, offset, length)
Forces cached data to be written back to the memory object.

pager_cache(pager_request_port, may_cache_object)
Tells the kernel whether it may retain cached data from the memory object even after all references to it have been removed.

pager_data_unavailable(pager_request_port, offset, size)
Notifies kernel that no data exists for that region of a memory object.

- Calls made by data manager on Mach kernel to control use of memory object

(Copy-on-Write)Filesystem Example

```
char *file_data;
int i, file_size;
extern float rand();    /* random in [0,1) */

/* Read the file -- ignore errors */
fs_read_file("filename", &file_data, file_size);

/* Randomly change contents */
for (i = 0; i < file_size; i++)
    file_data[(int)(file_size*rand())]++;

/* Write back some results -- ignore errors */
fs_write_file("filename", file_data, file_size/2);

/* Throw away working copy */
vm_deallocate(task_self(), file_data, file_size);
```

- Read file maps file into address space
- Explicitly write contents back to file

(Copy-on-Write)Filesystem Example

```
return_t fs_read_file(name, data, size)
    string_t name;
    char **data;
    int *size;
{
    port_t     new_object;

    /* Allocate a memory object (a port), */
    /* and accept request */
    port_allocate(task_self(), &new_object);
    port_enable(task_self(), new_object);

    /* Perform file lookup, find current file size,*/
    /* record association of file to new_object */
    ...

    /* Map the memory object into our address space*/
    vm_allocate_with_pager(task_self(), data, *size,
                                   TRUE, new_object, 0);

    return(success);
}
```

- Server maps file into own address space
- Kernel will issue pager_init

(Copy-on-Write)Filesystem Example

```
void pager_data_request(memory_object, pager_request,
        offset, size, access)
    port_t memory_object;
    port_t pager_request;
    vm_offset_t offset;
    vm_size_t size;
    vm_prot_t access;
{
    char *data;

    /* Allocate disk buffer */
    vm_allocate(task_self(), &data, size);

    /* Lookup memory_object; find actual disk data*/
    disk_read(disk_address(memory_object, offset),
                            data, size);

    /* Return the data with no locking */
    pager_data_provided(pager_request, offset, data,
                            size, VM_PROT_NONE);

    /* Deallocate disk buffer */
    vm_deallocate(task_self(), data, size);
}
```

- Give memory to kernel to act as cache

Lots of Flexibility

- E.g consistent network shared memory
  - Each client maps X with shared pager
  - Use primitives to tell kernel cache what to do
    - Locking
    - Flushing

Problems of External Memory Management

- External data manager failure looks like communication failure
  - e.g need timeouts
- Opportunities for data manager to deadlock on itself

Performance

- Does not prohibit caching
- Reduce number of copies of data occupying memory
  - Copy-to-user, copy-to-kernel
  - More memory for caching
- “compiling a small program cached in memory ... twice as fast”
- I/O operations reduced by factor of 10
- Context switch overhead?

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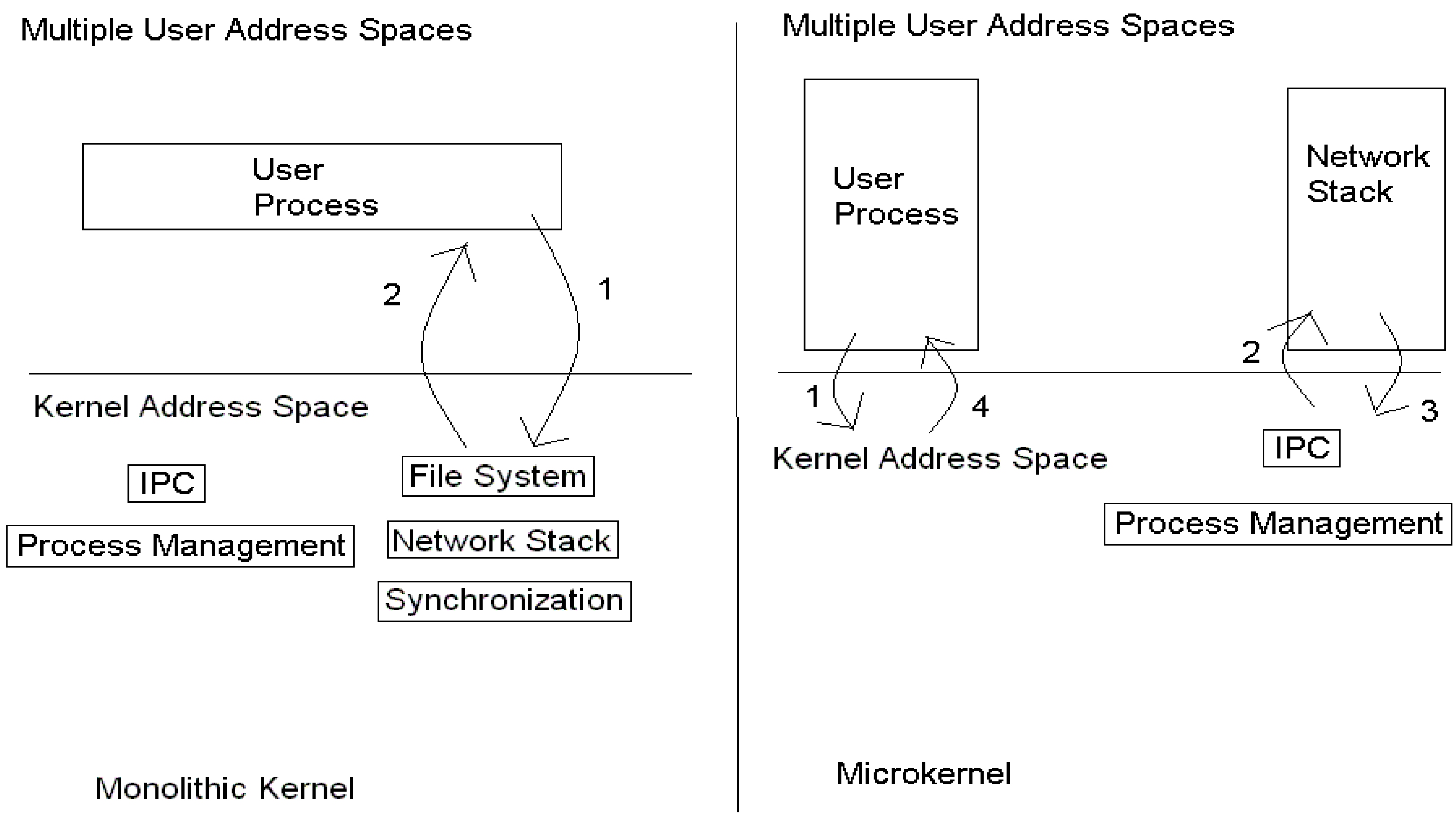
Context Switches



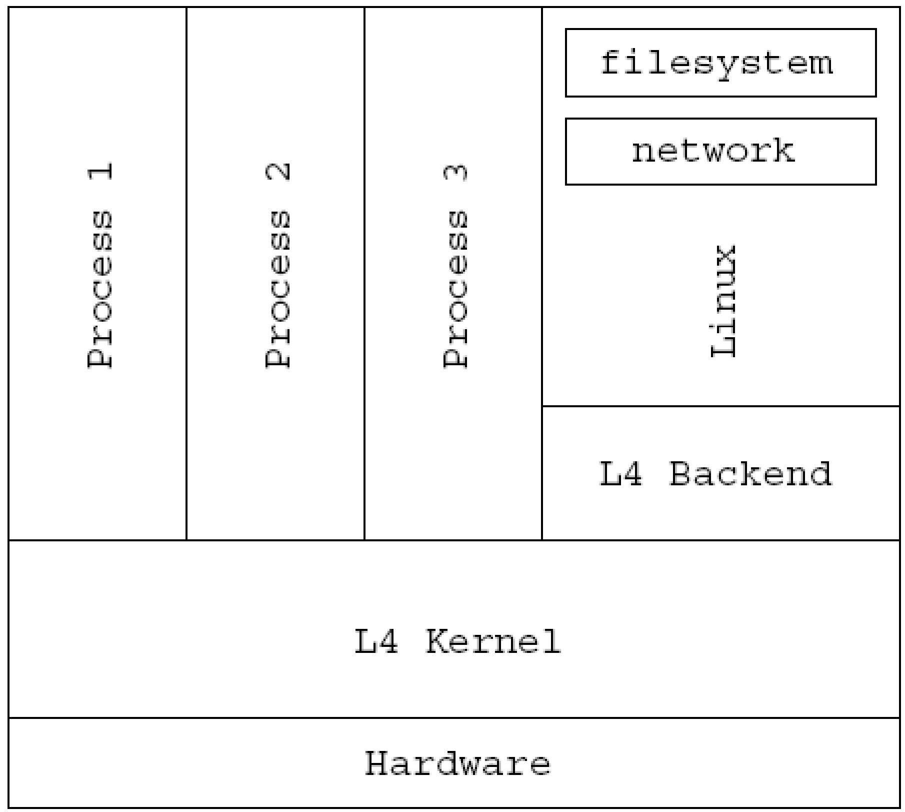
The Performance of μ-Kernel-based Systems

- Evaluates an L4 based system
  - Second generation microkernel
- Ports Linux to run on top of L4
- Suggests improvements

The L4 Microkernel

- Similar to Mach
  - Started from scratch, rather than monolithic
  - More strictly minimal
- Uses user-level pagers
- Tasks, threads, IPC

L4-Linux



L4-Linux

L4Linux

- Linux source has two cleanly separated parts
  - Architecture dependent
  - Architecture independent
- In L4Linux
  - Architecture dependent code is modified for 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 lib call the Linux kernel using IPC
- For unmodified native Linux applications there is a “trampoline”
  - The application traps
  - Control bounces to a user-level exception handler
  - The handler calls the modified shared library
- Binary compatible

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

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

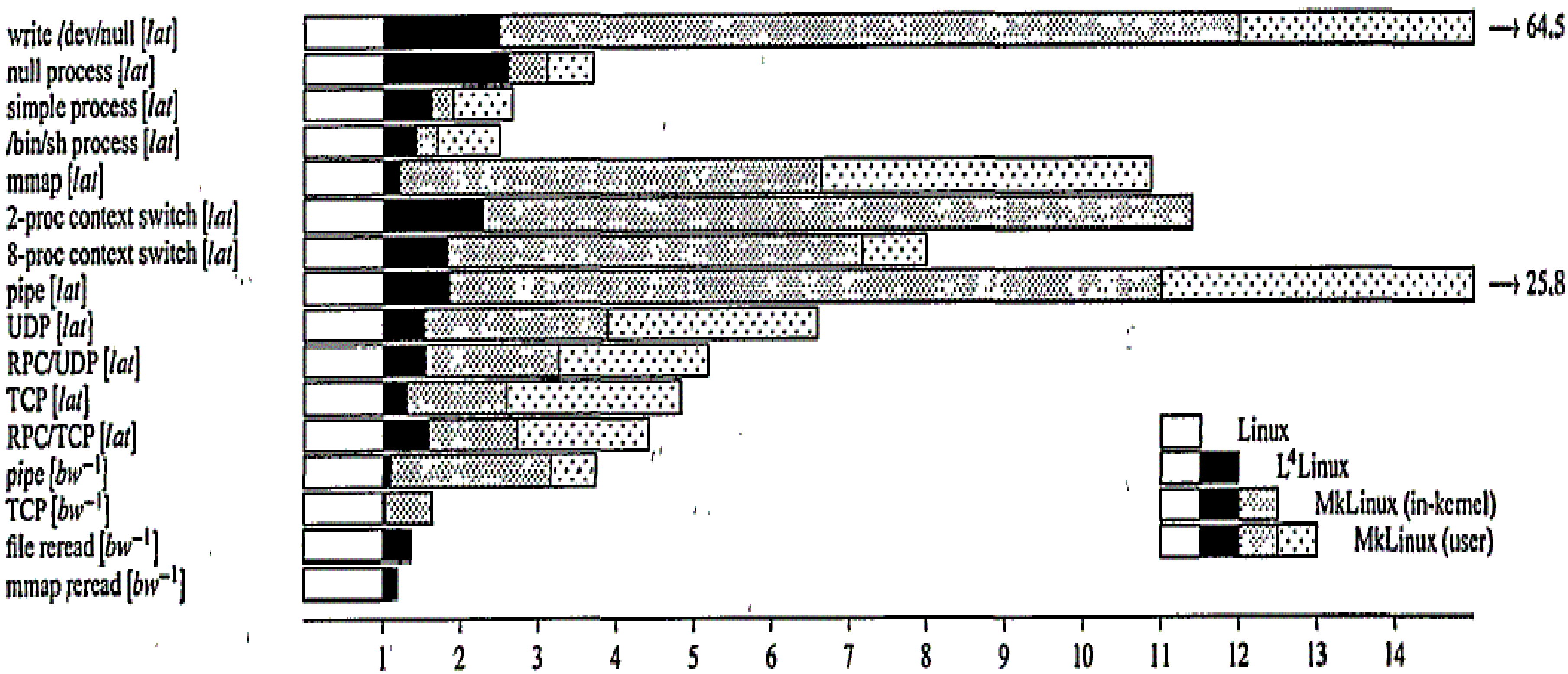


Figure 6: *lmbench results, normalized to native Linux.* These are presented as slowdowns: a shorter bar is a better result. [*lat*] is a latency measurement, [bw^{-1}] the inverse of a bandwidth one. Hardware is a 133 MHz Pentium.

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

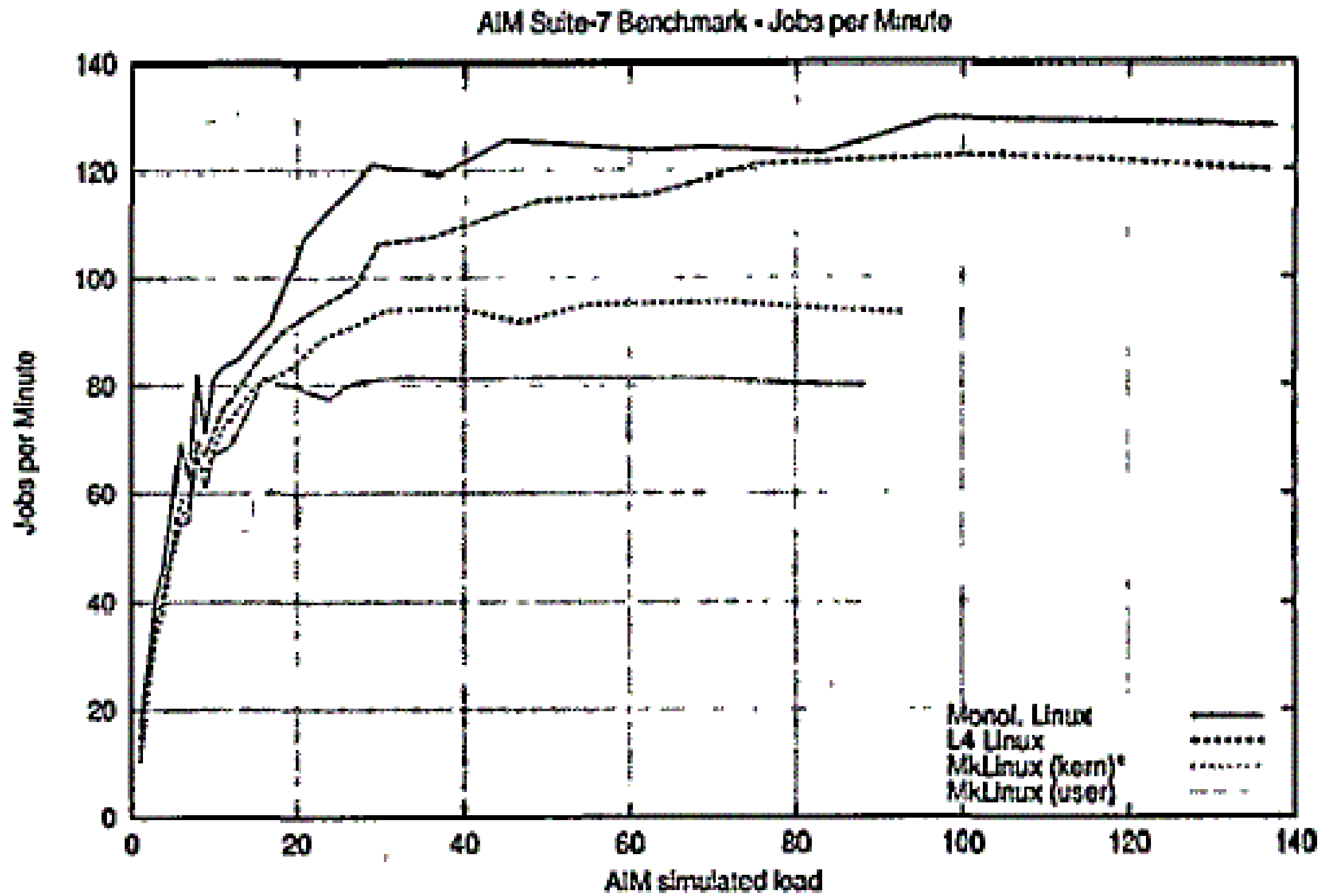


Figure 9: *AIM Multiuser Benchmark Suite VII.* Jobs completed per minute depending on AIM load units. (133 MHz Pentium)

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

L4 is Proof of Concept

- Pipes can be made faster using L4 primitives
- Linux kernel was essentially unmodified
  - Could be optimized for microkernel
- More options for extensibility

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Summary

- Microkernel has attractive properties
  - Extensibility benefits
  - Minimal/elegant
- Microkernel can perform well