Kernel construction and OS architecture

Advanced Operating Systems
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What is "OS Architecture"?

- Coarse-grained structure of the OS
- How the complexity is factored
- Mapping onto:
  - Programming language features
  - Execution environment presented to applications
  - Address spaces
  - Hardware protection features (rings, levels, etc.)
  - Execution patterns (subroutines, threads,. coroutines)
  - Hardware execution (interrupts, traps, call gates)

Architectural models

- There are many, and they are *models!*
  - Idealized, extreme view of how system is structured
  - Real systems always entail compromises
  - Hard to convey ⇒ it's good to build a few
- Think of these as tools for thinking about Oses
  - Each has its reasons
  - Solve particular problems at particular times

Outline

- Monolithic or component-based systems
- Kernel-based systems
- Microkernels
- Kernel thread models
  - Per-thread kernel stack
  - Single kernel stack
- Exokernel systems
  - Nemesis and Exokernel
- Multikernels
  - Barrelfish
- References

1. Monolithic/kernel-based systems

- Examples:
  - Cedar [Swinehart et al., 1986]
  - TinyOS [Hill et al., 2004]
  - Oberon
  - Singularity [Hunt and Larus, 2007]
- Hardware provides time multiplexing
  - Interrupts
  - threads (in Cedar's case)
- Language provides modularity & protection
  - Module calls
  - Inter-thread communication

Protection-based component-based systems

- Examples:
  - KeyKOS [Bromberger et al., 1992]
  - Pebble [Bruna et al., 1999]
- Even simpler kernel than microkernels
  - Kernel only mediates protection domain switches
  - Scheduling, threads, etc. implemented in "user space"
- Aimed at:
  - High security (very small TCB)
  - Embedded systems (highly configurable)

2. Kernel-based systems

- Examples:
  - Unix [Thompson, 1974],
  - VMS → Windows NT/2k/XP/Vista/7
- Hardware enforces user vs. kernel mode
- Machine in user space multiplexed into address spaces
- Kernel provides:
  - All shared services
  - All device abstraction

3. Microkernels

- Examples: L4, Mach, Amoeba, Chorus
- Kernel provides:
  - Threads
  - Address spaces
  - IPC
- All other functionality in server processes
  - Device drivers
  - File systems
  - Etc.
- Instead of syscalls, applications send IPC to servers

Kernel thread models

- Important design choices when implementing an OS:
  - *Do I support more than one execution context in the kernel?*
  - *Where is the stack for executing kernel code?*
  - *Can kernel code block? If so, how?*
- The answers determine the **kernel thread model**.

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- The answers determine the **kernel thread model**.
  - You have faced the same choices, although SOS may not be a kernel

Kernel thread models

There are two basic alternatives:

- **Per-thread kernel stack**:
  - Every thread has a matching kernel Stack
- **Single kernel stack**:
  - Only one stack is used in the kernel (per core).

Per-thread kernel stack

- Every user thread/process has its own kernel stack
- Thread's kernel state implicitly stored in kernel activation stack
- A kernel thread blocks ⇒ switch to another kernel stack
- Resuming: simply switch back to original stack
- Preemption is easy
- No conceptual difference between kernel- and user-mode

```
example(arg1, arg2) {
  P1(arg1, arg2);
  if (need_to_block) {
    thread_block();
    P2(arg2);
  } else {
    P3();
  }
  /* return to user */
  return SUCCESS;
}
```

Single kernel stack

- Challenges:
  - How can a single kernel stack support many threads?
  - How are system calls that block handled?
- Two basic approaches:
  - Continuations [Draves et al., 1991]
  - Stateless kernel [Ford et al., 1999]

Continuations

- State to resume blocked thread explicitly saved in TCB
  - Function pointer
  - Variables
- Stack can be discarded and reused for new thread
- Resuming involves discarding current stack and restoring the continuation

```
example(arg1, arg2) {
  P1(arg1, arg2);
  if (need_to_block) {
    save_context_in_TCB;
    thread_block(example_continue);
    panic("thread_block returned");
  } else {
    P3();
  }
  thread_syscall_return(SUCCESS);
}
example_continue() {
  recover_context_from_TCB;
  P2(recovered arg2);
  thread_syscall_return(SUCCESS);
}
```

Stateless kernel

- System calls simply do not block within kernel
- If a system call must block:
  - Modify user state to restart call when resources are available
  - Kernel stack content discarded
- Preemption within kernel difficult
  - Must (partially) roll back to a restart point
- Avoid page faults within kernel code
  - System call arguments in registers
  - Nested page fault is fatal

Kernel stack model summary

Per-thread kernel stack:

✓ Simple, flexible
- Kernel can always use threads
- No special technique for saving state when interrupted/blocked
- No conceptual difference between kernel and user mode

✗ Larger cache and memory footprint

- Used by L4Ka::Pistachio, UNIX, Linux, etc.

Kernel stack model summary

Single kernel stack

✓ Lower cache & memory footprint (always the same stack)

Continuations:

✗ Complex to program
✗ Must save state conservatively (whatever might be needed)
- Used by Mach, NICTA::Pistachio

Stateless kernel:

✗ Also complex to program
- Must request all resources prior to execution
- Blocking system calls must be restartable
✗ Processor-provided stack management can get in the way
- System calls need to be atomic
- Used by Fluke, Nemesis, Exokernel, Barrelfish

Why build a stateless kernel?

- It is the simplest model, if all kernel invocations are:
  - Atomic
  - Non-blocking
  - Bounded and short-running
  - Non-preemptable
  - Guaranteed not to page fault
- Restrictive, but quite appropriate for a uniprocessor µkernel with no blocking IPC.

4. Exokernels

- Examples: Exokernel, Nemesis, Xen 3, ESX...
- Kernel provides minimal multiplexing of h/w
- All other functionality in userspace libraries
  - Unlike microkernels, where this in servers
  - "LibraryOS" concept
- Enables:
  - Strong isolation between applications
  - High degree of application-specific policies

Exokernels: Exterminate all OS abstractions!

[Engler and Kaashoek, 1995]

A traditional operating system, and also a microkernel like L4:

- **Multiplexes** physical resources
  - Shared and secure access to CPU, memory, disk, network, etc.
- **Abstracts** the same physical resources
  - Processes/threads, address spaces, virtual file system, network stack

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- Multiplexing is required for security
  ...but why should an OS abstract what it multiplexes?

Exokernel systems

- Two different systems. Two different motivations:
  1. Complexity, adaptability, performance → **Exokernel** [Kaashoek et al., 1997]
  2. QoS crosstalk → **Nemesis** [Leslie et al., 1996]

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- The approach of both is similar:
  - Exterminate OS abstractions
  - Move all code possible into the application's address space → **library OSes**

Nemesis

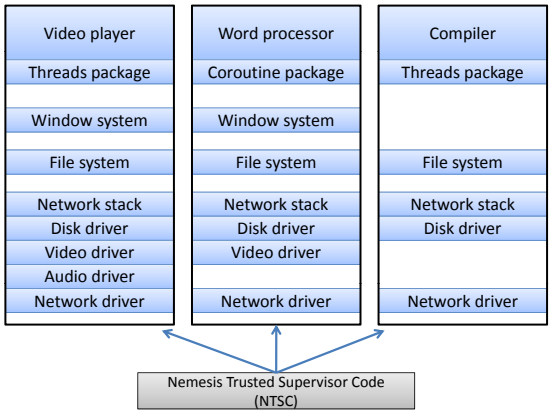
- Written for uniprocessor Alpha, 1992-95
- 64-bit single address space
  - Not a fundamental design motivation, as in Mungi
- *"Multi-service operating system"*
  - Mixture of soft real time, communication-oriented, interactive, batch jobs
  - Designed for workstations
- Strong networking influence
  - Published in JSAC!

What is an application?

In an Exokernel, functionally, *everything:*

- User code
- Network stack
- Filing system
- Window system
- Low-level I/O
- Intra-application communication

Nemesis Application Domains



Nemesis in action

Exokernel challenges

- Can you really expose all the hardware to the application and still stay sane?
- Can you multiplex the machine securely while removing (most) abstraction?

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Apparently, yes:

- Threads and processes: see *scheduler activations later*
- Networking: packet filtering
- Disks (file systems): block or track-level protection, careful management of metadata
- Window system: similar; blit tiles into protected windows

Programmability questions

- Isn't it all rather complex to move functionality into the app?
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  - Each application can efficiently implement its policy

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- Does the flexibility impact performance?
  - **No**: protection checks are mostly off the fast path
  - Each application can efficiently implement its policy
- What happens on a multiprocessor?
  - **Unclear**: a multiprocessor kernel requires plenty of embedded policy (e.g. locks)
  - Attempts to produce MP exokernels have not been as dramatically better at performance

6. The Multikernel

[Baumann et al., 2009]

An architecture aimed at **heterogeneous**, **manycore** machines:

- Lots of processors
- Not all of them the same
- Not all of them share memory
- Not all the shared memory is cache-coherent
- You don't know in advance what the machine looks like

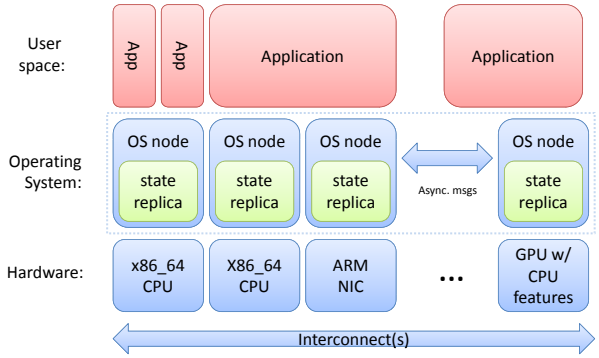
Very new: published last year (though similar designs have existed in the past).

Multikernel design principles

1. Use messages, not shared memory, between cores
2. Decouple OS structure from hardware configuration
3. Treat all (potentially global) OS data as a replica

Multikernel architecture

Instead of the kernel as a multithreaded, shared-memory program, treat the machine as a **distributed system**:



Advantages

- You need this for core heterogeneity
- You need this for non-shared memory
- Handles cores coming and going (power, failure, hot-plug)
- Separating structure (algorithms) from hardware scalability tradeoffs makes the design **agile**.

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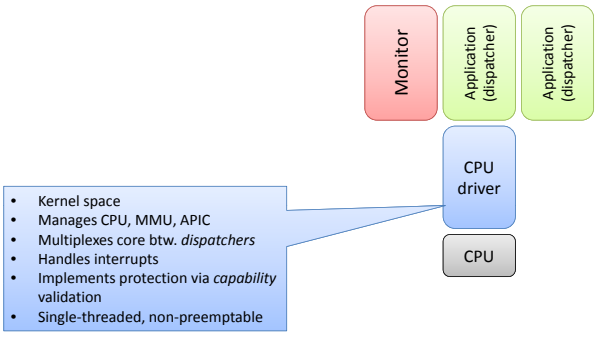
Or so we hope, anyway.

Challenges

- You need to communicate between cores efficiently
  - Message transports ("interconnect drivers") are highly specialized (=optimized)
  - We cover some known techniques later in this course
- You still need to design the kernel on each core! Key differences:
  - It is now implicitly a uniprocessor kernel
  - Highly communication-oriented (to other cores)
  - Can be highly architecture-specific (c.f. L4)

Barrelfish per-core architecture



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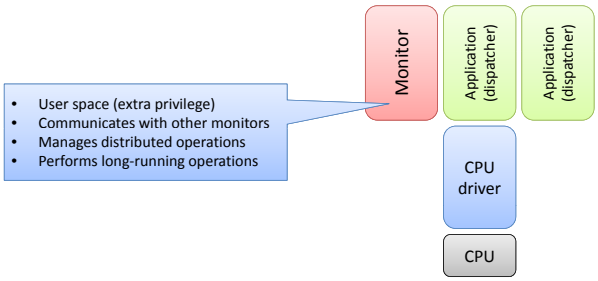

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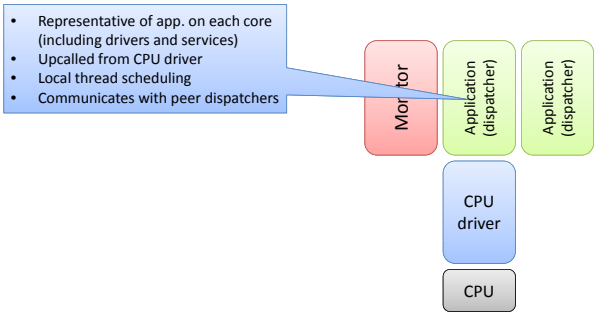
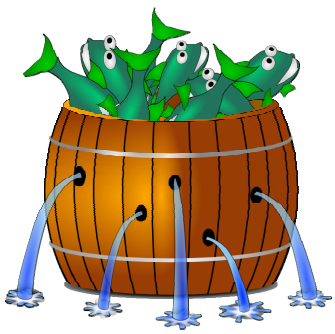


Barrelfish

- More information at www.barrelfish.org...



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