Unikernels: Library Operating Systems for the Cloud

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In The Context of the CS3551 Spire Class Project

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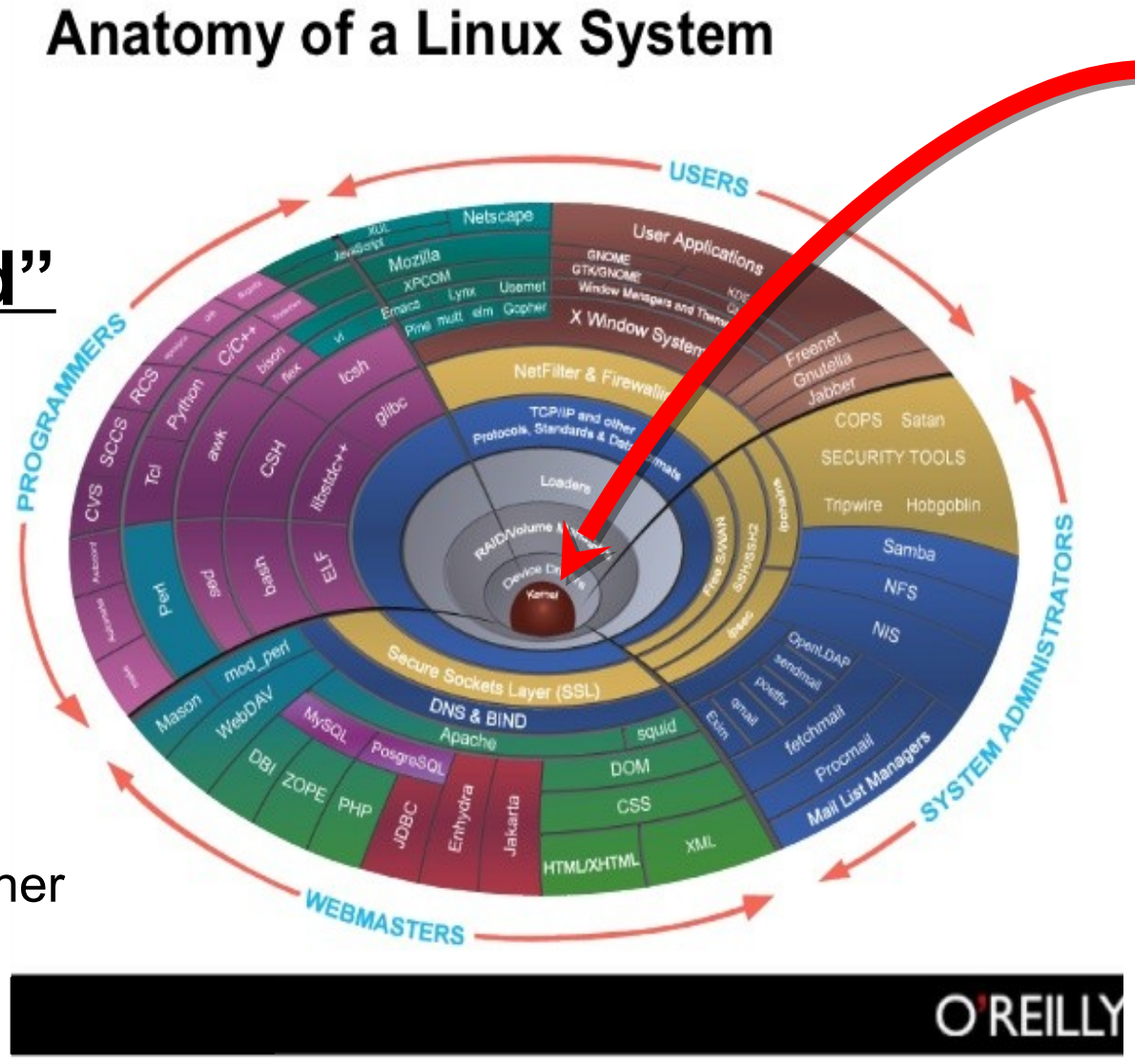
Teaching Moment - What is a Unikernel?

- To answer that question, we have to take a look at the structure of a modern operating system
- Doesn't matter if it's Microsoft Windows, Linux, UNIX, ~~Mac OS X~~ ~~OS X~~ macOS, etc.
- All the mainstream operating systems have the same fundamental anatomy

The Anatomy of an Operating System

“Userland”

- Where Applications Run
- No Privileges
- Can Not Access Resources
-
- Can Not “Talk” to Other Programs



“The Kernel”

- Runs in Special Hardware Mode
  - – “Ring 0”
- Only Program That Can Access or Allocate Resources
- Copies Data Between Programs

Growth of Operating Systems

- Linux Kernel is now 28 million lines of source code!
- Windows is estimated at 50 million lines of code!!
- With an industry average of 15-50 defects per 1000 lines of code*:
  - Linux (Just the kernel) = 420 thousand to 1.4 million defects
  - Windows = 750 thousand to 2.5 million defects
  - * Steve McConnel, “Code Complete 2”, 2005

It Gets Worse

- The “Userland” support software is often 10 to 20 times larger than the kernel
- Red Hat Enterprise Linux (RHEL) Userland is approximately 420 million lines of code
  - Try not to think about the 6.7 to 22 million defects running on the SCADA server controlling your power grid and drinking water

Can It Get Even Worse?

- The Linux kernel is full of junk!
- A large number of device drivers are routinely compiled into the kernel, regardless of the actual hardware in the computer
  - There are device drivers for hardware that no longer exists
    - Silicon Graphics video drivers were just added to the Linux 5.5 kernel!
  - Amazon AMI images ~~have~~ had drivers for floppy disks and audio cards!
    - In 2015, the Venom vulnerability (CVE-2015-3456) used a flaw in the floppy disk controller (FDC) driver to compromise both physical and virtual machines

And It Doesn't End There

- Likewise, there are thousands of storage and communications protocols in the kernel that will not be used in your application
- Linux recognizes 7 different executable formats, even though the vast majority of applications (including Spire) are in ELF format
- Each of these extra, unused chunks of code (with its 15-50 defects/1000 SLOC) is a potential entry point for compromise

What If We Cut Out the Parts We Don't Need?

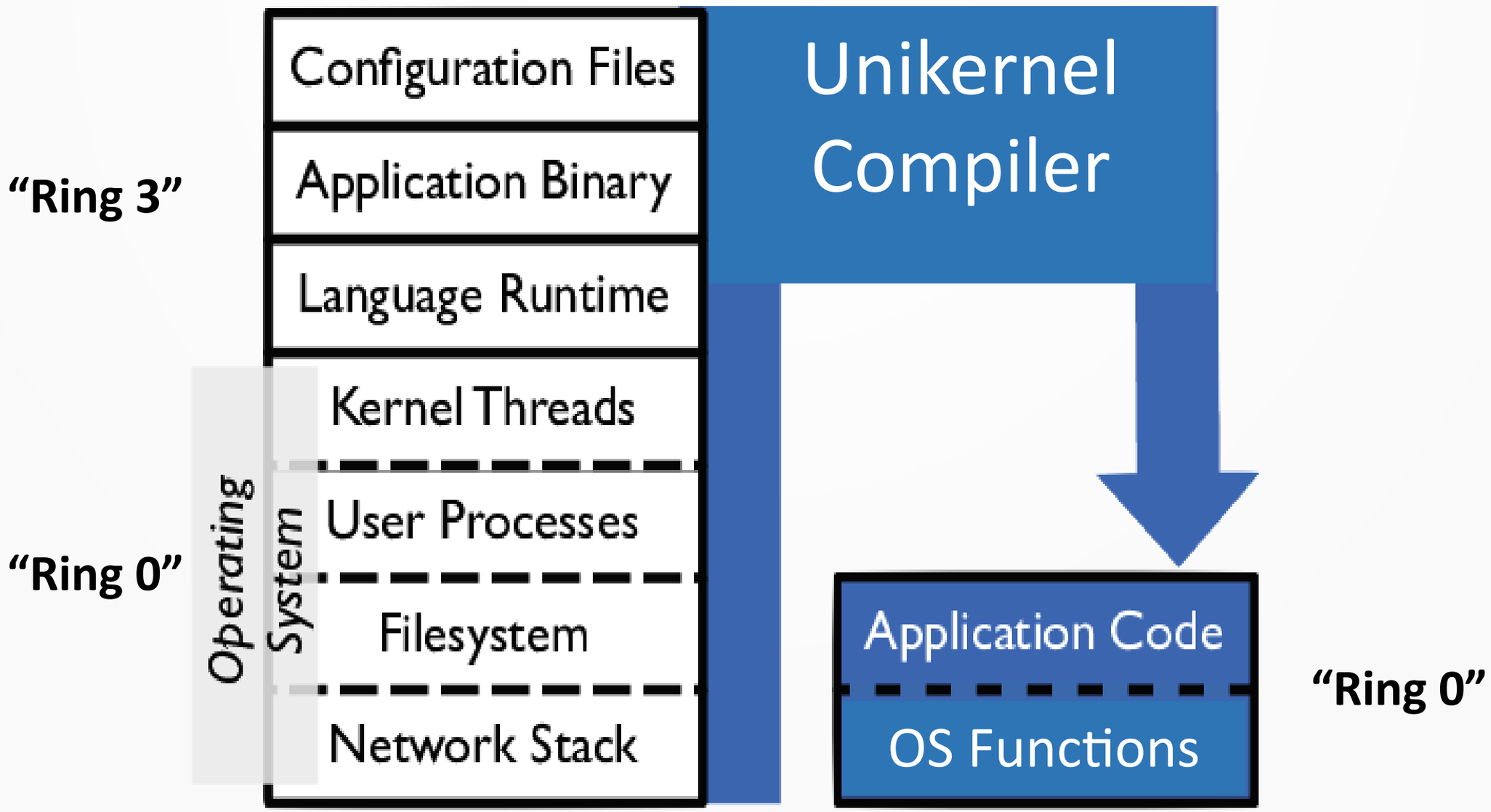
- Code traces show that the average application uses less than 0.08% of the total code in the kernel
- Take the standard C library as an example
  - The C library contains thousands of functions, but a modern linker only includes the actual functions (and code) that an application uses
- Could we do the same with our operating system?

We Can Create A Library of Operating System Functions

- Common operating system functions, drivers, and protocols are written as a library of functions
- When you link these “library operating system” functions to your application, you have a single executable that runs directly on hardware or a hypervisor as a stand-alone virtual machine (VM)…
  - Only the functions, drivers, and protocols actually used in the application are linked into the executable/VM

…You have a Unikernel!

So What Does a Unikernel Look Like?



Unikernel Approaches

- "From the Ground Up" - Programmer writes code specifically for the Unikernel library functions
  - Mirage
- "Partition an Existing Kernel" - Extract all the functions of an existing kernel and include only needed functions during compile
  - Rump kernel
- "POSIX/Linux Interface to New Library Functions" - New, modernized functions are written for the library, but clients call the functions through existing interfaces
  - IncludeOS

The Paper's Focus

- Mirage
  - A set of libraries that perform the functions commonly associated with the operating system for memory management, execution, and communications
  - Written in a strongly typed functional language, OCaml
  - OCaml applications linked with the Mirage libraries form virtual machine images (unikernels) designed to be run on the Xen hypervisor
  - Mirage unikernels use Xen for device drivers and scheduling

The Paper - Why Unikernels?

- Enhanced Security
  - Hardware-Enforced Access Controls
  - Less Code
  - Immutable
  - No System Calls
  - Per-Compile Randomization
- Single Address Space
  - No Expensive Context Switches
  - Zero Copy
- Small Executable Size
- Reduced Runtime Complexity (No Scheduler)

Architecture of a Unikernel (1/3)

- Configuration and Deployment
  - Instead of /etc and config files, the application configuration is defined at compile time and compiled directly into the executable code.
  - Configurations are explicit and manipulated directly by the high level language making them subject to type checking and static anaysis
  - Reduced effort to configure multi-service applications
- Compactness and Optimization
  - Using only the required functions makes for compact code
  - Since the compiler sees all the code, it can apply optimizations to the entire unikernel

Architecture of a Unikernel (2/3)

- Threat Model
  - Tenants in a shared cloud environment (possibly Spire data center controllers)
  - Across the network (definitely Spire)
  - Hypervisor provides isolation and access control
  - Compile time specialization (no system calls, no scheduler, etc.)
- Single Image
  - Removal of all unused functions and code
- Pervasive Type Safety
  - Mirage uses a single, strongly typed language

Architecture of a Unikernel (3/3)

- Sealing and Privilege Dropping
  - Mark code as immutable, enforced by hypervisor
    - Code pages are marked “read-only”
    - Data pages (stack, heap, mmap, etc.) are marked “non-executable”
  - Harvard architecture instead of Von Neumann architecture
- Compile-Time Address Space Randomization
  - Mirage unikernel toolchain can produce randomized internal addresses (equivalent to ASLR)

Components of the Mirage Unikernel (1/4)

- OCaml
  - The majority of the operating system functions are written from scratch in OCaml, a strongly typed functional language
  - The authors attribute much of Mirage's reliability to the use of OCaml
- PVBoot Library
  - Minimal code required to:
    - Create a single 64 bit address space
    - Load unikernel image
    - Allocate required memory to unikernel data structures
    - Use 1 vCPU
    - Connect to Xen event channels
  - Compiled directly into the unikernel image

Components of the Mirage Unikernel (2/4)

- Language Runtime
  - Mirage uses a specialized OCaml runtime library
    - Modified for single address space layout
    - Memory mapped I/O between Mirage unikernel VMs on the same Xen hypervisor
  - PVBoot provides a single event-driven execution loop
  - Thread concurrency comes from a Lightweight Thread Library written in OCaml
- Device Drivers
  - Mirage uses Xen device drivers
  - Xen device drivers communicate with VMs using a single shared memory page of “slots” arranged in a ring buffer, with event channels for signaling
  - Mirage wraps this Xen ring I/O within OCaml functions for type safety enforcement

Components of the Mirage Unikernel (3/4)

- Zero-Copy Device I/O
  - With a single address space, no need to copy data from kernel space to user space
- Type-Safety Protocol I/O
  - All I/O is wrapped in OCaml for type safety, eliminating buffer overflow errors/attacks

Components of the Mirage Unikernel (4/4)

- Network Processing
  - Fast shared memory between unikernels in the same hypervisor
  - “Scatter/Gather” approach to build and send Ethernet TCP/IP I/O
- Storage
  - Uses “shared page” I/O ring buffer with Xen hypervisor for block storage
  - OCaml library in unikernel provides filesystem abstraction over the blocks

Evaluation (1/3)

- Microbenchmarks
  - Boot Time
    - Mirage boots in 50 milliseconds, versus 500 milliseconds for an equivalent Linux VM
  - Threading
    - Mirage can launch 20 million threads per second, versus 4 seconds for an equivalent Linux VM
  - Networking and Storage
    - Mirage was 4-10% slower than Linux VM when processing ICMP Ping requests
    - Mirage was slightly faster than Linux on IPv4 reads (zero-copy) and slightly slower on writes because of CPU operations in protocol libraries
    - Mirage and Linux direct I/O storage throughput effectively the same (1.6 GB/sec)

Evaluation (2/3)

- DNS Server Appliance (Unikernel image – 183.5 kB versus Linux image - 462MB)
  - BIND9 – 55K queries per second
  - NSD – 70K queries per second
  - Mirage DNS appliance – 75-80K queries per second
- OpenFlow Controller Appliance

Program	Batch	Single Request
Maestro	20K	10K
NOX	120K	40K
Mirage Appliance	100K	35K

Evaluation (3/3)

- Dynamic Web Server Appliance
  - Twitter application
    - Mirage appliance – 800 sessions per second
    - Linux – 200 sessions per second
  - Static web server
    - Mirage appliance ~ 2000 connections per second
    - Apache2 ~ 1700 connections per second
- Code and Binary Size
  - Mirage unikernels are 4-5 X fewer SLOC than an equivalent Linux appliance (after maximum stripping of Linux)

Paper Conclusions

- Demonstrated that the unikernel approach significantly improves safety and efficiency for cloud appliances
- Contributed a “clean slate” library OS based on the strong typed OCaml functional language
- Performance equal to, and in some cases better than, conventional operating system-hosted applications
- By relaxing (abandoning) backwards compatibility, safety and efficiency can be improved

Differences Between Mirage and Our Spire Project

- Mirage Assumes New Code Development - “From the Ground Up”
- We Will Be Using a Unikernel Library Designed to Support Existing POSIX/Linux Software
- While Mirage Can Randomize Internal Addresses, Most Unikernel Libraries Can Not
- Combine Unikernel Approach With MultiCompiler Approach
  - “Do Nothing ;-)”

What Do We Need for Spire?

- Run a single application per server (no scheduler required)
- Run as a single user
- Uses a known set of hardware drivers
- Uses 1 or 2 communications protocols
- Needs security (from unauthorized access - “hacking”)
- Needs reliability
- Nice to-have: Speed (low startup and processing latency)

Keeping Only The OS Functions That Spire Requires

- What does that buy us?
- Let's start with security:
  - Greatly reduced attack surface (99.92% reduction)
- We don't need any userland applications (bye-bye 410 million lines of potentially flawed code!)
  - No shell (/bin/sh)
- No ability to run malicious or hacking tools on the same VM
- Function calls instead of system calls (more secure)
- No time consuming context switches
- Static linking with prevent injection attacks
- No re-configuration attacks

How To Include Only Required Code?

- The C Library Analogy Is The Key
- The C Library Is Actually A “Middle Ware Layer”
  - It Converts Standard C Function Calls Into Equivalent Kernel System Calls
  - Instead of Handing the Function Call Off as a System Call, What If We Extended the C Library to Include the Appropriate Kernel Code?
  - Instead of the C Library Passing a “Print()” Call To The Kernel, the Library Can Include the Machine Instructions to Do The Actual I/O

Increased Performance

- Smaller, Less Memory Intensive Images Mean More Virtual Machines Per Hardware Server
  - 5 Megabyte Virtual Machines = 10,000 VMs Per Physical Server
  - Smaller Than Most Docker Containers
- 6 Millisecond Boot Times
  - Jitsu – Boot-On-Demand
- 45 Microsecond Throughput Times
  - No Context Switches
  - No Information Copying
  - Single Address Space