Operating System Principles: Services, Resources, and Interfaces

CS 111 Operating Systems

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Outline

- Operating systems services
- System service layers and mechanisms
- Service interfaces and standards
- Service and interface abstractions

OS Services

- The operating system offers important services to other programs
- Generally offered as abstractions
- Important basic categories:
  - CPU/Memory abstractions
    - Processes, threads, virtual machines
    - Virtual address spaces, shared segments
  - Persistent storage abstractions
    - Files and file systems
  - Other I/O abstractions
    - Virtual terminal sessions, windows
    - Sockets, pipes, VPNs, signals (as interrupts)

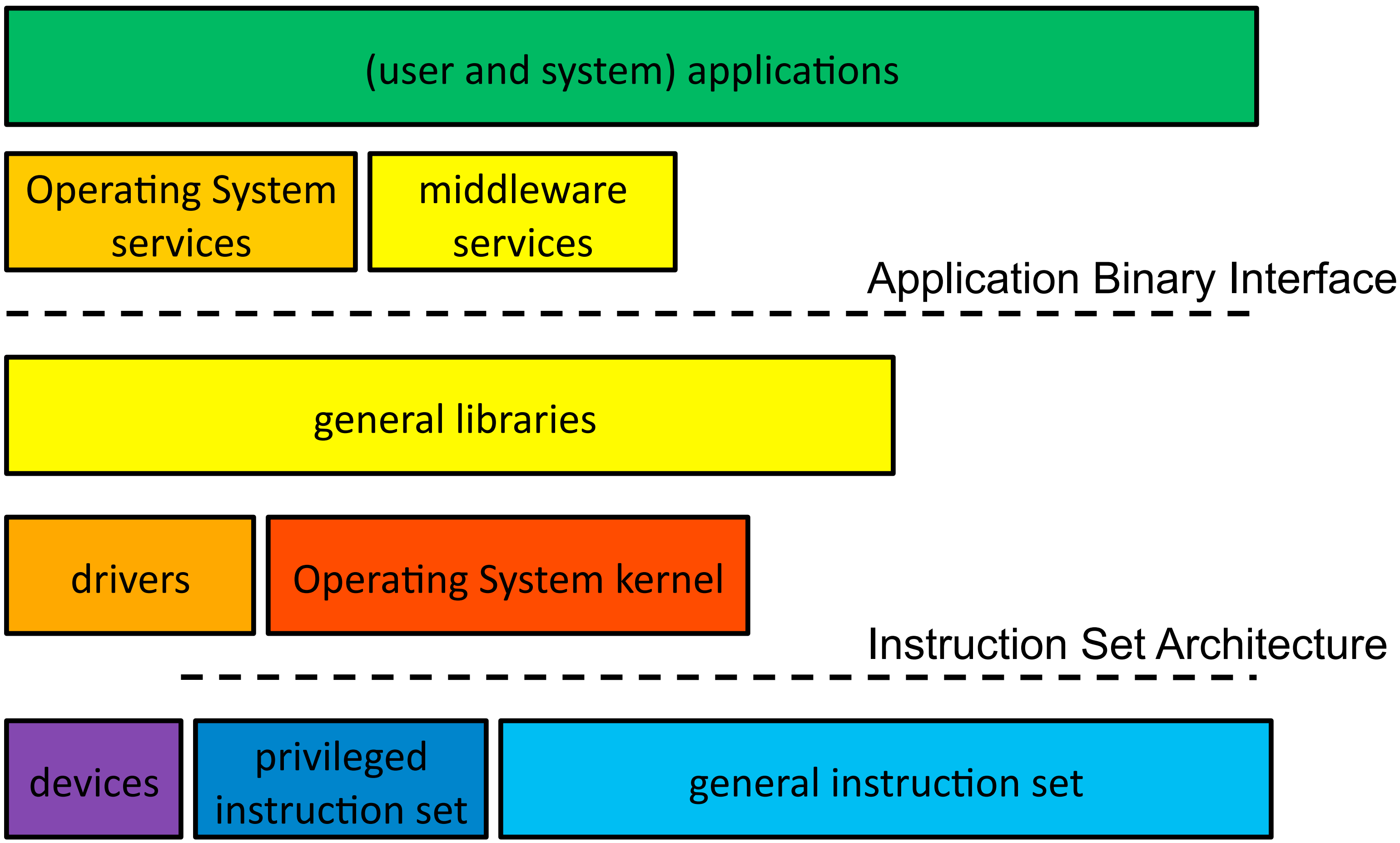
Services: Higher Level Abstractions

- Cooperating parallel processes
  - Locks, condition variables
  - Distributed transactions, leases
- Security
  - User authentication
  - Secure sessions, at-rest encryption
- User interface
  - GUI widgets, desktop and window management
  - Multi-media

Services: Under the Covers

- Not directly visible to users
- Enclosure management
  - Hot-plug, power, fans, fault handling
- Software updates and configuration registry
- Dynamic resource allocation and scheduling
  - CPU, memory, bus resources, disk, network
- Networks, protocols and domain services
  - USB, BlueTooth
  - TCP/IP, DHCP, LDAP, SNMP
  - iSCSI, CIFS, NFS

Software Layering



How Can the OS Deliver These Services?

- Several possible ways
  - Applications could just call subroutines
  - Applications could make system calls
  - Applications could send messages to software that performs the services
- Each option works at a different *layer* of the stack of software

OS Layering

- Modern OSes offer services via layers of software and hardware
- High level abstract services offered at high software layers
- Lower level abstract services offered deeper in the OS
- Ultimately, everything mapped down to relatively simple hardware

Service Delivery via Subroutines

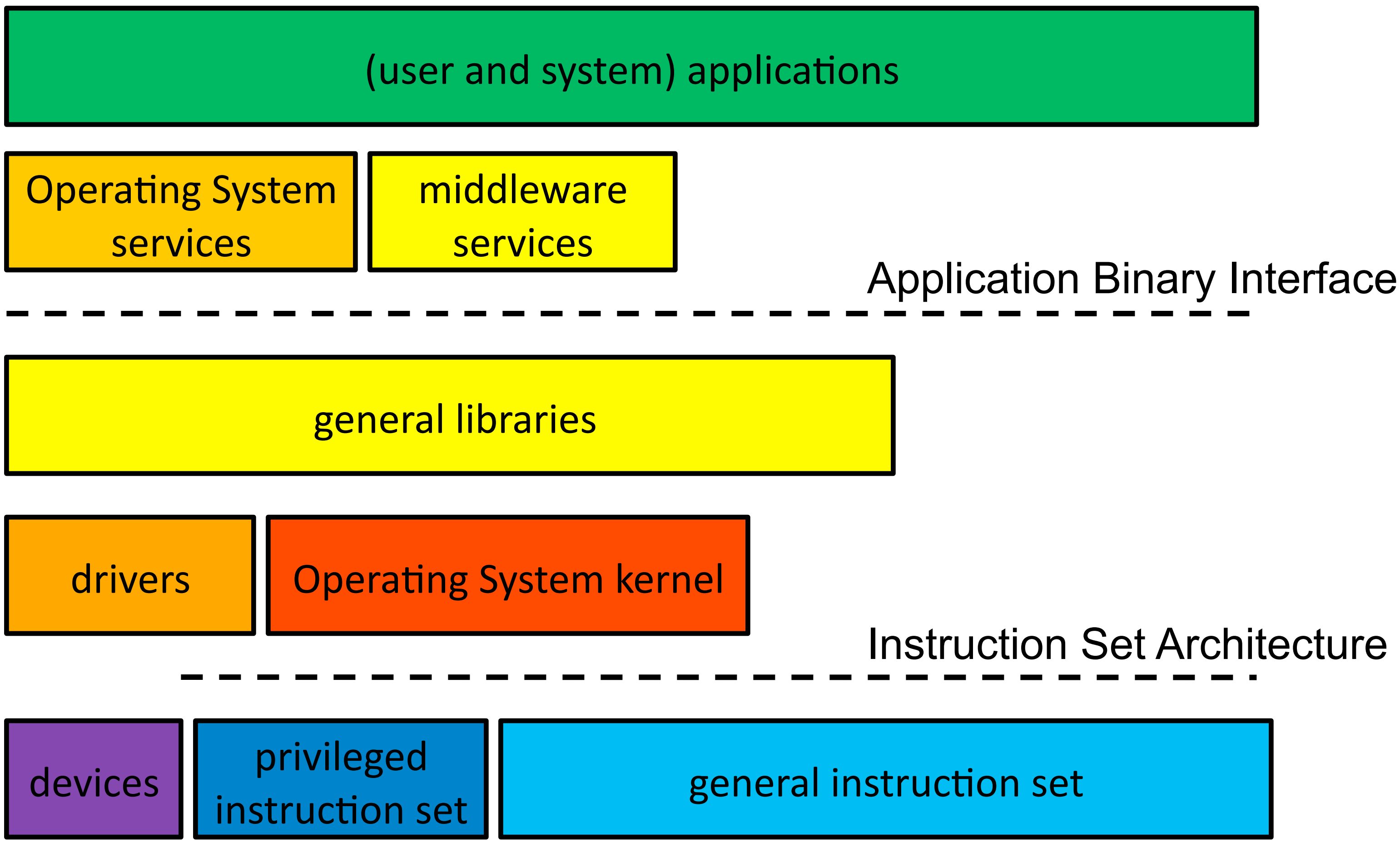
- Access services via direct subroutine calls
  - Push parameters, jump to subroutine, return values in registers on on the stack
- Typically at high layers
- Advantages
  - Extremely fast (nano-seconds)
  - Run-time implementation binding possible
- Disadvantages
  - All services implemented in same address space
  - Limited ability to combine different languages
  - Can't usually use privileged instructions

Why?

Layers: Libraries

- One subroutine service delivery approach
- Programmers need not write all code for programs
  - Standard utility functions can be found in libraries
- A library is a collection of object modules
  - A single file that contains many files (like a zip or jar)
  - These modules can be used directly, w/o recompilation
- Most systems come with many standard libraries
  - System services, encryption, statistics, etc.
  - Additional libraries may come with add-on products
- Programmers can build their own libraries
  - Functions commonly needed by parts of a product

The Library Layer



Characteristics of Libraries

- Many advantages
  - Reusable code makes programming easier
  - A single well written/maintained copy
  - Encapsulates complexity … better building blocks
- Multiple bind-time options
  - Static … include in load module at link time
  - Shared … map into address space at exec time
  - Dynamic … choose and load at run-time
- It is only code … it has no special privileges

Shared Libraries

- Library modules are usually added to a program's load module
  - Each load module has its own copy of each library
    - This dramatically increases the size of each process
  - Program must be re-linked to incorporate new library
    - Existing load modules don't benefit from bug fixes
- Instead, make each library a sharable code segment
  - One in memory copy, shared by all processes
  - Keep the library separate from the load modules
  - Operating system loads library along with program

Advantages of Shared Libraries

- Reduced memory consumption
  - One copy can be shared by multiple processes/programs
- Faster program start-ups
  - If it's already in memory, it need not be loaded again
- Simplified updates
  - Library modules are not included in program load modules
  - Library can be updated (e.g., a new version with bug fixes)
  - Programs automatically get the newest version when they are restarted

Limitations of Shared Libraries

- Not all modules will work in a shared library?

  Why?
  - They cannot define/include global data storage
- They are read into program memory
  - Whether they are actually needed or not
- Called routines must be known at compile-time
  - Only the fetching of the code is delayed 'til run-time
  - Symbols known at compile time, bound at link time
- Dynamically Loadable Libraries are more general
  - They eliminate all of these limitations ... at a price

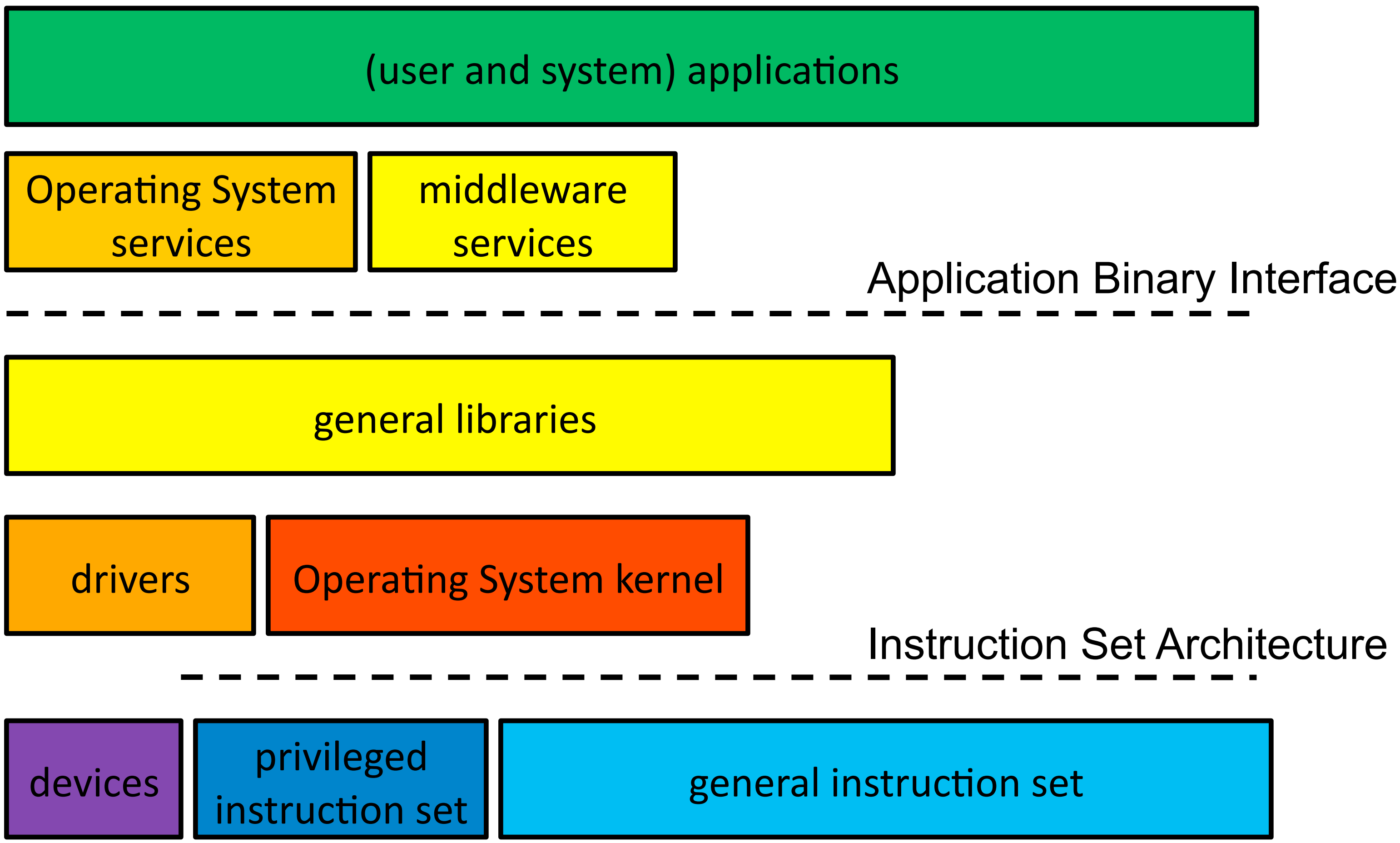
Service Delivery via System Calls

- Force an entry into the operating system
  - Parameters/returns similar to subroutine
  - Implementation is in shared/trusted kernel
- Advantages
  - Able to allocate/use new/privileged resources
  - Able to share/communicate with other processes
- Disadvantages
  - All implemented on the local node
  - 100x-1000x slower than subroutine calls

Layers: The Kernel

- Primarily functions that require privilege
  - Privileged instructions (e.g., interrupts, I/O)
  - Allocation of physical resources (e.g., memory)
  - Ensuring process privacy and containment
  - Ensuring the integrity of critical resources
- Some operations may be out-sourced
  - System daemons, server processes
- Some plug-ins may be less-trusted
  - Device drivers, file systems, network protocols

The Kernel Layer

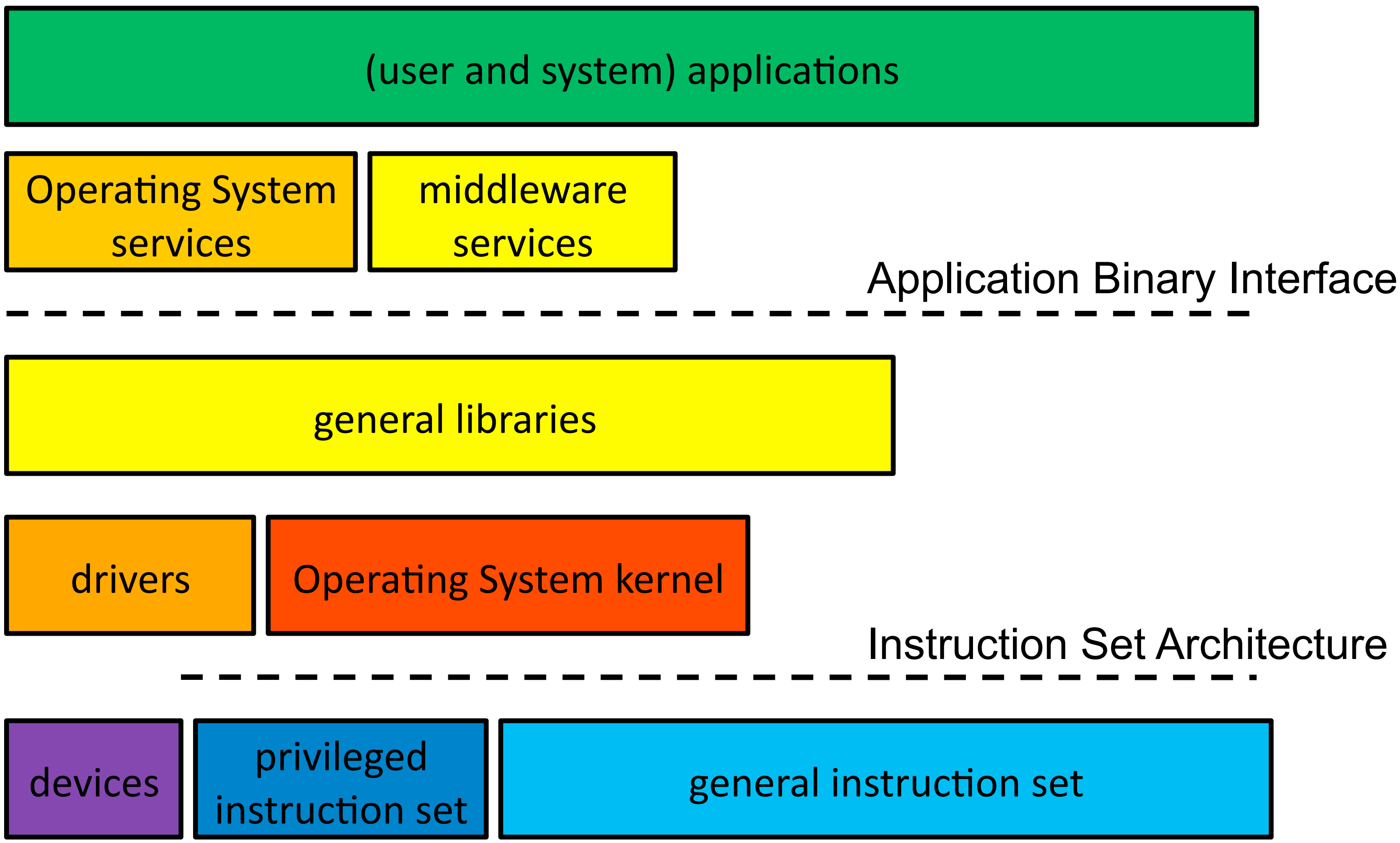


Layers: System Services

- Not all trusted code must be in the kernel
  - It may not … kernel data structures
  - It … privileged instructions
- Some … ewhat privileged processes
  - Login can create/set user credentials
  - Some can directly execute I/O operations
- Some are merely trusted
  - sendmail is trusted to properly label messages
  - NFS server is trusted to honor access control data

> What will we need to use these system service processes?

System Service Layer



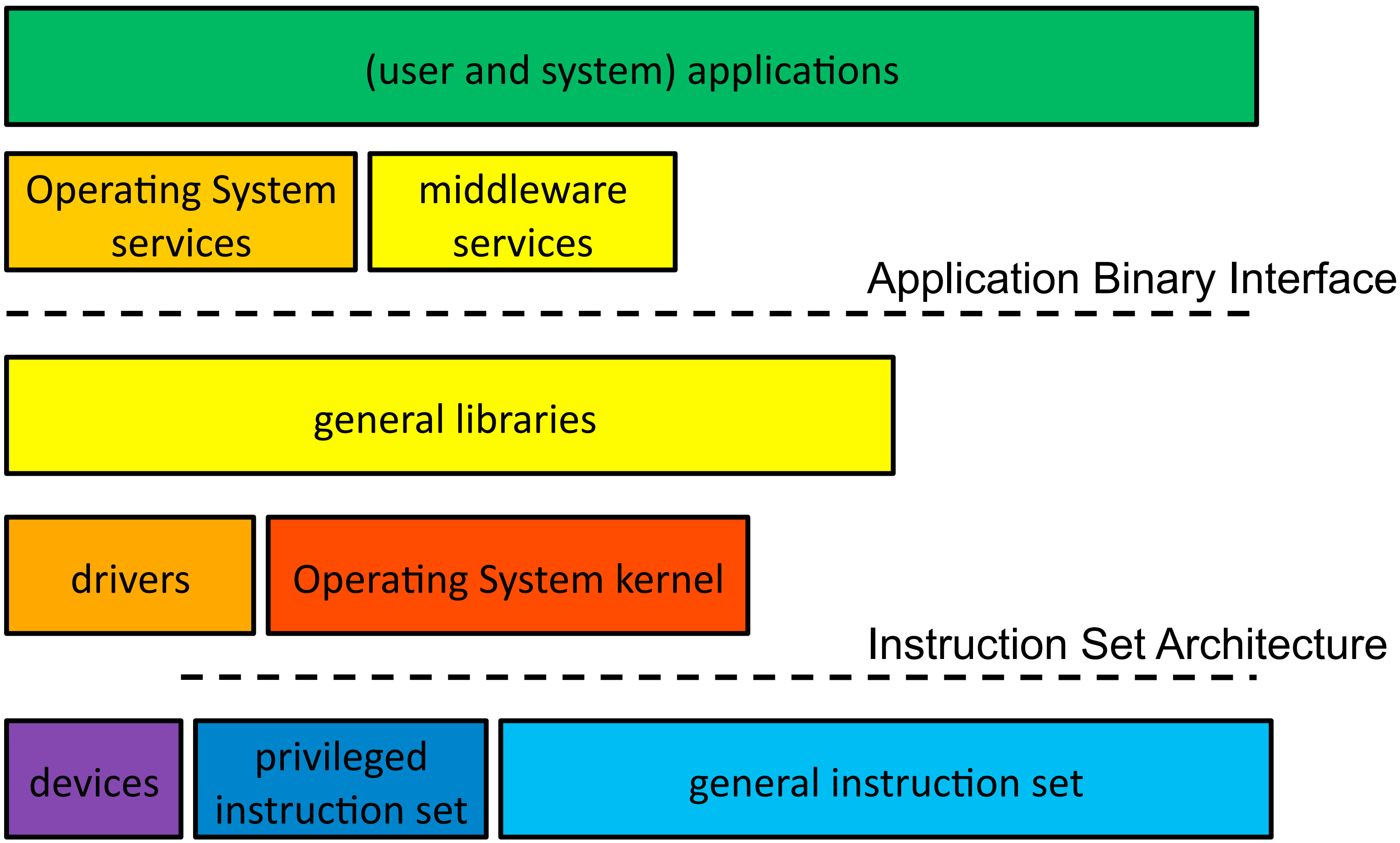
Service Delivery via Messages

- Exchange messages with a server (via syscalls)
  - Parameters in request, returns in response
- Advantages:
  - Server can be anywhere on earth
  - Service can be highly scalable and available
  - Service can be implemented in user-mode code
- Disadvantages:
  - 1,000x-100,000x slower than subroutine
  - Limited ability to operate on process resources

Layers: Middleware

- Software that is a key part of the application or service platform, but <u>not part of the OS</u>
  - Database, pub/sub messaging system
  - Apache, Nginx
  - Hadoop, Zookeeper, Beowulf, OpenStack
  - Cassandra, RAMCloud, Ceph, Gluster
- Kernel code is very expensive and dangerous
  - User-mode code is easier to build, test and debug
  - User-mode code is much more portable
  - User-mode code can crash and be restarted

The Middleware Layer



OS Interfaces

- Nobody buys a computer to run the OS
- The OS is meant to support other programs
  - Via its abstract services
- Usually intended to be very general
  - Supporting many different programs
- Interfaces are required between the OS and other programs to offer general services

Interfaces: APIs

- Application Program Interfaces
  - A source level interface, specifying:
    - Include files, data types, constants
    - Macros, routines and their parameters
- A basis for software portability
  - Recompile program for the desired architecture
  - Linkage edit with OS-specific libraries
  - Resulting binary runs on that architecture and OS
- An API compliant program will compile & run on any compliant system
  - APIs are primarily for programmers

Interfaces: ABIs

- Application Binary Interfaces
  - A binary interface, specifying:
    - Dynamically loadable libraries (DLLs)
    - Data formats, calling sequences, linkage conventions
  - The binding of an API to a hardware architecture
- A basis for binary compatibility
  - One binary serves all customers for that hardware
    - E.g. all x86 Linux/BSD/MacOS/Solaris/…
- An ABI compliant program will run (unmodified) on any compliant system
- ABIs are primarily for users

Why Does My OS Need to Support an ABI?

- Why not just support an API?
- Users would not like that much
- API-only compatibility requires them to obtain and compile their applications' sources
  - If it doesn't build, they have to debug it
- ABI compatibility allows merely loading and running the application (binary)
  - Of course, if it doesn't run, they're out of luck

User Mode Instruction Set vs. ABI

- Why distinguish the user mode instruction set from the Application Binary?
- The user mode instruction set is defined and implemented by hardware
  - It is thus ISA specific
- The Application Binary Interface is defined and implemented by software
  - It is thus OS specific
- Compilers generate code from the user-mode instruction set
- Code that exploits features in the Application Binary Interface is written by people (or higher level tools)

Libraries and Interfaces

- Normal libraries (shared and otherwise) are accessed through an API
  - Source-level definitions of how to access the library
  - Readily portable between different machines
- Dynamically loadable libraries also called through an API
  - But the dynamic loading mechanism is ABI-specific
  - Issues of word length, stack format, linkages, etc.

Other Important OS Interfaces

- Data formats and information encodings
  - Multi-media content (e.g. MP3, JPG)
  - Archival (e.g. tar, gzip)
  - File systems (e.g. DOS/FAT, ISO 9660)
- Protocols
  - Networking (e.g. ethernet, WLAN, TCP/IP)
  - Domain services (e.g. IMAP, LPD)
  - System management (e.g. DHCP, SNMP, LDAP)
  - Remote data access (e.g. FTP, HTTP, CIFS, S3)

Interfaces and Interoperability

- Strong, stable interfaces are key to allowing programs to operate together
- Also key to allowing OS evolution
- You don't want an OS upgrade to break your existing programs
- Which means the interface between the OS and those programs better not change

Interoperability Requires Stability

- No program is an island
  - Programs use system calls
  - Programs call library routines
  - Programs operate on external files
  - Programs exchange messages with other software
  - If interfaces change, programs fail
- API requirements are frozen at compile time
  - Execution platform must support those interfaces
  - All partners/services must support those protocols
  - All future upgrades must support older interfaces

Interoperability Requires Compliance

- Complete interoperability testing is impossible
  - Cannot test all applications on all platforms
  - Cannot test interoperability of all implementations
  - New apps and platforms are added continuously
- Instead, we focus on the interfaces
  - Interfaces are completely and rigorously specified
  - Standards bodies manage the interface definitions
  - Compliance suites validate the implementations
- And hope that sampled testing will suffice

Side Effects

- A *side effect* occurs when an action one object has non-obvious consequences
  - Perhaps even to other objects
  - Effects not specified by interfaces
- Often due to shared state between seemingly independent modules and functions
- Side effects lead to unexpected behaviors
- And the resulting bugs can be hard to find
- In other words, not good

Standards

- Different than interfaces
- Interfaces can differ from OS to OS
  - And machine to machine
- Standards are more global
- Either you follow a standard or you don't
  - If you do, others can work with you
  - If you don't, they can't

The Role of Standards

- There are many software standards
  - Subroutines, protocols and data formats, …
  - Both portability and interoperability
  - Some are general (e.g. POSIX 1003, TCP/IP)
  - Some are very domain specific (e.g. MPEG2)
- Key standards are widely required
  - Non-compliance reduces application capture
  - Non-compliance raises price to customers
- Bottom line: if you don’t meet the standard, your system isn’t used

Where Do Standards Stop?

- Why not just one browser for everyone?
- And just one image format?
- And just one email program?
- Those could be standards themselves
- Why not?
- Why not just bundle everything into the OS?

?

Abstractions

- Many things an operating system handles are complex
  - Often due to varieties of hardware, software, configurations
- Life is easy for application programmers and users if they work with a simple abstraction
- The operating system creates, manages, and exports such abstractions

Abstractions: An Object-Oriented View

- My execution platform implements *objects*
  - They may be bytes, longs, and strings
  - They may be processes, files, and sessions
- An object is defined by
  - Its properties, methods, and their semantics
- What makes a particular set of objects good?
  - They are powerful enough to do what I need
  - They don't force me to do a lot of extra work
  - They are simple enough for me to understand

Simplifying Abstractions

- Hardware is fast, but complex and limited
  - Using it correctly is extremely complex
  - It may not support the desired functionality
  - It is not a solution, but merely a building block
- Abstractions . . .
  - Encapsulate implementation details
    - Error handling, performance optimization
    - Eliminate behavior that is irrelevant to the user
  - Provide more convenient or powerful behavior
    - Operations better suited to user needs

Critical OS Abstractions

- The OS provides some core abstractions that our computational model relies on
  - And builds others on top of those
- Memory abstractions
- Processor abstractions
- Communications abstractions

Abstractions of Memory

- Many resources used by programs and people relate to data storage
  - Variables
  - Chunks of allocated memory
  - Files
  - Database records
  - Messages to be sent and received
- These all have some similar properties

The Basic Memory Operations

- Regardless of level or type, memory abstractions support a couple of operations
  - WRITE(name, value)
    - Put a value into a memory location specified by name
  - value <- READ(name)
    - Get a value out of a memory location specified by name
- Seems pretty simple
- But going from a nice abstraction to a physical implementation can be complex

Some Complicating Factors

- Persistent vs. transient memory
- Size of operations
  - Size the user/application wants to work with
  - Size the physical device actually works with
- Coherence and atomicity
- Latency
- Same abstraction might be implemented with many different physical devices
  - Possibly of very different types

Where Do the Complications Come From?

- At the bottom, the OS doesn't have abstract devices with arbitrary properties
- It has particular physical devices
  - With unchangeable, often inconvenient, properties
- The core OS abstraction problem:
  - Creating the abstract device with the desirable properties from the physical device without them

An Example

- A typical file
- We can read or write the file
- We can read or write arbitrary amounts of data
- If we write the file, we expect our next read to reflect the results of the write
  - *Coherence*
- If there are several reads/writes to the file, we expect each to occur in some order
  - With respect to the others

What Is Implementing the File?

- Commonly a hard disk drive
- Disk drives have peculiar characteristics
  - Long, and worse, variable access latencies
  - Accesses performed in chunks of fixed size
    - Atomicity only for accesses of that size
  - Highly variable performance depending on exactly what gets put where
  - Unpleasant failure modes
- So the operating system needs to smooth out these oddities

What Does That Lead To?

- Great effort by file system component of OS to put things in the right place on a disk
- Reordering of disk operations to improve performance
  - Which complicates providing atomicity
- Optimizations based on caching and read-ahead
  - Which complicates maintaining consistency
- Sophisticated organizations to handle failures

Abstractions of Interpreters

- An interpreter is something that performs commands
- Basically, the element of a computer (abstract or physical) that gets things done
- At the physical level, we have a processor
- That level is not easy to use
- The OS provides us with higher level interpreter abstractions

Basic Interpreter Components

- An instruction reference
  - Tells the interpreter which instruction to do next
- A repertoire
  - The set of things the interpreter can do
- An environment reference
  - Describes the current state on which the next instruction should be performed
- Interrupts
  - Situations in which the instruction reference pointer is overridden

An Example

- A process
- The OS maintains a program counter for the process
  - An instruction reference
- Its source code specifies its repertoire
- Its stack, heap, and register contents are its environment
  - With the OS maintaining pointers to all of them
- No other interpreters should be able to mess up the process' resources

Implementing the Process Abstraction in the OS

- Easy if there's only one process
- But there almost always are multiple processes
- The OS has a certain amount of physical memory
  – To hold the environment information
- There is usually only one set of registers
- The process doesn't have exclusive access to the CPU
  – Due to other processes

What Does That Lead To?

- Schedulers to share the CPU among various processes
- Memory management hardware and software
  - To multiplex memory use among the processes
  - Giving each the illusion of full exclusive use of memory
- Access control mechanisms for other memory abstractions
  - So other processes can't fiddle with my files

Abstractions of Communications

- A communication link allows one interpreter to talk to another
  - On the same or different machines
- At the physical level, memory and cables
- At more abstract levels, networks and interprocess communication mechanisms
- Some similarities to memory abstractions
  - But also differences

Basic Communication Link Operations

- SEND(link_name, outgoing_message_buffer)
  - Send some information contained in the buffer on the named link
- RECEIVE(link_name, incoming_message_buffer)
  - Read some information off the named link and put it into the buffer
- Like WRITE and READ, in some respects

Why Are Communication Links Distinct From Memory?

- Highly variable performance
- Often asynchronous
  - And usually issues with synchronizing the parties
- Receiver may only perform the operation because the SEND occurred
  - Unlike a typical READ
- Additional complications when working with a remote machine

An Example Communications Link

- A Unix-style socket
- SEND interface:
  - `send(int sockfd, const void *buf, size_t len, int flags)`
  - The `sockfd` is the link name
  - The `buf` is the outgoing message buffer
- RECEIVE interface:
  - `recv(int sockfd, void *buf, size_t len, int flags)`
  - Same parameters as for send

Implementing the Communications Link Abstraction in the OS

- Easy if both ends are on the same machine
  - Not so easy if they aren't
- On same machine, use memory to perform the transfer
  - Either copy the message from sender's memory to receiver's
  - Or transfer control of memory containing the message from sender to receiver
- Again, more complicated when remote

Generalizing Abstractions

- How can applications deal with many varied resources?
- Make many different things appear the same
  - Applications can all deal with a single class
  - Often Lowest Common Denominator + sub-classes
- Requires a common/unifying model
  - Portable Document Format (PDF) for printed output
  - SCSI/SATA/SAS standard for disks, CDs, SSDs
- Usually involves a *federation framework*

Federation Frameworks

- A structure that allows many similar, but somewhat different, things to be treated uniformly
- By creating one interface that all must meet
- Then plugging in implementations for the particular things you have
- E.g., make all hard disk drives accept the same commands
  - Even though you have 5 different models installed

Are Federation Frameworks Too Limiting?

- Does the common model have to be the "lowest common denominator"?
- Not necessarily
  - The model can include "optional features",
    - Which (if present) are implemented in a standard way
    - But may not always be present (and can be tested for)
- Many devices will have features that cannot be exploited through the common model
  - There are arguments for and against the value of such features

Abstractions and Layering

- It's common to create increasingly complex services by layering abstractions
  - E.g., a file system layers on top of an abstract disk, which layers on top of a real disk
- Layering allows good modularity
  - Easy to build multiple services on a lower layer
    - E.g., multiple file systems on one disk
  - Easy to use multiple underlying services to support a higher layer
  - E.g., file system can have either a single disk or a RAID below it

A Downside of Layering

- Layers typically add performance penalties
- Often expensive to go from one layer to the next
  - Since it frequently requires changing data structures or representations
  - At least involves extra instructions
- Another downside is that lower layer may limit what the upper layer can do
  - E.g., an abstract disk prevents disk operation reorderings to maximize performance

Other OS Abstractions

- There are many other abstractions offered by the OS
- Often they provide different ways of achieving similar goals
  - Some higher level, some lower level
- The OS must do work to provide each abstraction
  - The higher level, the more work
- Programmers and users have to choose the right abstractions to work with