CS354
Operating Systems

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Module I

Course Overview
And
Introduction To Operating Systems

COURSE MOTIVATION AND SCOPE

Scope

This is a course about the design and structure of computer operating systems. It covers the concepts, principles, functionality, tradeoffs, and implementation of systems that support concurrent processing.

What We Will Cover

- Operating system fundamentals
- Functionality an operating system offers
- Major system components
- Interdependencies and system structure
- The key relationships between operating system abstractions and the underlying hardware (especially processes and interrupts)
- A few implementation details and examples

What You Will Learn

- Fundamental
  - Principles
  - Design options
  - Tradeoffs
- How to modify and test operating system code
- How to design and build an operating system

What We Will NOT Cover

- A comparison of large commercial and open source operating systems
- A description of features or instructions on how to use a particular commercial system
- A survey of research systems and alternative approaches that have been studied
- A set of techniques for building operating systems on unusual hardware

How Operating Systems Changed Programming

- Before operating systems
  - Only one application could run at any time
  - The application contained code to control specific I/O devices
  - The application had to overlap I/O and processing
- Once an operating system was in place
  - Multiple applications could run at the same time
  - An application is not built for specific I/O devices
  - A programmer does not need to overlap I/O and processing
  - An application is written without regard to other applications

Why Operating Systems Are Difficult To Build

- The gap between hardware and high-level services is huge
  - Hardware is ugly
  - Operating system abstractions are beautiful
- Everything is now connected by computer networks
  - An operating system must offer communication facilities
  - Distributed mechanisms (e.g., remote file access) are more difficult to create than local mechanisms

An Observation About Efficiency

- Our job in Computer Science is to build beautiful new abstractions that programmers can use
- It is easy to imagine magical new abstractions
- The hard part is that we must find abstractions that map onto the underlying hardware efficiently
- We hope that hardware engineers eventually build hardware for our abstractions (or at least build hardware that makes out abstractions more efficient)

The Once And Future Hot Topic

- In the 1970s and early 1980s, operating systems was one of the hottest topics in CS
- By the mid-1990s, OS research had stagnated
- Now things have heated up again, and new operating systems are being designed for
  - Smart phones
  - Multicore systems
  - Data centers
  - Large and small embedded devices (the Internet of Things)

XINU AND THE LAB

Motivation For Studying A Real Operating System

- Provides examples of the principles
- Makes everything clear and concrete
- Shows how abstractions map to current hardware
- Gives students a chance to experiment and gain first-hand experience

Can We Study Commercial Systems?

- Windows
  - Millions of line of code
  - Proprietary
- Linux
  - Millions of line of code
  - Lack of consistency across modules
  - Duplication of functionality with slight variants

An Alternative: Xinu

- Small — can be read and understood in a semester
- Complete — includes all the major components
- Elegant — provides an excellent example of clean design
- Powerful — has dynamic process creation, dynamic memory management, flexible I/O, and basic Internet protocols
- Practical — has been used in real products

The Xinu Lab

- Innovative facility for rapid OS development and testing
- Allows each student to create, download, and run code on bare hardware
- Completely automated
- Handles hardware reboot when necessary
- Provides communication to the Internet as well as among computers in the lab

How The Xinu Lab Works

- A student
  - Logs into a conventional desktop system called a *front-end*
  - Modifies and compiles a version of the Xinu OS
  - Requests a computer to use for testing
- Lab software
  - Allocates one of the *back-end* computers for the student to use
  - Downloads the student's Xinu code into the back-end
  - Connects the console from the back-end to the student's window
  - Allows the student to release the back-end for others to use

REQUIRED BACKGROUND AND PREREQUISITES

Background Needed

- A few concepts from earlier courses
  - I/O: you should know the difference between standard library functions (e.g., *fopen*, *putc*, *getc*, *fread*, *fwrite*) and system calls (e.g., *open*, *close*, *read*, *write*)
  - File systems and hierarchical directories
  - Symbolic and hard links
  - File modes and protection
- Concurrent programming experience: you should have written a program that uses *fork* or *threads*

Background Needed
(continued)

- An understanding of runtime storage components
  - Segments (text, data, and bss) and their layout
  - Runtime stack used for function call; argument passing
  - Basic heap storage management (malloc and free)
- C programming
  - At least one nontrivial program
  - Comfortable with low-level constructs (e.g., bit manipulation and pointers)

Background Needed
(continued)

- Working knowledge of basic UNIX tools (needed for programming assignments)
  - Text editor (e.g., emacs)
  - Compiler / linker / loader
  - Tar archives
  - Make and Makefiles
- Desire to learn

How We Will Proceed

- We will examine the major components of an operating system
- For a given component we will
  - Outline the functionality it provides
  - Understand principles involved
  - Study one particular design choice in depth
  - Consider implementation details and the relationship to hardware
  - Quickly review other possibilities and tradeoffs
- Note: we will cover components in a linear order that allows us to understand one component at a time without relying on later components

Introduction To Operating Systems (Definitions And Functionality)

What Is An Operating System?

- Answer: a large piece of sophisticated software that provides an abstract computing environment
- An OS manages resources and supplies computational services
- An OS hides low-level hardware details from programmers
- Note: operating system software is among the most complex ever devised

Example Services An OS Supplies

- Support for concurrent execution (multiple apps running at the same time)
- Process synchronization
- Process-to-process communication mechanisms
- Process-to-process message passing and asynchronous events
- Management of address spaces and virtual memory support
- Protection among users and running applications
- High-level interface for I/O devices
- File systems and file access facilities
- Internet communication

What An Operating System Is NOT

- A hardware mechanism
- A programming language
- A compiler
- A windowing system or a browser
- A command interpreter
- A library of utility functions
- A graphical desktop

AN OPERATING SYSTEM FROM THE OUTSIDE

The System Interface

- A single copy of the OS runs at any time
  - Hidden from users
  - Accessible only to application programs
- The *Application Program Interface (API)*
  - Defines services OS makes available
  - Defines arguments for the services
  - Provides access to OS abstractions and services
  - Hides hardware details

OS Abstractions And The Application Interface

Two types of chips
ASIC: application-specific integrated circuit
application is not stored in RAM but built in CPU, super fast but not easily edible
Universal Computer: program and data can be stored in RAM

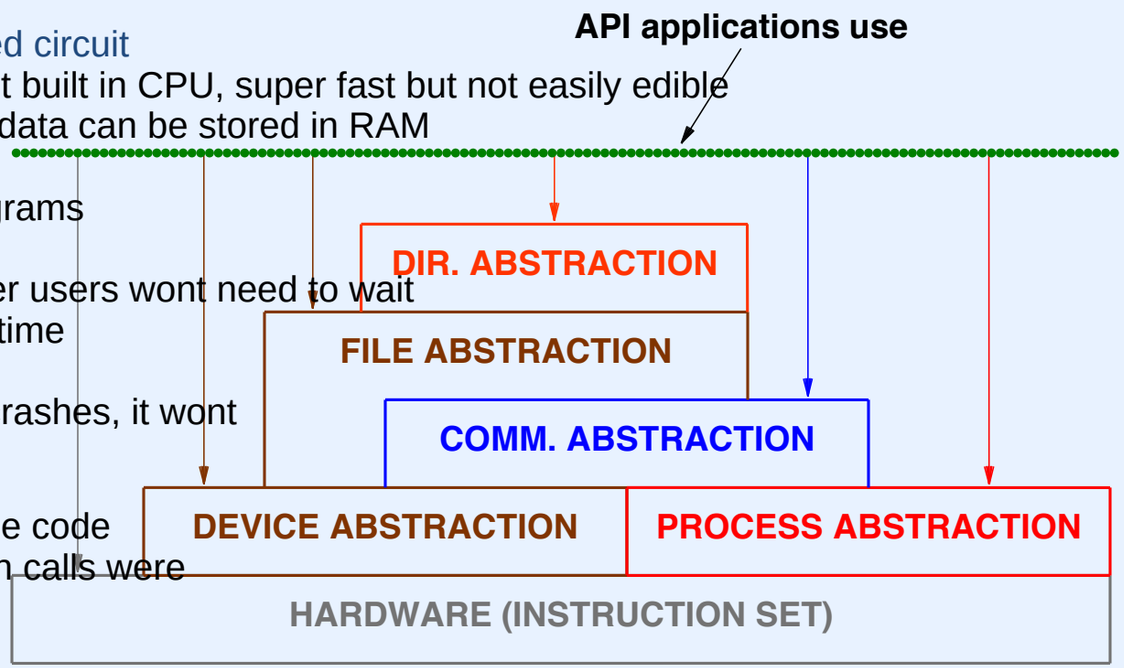
Main memory stores data and programs

Scheduling: context switch, so other users wont need to wait if one user's program takes a long time

isolation program: if one program crashes, it wont effect other processes

70s -80s programmers use machine code "goto" which is buggy, then function calls were promoted.

A running program is called a process



- Modules in the OS offer services to applications
- Internally, some services build on others

machine has CPU runs instruction set (software)
machine has memory (registers)

RAM has address that is 1 byte each
One byte is eight bits
So 32-bit system delivers 4 bytes (32-bits) a time
RAM is violtile, erase when power is down
hard disk is persistent
OS code cannot be stored in SSD, otherwise we need to copy it into RM first

frontend compiles and links and creates xinu.xbin. then send the OS code to xboot and xboot assign a backend and run the OS code

Interface To System Services

- Appears to operate like a function call mechanism
  - OS makes set of “functions” available to applications
  - Application supplies arguments using standard mechanism
  - Application “calls” an OS function to access a service
- Control transfers to OS code that implements the function
- Control returns to caller when function completes

Run-time stack in RAM (where local variables are and communicate arguments)
code(text) + data + stack
stack is a run-time resources
SP (stack pointer) a designated pointer that points to the address of stack area of current running program
because if abc(){
  def(5, 10)
}
abc was given a memory area in stack called stack frame
when it calls def, def now also gets a stack frame
once def returns, the stack area given to def is now gone

CDECL

Interface To System Services
(continued)

- Requires a special hardware instruction to invoke an OS function
  - Moves from the application's *address space* to OS's address space
  - Changes from application *mode* or *privilege level* to OS mode
- Terminology used by various hardware vendors
  - *System call*
  - *Trap*
  - *Supervisor call*
- We will use the generic term *system call*

An Example Of System Call In Xinu: Write A Character On The Console

```
/* ex1.c - main */

#include <xinu.h>

/*------------------------------------------------------------------------
 * main  -  Write "hi" on the console
 *------------------------------------------------------------------------
 */
void    main(void)
{
        putc(CONSOLE, 'h');
        putc(CONSOLE, 'i');
        putc(CONSOLE, '\n');
}
```

alternative in Linux

```
char a;
a = 'h';
write(1,&a,1);
a = 'i';
write(1,&a,1);
a = '\n';
write(1,&a,1);
```

- Note: we will discuss the implementation of *putc* later

OS Services And System Calls

- Each OS service accessed through system call interface
- Most services employ a set of several system calls
- Examples
  - Process management service includes functions to *suspend* and then *resume* a process
  - *Socket API* used for Internet communication includes many functions

System Calls Used With I/O

- Open-close-read-write paradigm
- Application
  - Uses *open* to connect to a file or device
  - Calls functions to *write* data or *read* data
  - Calls *close* to terminate use
- Internally, the set of I/O functions coordinate
  - *Open* returns a descriptor, *d*
  - *Read* and *write* operate on descriptor *d*

Concurrent Processing

- Fundamental concept that dominates OS design
- *Real concurrency* is only achieved when hardware operates in parallel
  - I/O devices operate at same time as processor
  - Multiple processors/cores each operate at the same time
- *Apparent concurrency* is achieved with *multitasking* (aka *multiprogramming*)
  - Multiple programs appear to operate simultaneously
  - The most fundamental role of an operating system

How Multitasking Works

- User(s) start multiple computations running
- The OS switches processor(s) among available computations quickly
- To a human, all computations appear to proceed in parallel

Terminology

- A *program* consists of static code and data
- A *function* is a unit of application program code
- A *process* (also called a *thread of execution*) is an active computation (i.e., the execution or "running" of a program)

A Process

- Is an OS abstraction
- Can be created when needed (an OS system call allows a running process to create a new process)
- Is managed entirely by the OS and is unknown to the hardware
- Operates concurrently with other processes

process upon created is running in user mode
when it makes system call
it changes to kernel mode (hardware)

Example Of Process Creation In Xinu (Part 1)

```
/* ex2.c - main, sndA, sndB */

#include <xinu.h>

void    sndA(void), sndB(void);

/*------------------------------------------------------------------------
 * main  -  Example of creating processes in Xinu
 *------------------------------------------------------------------------
 */
void    main(void)
{
        resume( create(sndA, 1024, 20, "process 1", 0) );
        resume( create(sndB, 1024, 20, "process 2", 0) );
}

/*------------------------------------------------------------------------
 * sndA  -  Repeatedly emit 'A' on the console without terminating
 *------------------------------------------------------------------------
 */
void    sndA(void)
{
        while( 1 )
                putc(CONSOLE, 'A');
}
```

function, size of stack to allocate, priority, text string, num of args

when process created, process is suspended, resume makes a process ready

once sendB is created and resumed, sendB will always run if it has the highest prior and has a while loop that runs forever. So sendA cant run and A will never be printed

if processes have the same prior, everyone gets to run for a while (run robin?)

Example Of Process Creation In Xinu (Part 2)

```
/*------------------------------------------------------------------------
 * sndB  -  Repeatedly emit 'B' on the console without terminating
 *------------------------------------------------------------------------
 */
void    sndB(void)
{
        while( 1 )
                putc(CONSOLE, 'B');
}
```

The Difference Between Function Call And Process Creation

- A normal function call
  - Only involves a single computation
  - Executes synchronously (caller waits until the call returns)
- The *create* system call
  - Starts a new process and returns
  - Both the old process and the new process proceed to run after the call

The Distinction Between A Program And A Process

- A sequential program is
  - Declared explicitly in the code (e.g., with the name *main*)
  - Is executed by a single thread of control
- A process
  - Is an OS abstractions that is not visible in a programming language
  - Is created independent of code that is executed
  - Important idea: multiple processes can execute the same code concurrently
- In the following example, two processes execute function *sndch* concurrently

Example Of Two Processes Running The Same Code

```
/* ex3.c - main, sndch */

#include <xinu.h>

void    sndch(char);

/*------------------------------------------------------------------------
 * main  -  Example of 2 processes executing the same code concurrently
 *------------------------------------------------------------------------
 */
void    main(void)
{
        resume( create(sndch, 1024, 20, "send A", 1, 'A') );
        resume( create(sndch, 1024, 20, "send B", 1, 'B') );
}

/*------------------------------------------------------------------------
 * sndch  -  Output a character on a serial device indefinitely
 *------------------------------------------------------------------------
 */
void    sndch(
          char  ch              /* The character to emit continuously   */
        )
{
        while ( 1 )
                putc(CONSOLE, ch);
}
```

Storage Allocation When Multiple Processes Execute

- Various memory models exist for concurrent processes
- Each process requires its own storage for
  - A runtime stack of function calls
  - Local variables
  - Copies of arguments passed to functions
- A process *may* have private heap storage as well

Consequence For Programmers

A copy of function arguments and local variables is associated with each process executing a particular function, *not* with the code in which the variables and arguments are declared.

AN OPERATING SYSTEM FROM THE INSIDE

Operating System Properties

- An OS contains well-understood subsystems
- An OS must handle dynamic situations (processes come and go)
- Unlike most applications, an OS uses a heuristic approach
  - A heuristic can have corner cases
  - Policies from one subsystem can conflict with policies from others
- Complexity arises from interactions among subsystems, and the side-effects can be
  - Unintended
  - Unanticipated, even by the OS designer
- We will see examples

Building An Operating System

Building An Operating System

- The intellectual challenge comes from the design of a "system" rather than from the design of individual pieces
- Structured design is needed
- It can be difficult to understand the consequences of individual choices
- We will study a hierarchical microkernel design that helps control complexity and provides a unifying architecture

Major OS Components

- Process manager
- Memory manager
- Device manger
- Clock (time) manager
- File manager
- Interprocess communication system
- Intermachine communication system
- Assessment and accounting

Our Multilevel Structure

- Organizes all components
- Controls interactions among subsystems
- Allows an OS to be understood and built incrementally
- Differs from a traditional layered approach
- Will be employed as the design paradigm throughout the text and course

Multilevel Vs. Multilayered Organization

Xinu's approach

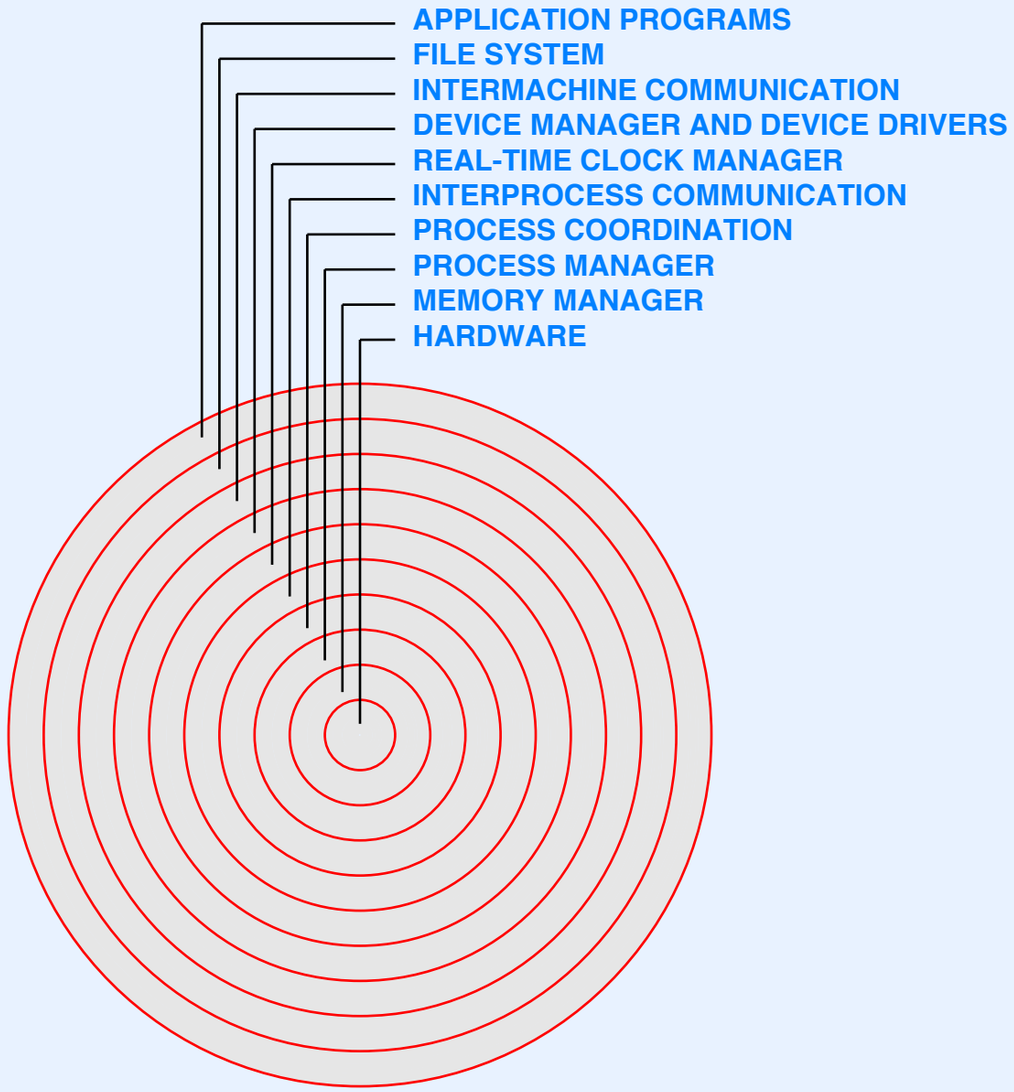
unefficient: a layer can only talks to a level above and a level below

- Multilayer structure
  - Visible to the user as well as designer
  - Software at a given layer only uses software at the layer directly beneath
  - Examples
    * Internet protocol layering
    * MULTICS layered security structure
- Can be extremely inefficient

Multilevel Vs. Multilayered Organization
(continued)

- Multilevel structure
  - Separates all software into multiple levels
  - Allows software at a given level to use software at *all* lower levels
  - Especially helpful during system construction
  - Focuses a designer's attention on one aspect of the OS at a time
  - Helps keeps policy decisions independent and manageable
  - Is efficient

Multilevel Structure Of Xinu



How To Understand An OS

- Use the same approach as when designing a system
- Work one level at a time
- Understand the service to be provided at the level
- Consider the overall *goal* for the service
- Examine the *policies* that are used to achieve the goal
- Study the *mechanisms* that enforce the policies
- Look at an *implementation* that runs on specific hardware

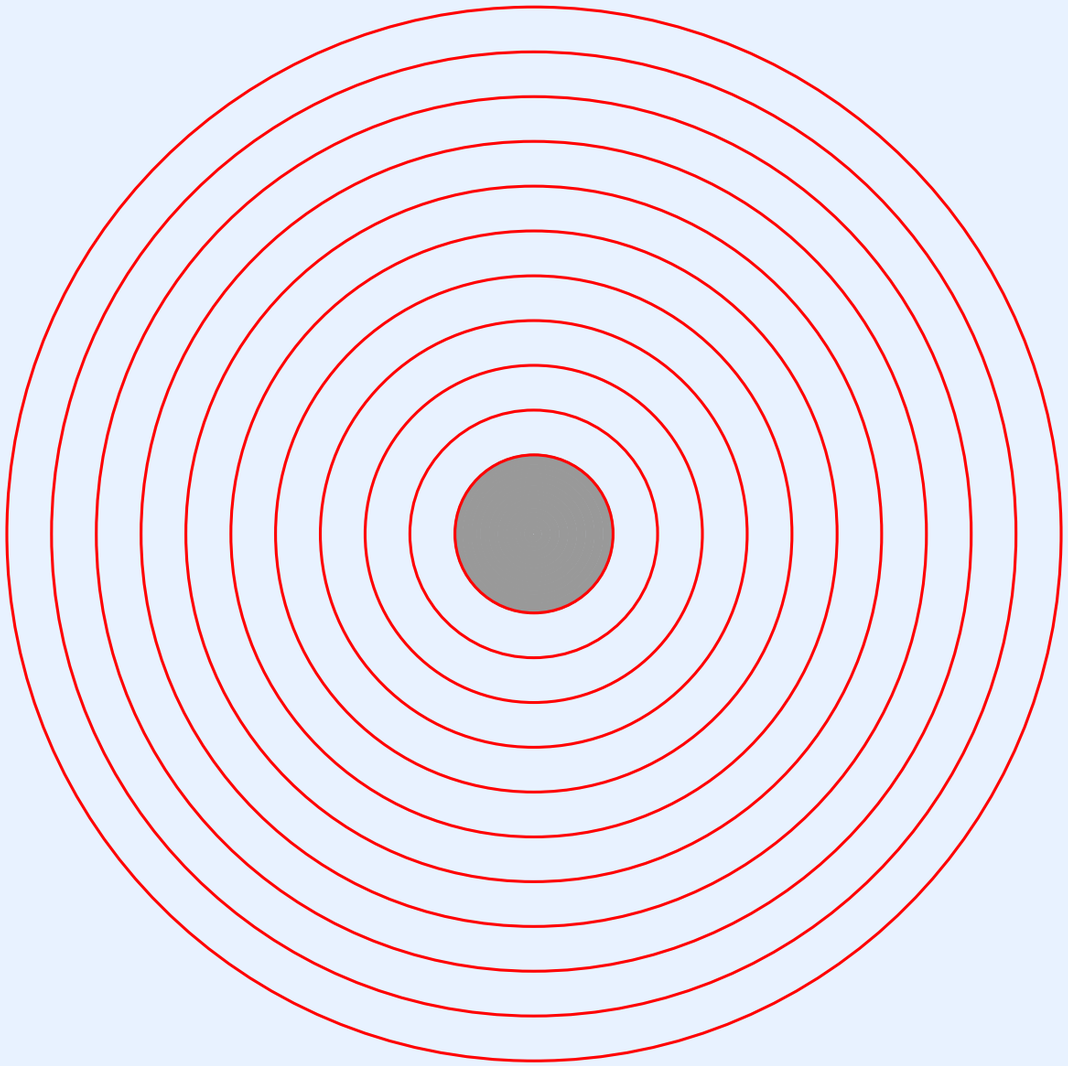
A Design Example

- Example: access to I/O
- Goal: “fairness”
- Policy: First-Come-First-Served access to a given I/O device
- Mechanism: a queue of pending requests (FIFO order) first in first out
- Implementation: program written in C

Module II

Quick Review Of Hardware And Runtime Features
Process Management:
Scheduling And Context Switching

Location Of Hardware In The Hierarchy



Hardware Features An OS Uses Directly

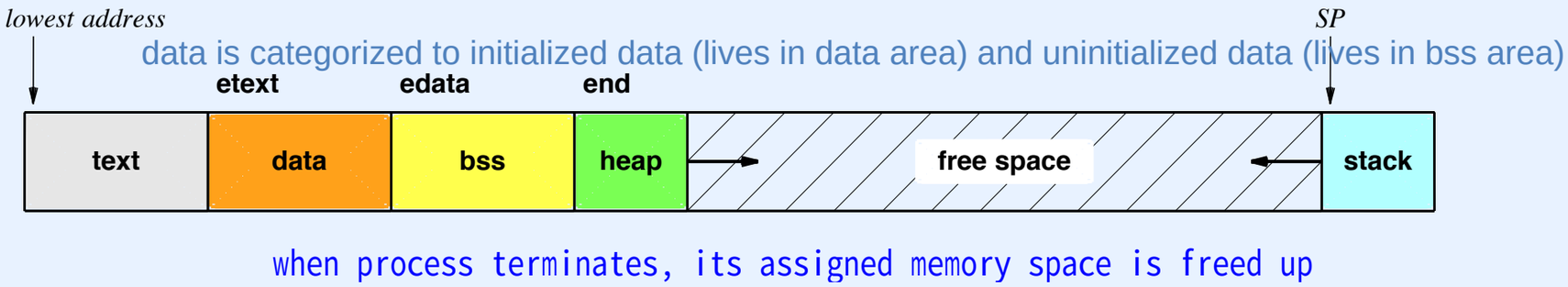
- The processor's *instruction set*
- The *general-purpose registers*
  - Used for computation
  - Saved and restored during subprogram invocation
- The main memory system
  - Consists of an array of bytes
  - Holds code as well as data
  - Imposes endianness for integers
  - May provide address mapping for virtual memory

Hardware Features An OS Uses Directly
(continued)

- I/O devices
  - Accessed over a bus
  - Can be *port-mapped* or *memory-mapped* (we will see more later)
- Calling Conventions
  - The set of steps taken during a function call
  - The hardware specifies ways that function calls can operate; a compiler may choose among possible variants

Run-Time Features Pertinent To An OS

- A program is compiled into four segments in memory: text, data, bss, stack



when process terminates, its assigned memory space is freed up

- The stack grows downward (toward lower memory addresses)
- The heap grows upward

Run-Time Features Pertinent To An OS (continued)

Next topic:
isolation/protection:
prevent a program crash to negatively impact the rest of the system
now: make sure every process has firewall (sandbox): isolate corrupted process from nearby processes
xinu approach: kernel mode + user mode
whenever a bug occurs, it occurs in user mode

- A compiler includes global variable names that a program can use to find segment addresses
  - Symbol *etext* lies beyond text segment
  - Symbol *edata* lies beyond data segment
  - Symbol *end* lies beyond bss segment

sychronus: current instruction causes interrupts
asychronus: I/O devices trigger interrupts
common interrupts are specified names (e,g. divide by zero)

IDT: (interrupt descripter table) In ram there is an interrupt table with 256 rows each 8 bytes long (support up to 256 interrupts)
In each interrupt space: it has a function pointer: points to the address or label of interrupts handler kernel function to resolve interrupts

4 features:
1kernel mode/ user mode
process is always in user mode (only make system call that can enter kernel mode and run the system call which is programmed by competent programmers)

- A programmer can access the names by declaring them *extern*

2Trap instruction (handle hardware interrupts)

```
extern  int   end;
```

3memory protection: a process cannot read from memory spaces belong to another process

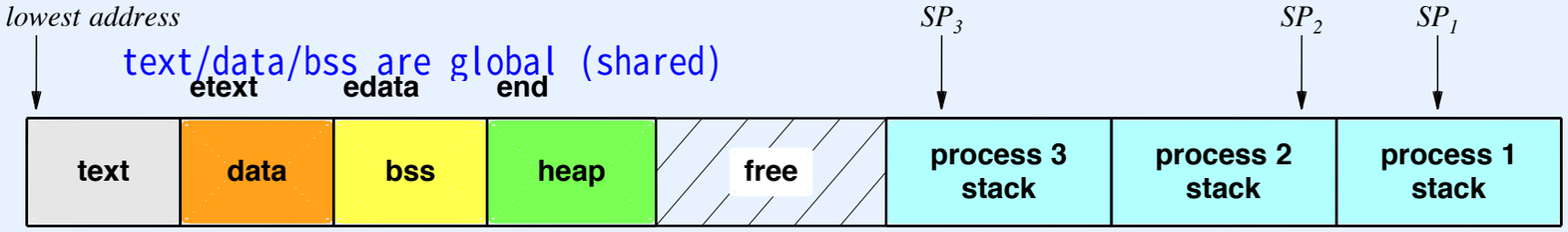
- Only the addresses are significant; the values are irrelevant
- Note: in assembly language, external names have an underscore prepended (e.g., *_end*)

in linux/unix, process memory spaces are disjointed

cpu:
fetch the next instruction
decode (figure out what to do)
execute

Runtime Storage For Xinu Processes

stack per process, runtime stacks are private



- All processes share
  - A single text segment
  - A single data segment
  - A single bss segment
- Each process has its own stack segment
  - The stack for a process is allocated when the process is created
  - The stack for a process is released when the process terminates

copy binary(x.xbin) into ssd memory -> start BOIS: basic input output system (that checks all conditions)-> when passing, start boot loader (GRUB)->OS starts
network boot: compile a new image, and through ethernet load the image into backend.
Xboot: combines network boot and boot loader
when x86 turns on, it start in real mode then transit to protected mode
when Xinu is loaded into memory, Xinus runs start.S inside system/ -> call nulluser() inside initialize.c, that calls create(...,startup,...)., then startup calls create(main,....)

kernel (OS) contains two subsystem, then upperhalf (closes to software level, the app process makes system call) and lowerhalf (closer to the hardware level, hardware issues interrupts, disk, cpu)
when Xinu makes system call, it switchs to kernel mode, when its done, switch back to user mode
also when hardware issues interrupes, OS will switchs to kernel mode