Syscalls, exceptions, and interrupts, …oh my!

CS 3410
Computer System Organization & Programming

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Clicker Question

Which of the following is **not** a viable solution to protect against a buffer overflow attack?
(There are *multiple* right & wrong answers. Pick 1 right one.)

(A) Prohibit the execution of anything stored on the Stack.
(B) Randomize the starting location of the Stack.
(C) Use only library code that requires a buffer length to make sure it doesn't overflow.
(D) Write only to buffers on the OS Stack where they will be protected.
(E) Compile the executable with the highest level of optimization flags.

November 1988: Internet Worm

Internet Worm attacks thousands of Internet hosts

Best Wikipedia quotes:

“According to its creator, the Morris worm was not written to cause damage, but to gauge the size of the Internet. The worm was released from MIT to disguise the fact that the worm originally came from Cornell.”

“The worm …determined whether to invade a new computer by asking whether there was already a copy running. But just doing this would have made it trivially easy to kill: everyone could run a process that would always answer "yes”. To compensate for this possibility, Morris directed the worm to copy itself even if the response is "yes" 1 out of 7 times. This level of replication proved excessive, and the worm spread rapidly, infecting some computers multiple times. Morris remarked, when he heard of the mistake, that he "should have tried it on a simulator first”.”

Computer Virus TV News Report 1988

Operating System

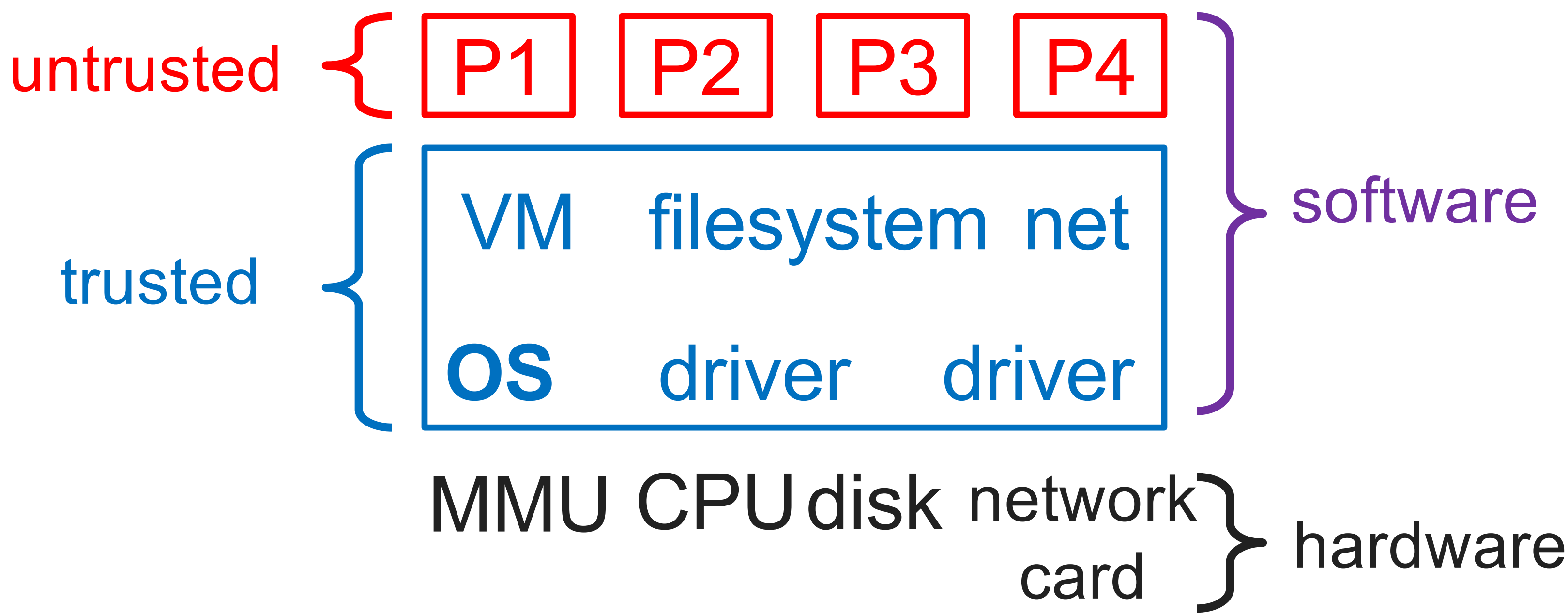
- Manages all of the software and hardware on the computer
- Many processes running at the same time, requiring resources
  - CPU, Memory, Storage, *etc.*

OS multiplexes these resources amongst different processes, and isolates and protects processes from one another!

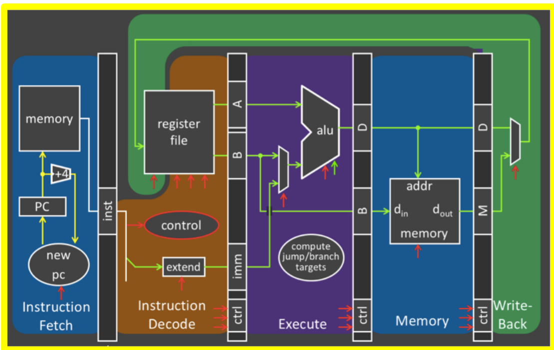
Operating System

Operating System (OS) is a trusted mediator:

- *Safe control transfer between processes*
- *Isolation (memory, registers) of processes*



One Brain, Many Personalities



Brain

You are what you execute.

Personalities:

hailstone_recursive

Microsoft Word

Minecraft

Linux ← *yes, this is just software like every other program that runs on the CPU*

Are they all equal?

Trusted vs. Untrusted

- Only trusted processes should access & change important things
  - Editing TLB, Page Tables, OS code, OS $sp, OS $fp…

- If an untrusted process could change the OS' $sp/$fp/$gp/*etc.*, OS would crash!

Privileged Mode

CPU Mode Bit in Process Status Register

- Many bits about the current process
  (Mode bit is just one of them)

0 = user mode = untrusted

  "Privileged" instructions and registers are disabled by CPU

1 = kernel mode = trusted

  All instructions and registers are enabled

MIPS Privileged Instructions

Table 3-22 Privileged Instructions

Mnemonic	Instruction
CACHE	Perform Cache Operation
ERET	Exception Return
MFC0	Move from Coprocessor 0
MTC0	Move to Coprocessor 0
TLBP	Probe TLB for Matching Entry
TLBR	Read Indexed TLB Entry
TLBWI	Write Indexed TLB Entry
TLBWR	Write Random TLB Entry
WAIT	Enter Standby Mode

Privileged Mode at Startup

1. Boot sequence
   - load first sector of disk (containing OS code) to predetermined address in memory
   - Mode ← 1; PC ← predetermined address

2. OS takes over
   - initializes devices, MMU, timers, etc.
   - loads programs from disk, sets up page tables, *etc.*
   - Mode ← 0; PC ← program entry point
     – User programs regularly yield control back to OS

Users need access to resources

If an untrusted process does not have privileges to use system resources, how can it

- Use the screen to print?
- Send message on the network?
- Allocate pages?
- Schedule processes?

Solution: System Calls

System Call Examples

`putc()`: print character to screen

- Need to multiplex screen between competing processes

`send()`: send a packet on the network

- Need to manipulate the internals of a device

`sbrk()`: allocate a page

- Needs to update page tables & MMU

`sleep()`: put current program to sleep, wake another

- Need to update page table base register

System Calls

System call: **not** just a function call

- Don’t let process jump just anywhere in OS code
- OS can’t trust process’ registers (sp, fp, gp, etc.)

SYSCALL insn: safe control transfer to OS

MIPS system call convention:

- Exception handler saves temp regs, saves ra, …
- $v0 = system call number, which specifies the operation the application is requesting

Libraries and Wrappers

Compilers do not emit SYSCALL instructions

- Compiler doesn't know OS interface

Libraries implement standard API from system API

libc (standard C library):

- gets() → getc()
- getc() → syscall
- sbrk() → syscall
- printf() → write()
- write() → syscall
- malloc() → sbrk()
- …

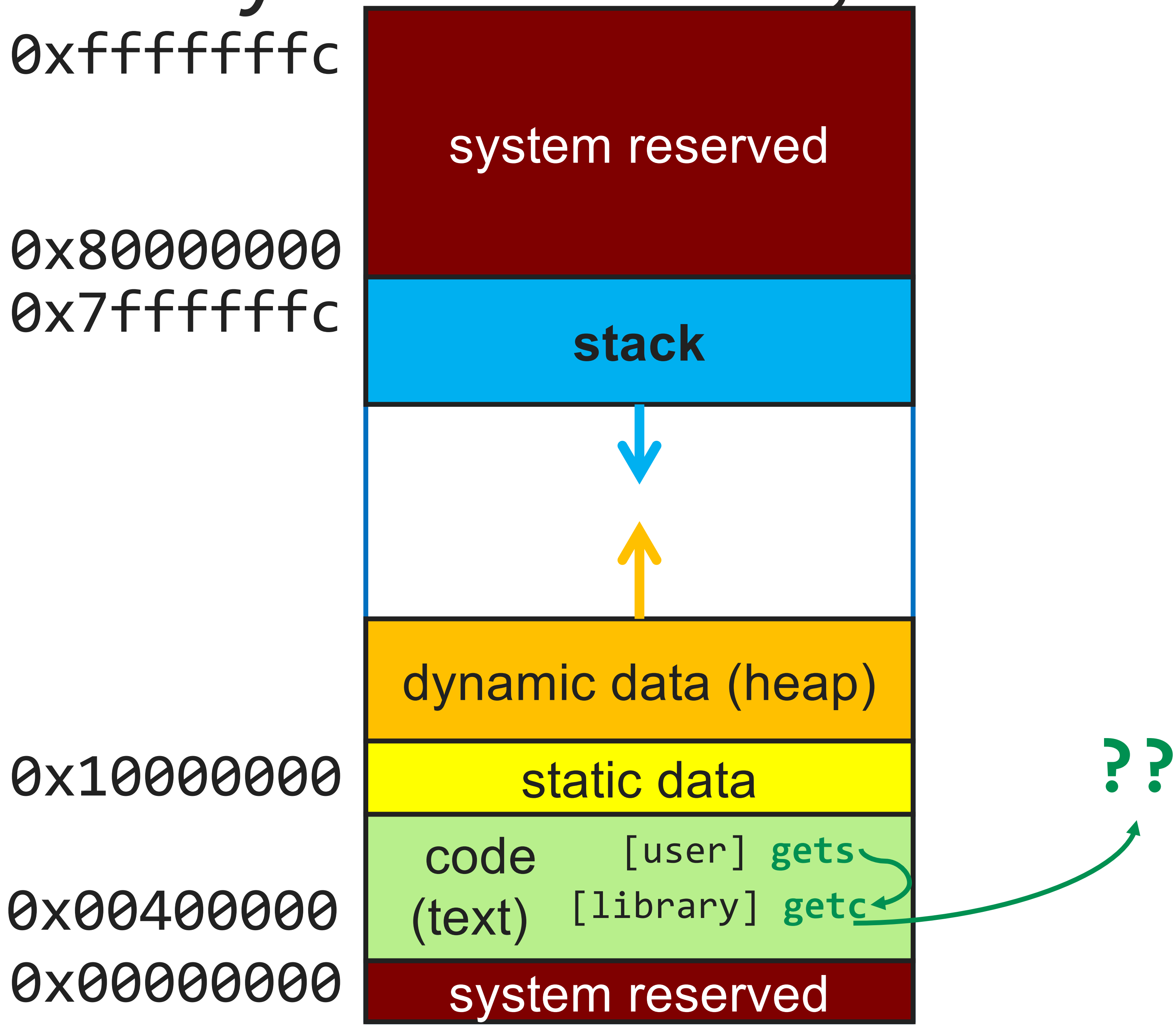
Invoking System Calls

```
char *gets(char *buf) {
  while (...) {
    buf[i] = getc();
  }
}

int getc() {
  asm("addiu $v0, $0, 4");
  asm("syscall");
}
```

4 is number for getc syscall

Anatomy of a Process, v1



Clicker Questions

Where are the following program components located?

A. System Reserved
B. Stack
C. Heap
D. Data
E. Text

```
char big_array[1«24];
char *p1, *p2;

int main()
{
    int beyond;

    p1 = malloc(1 «28);
    p2 = malloc(1 « 8);
}
```

1) P1
2) the address that p1 points to
3) malloc()
4) main()
5) beyond
6) big_array

Where does the OS live?

In its own address space?

- Syscall has to switch to a different address space
- Hard to support syscall arguments passed as pointers

. . . So, NOPE

In the same address space as the user process?

- Protection bits prevent user code from writing kernel
- Higher part of virtual memory
- Lower part of physical memory

. . . Yes, *this is how we do it.*

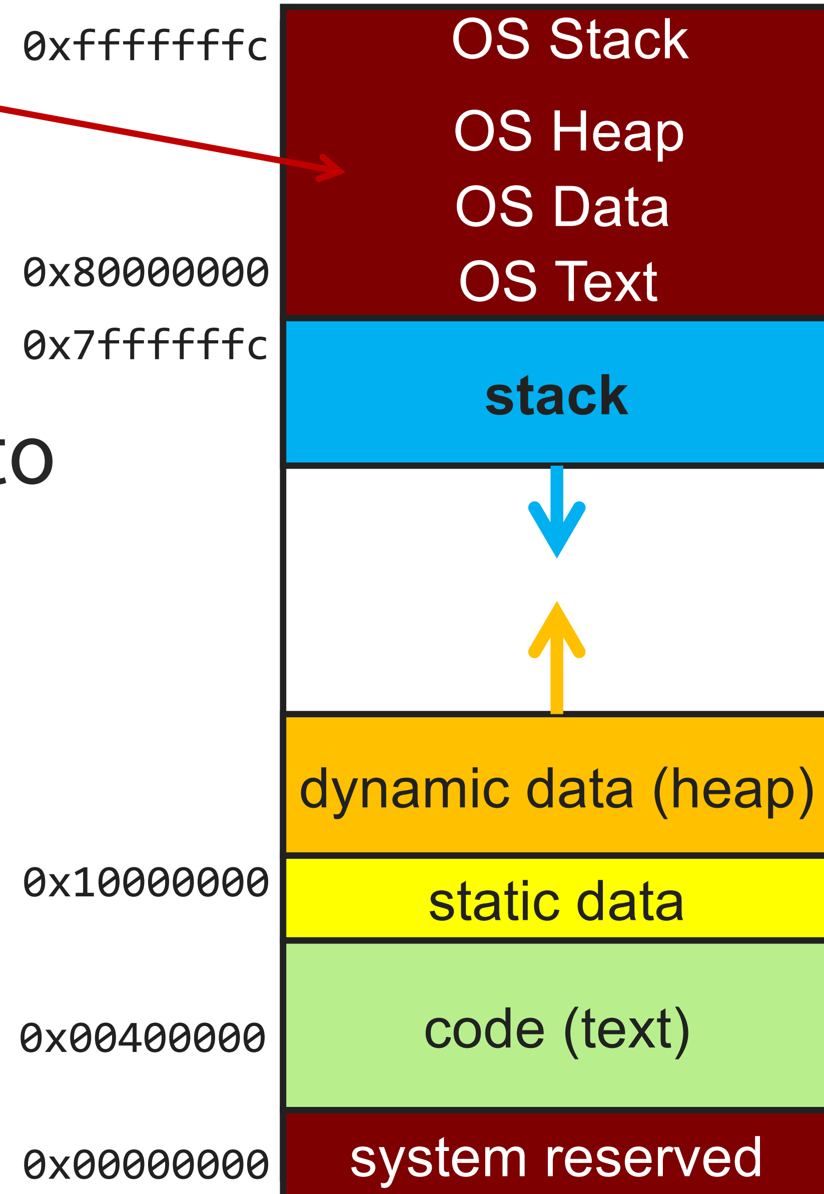
Full System Layout

All kernel text & most data:

- At same virtual address in every address space

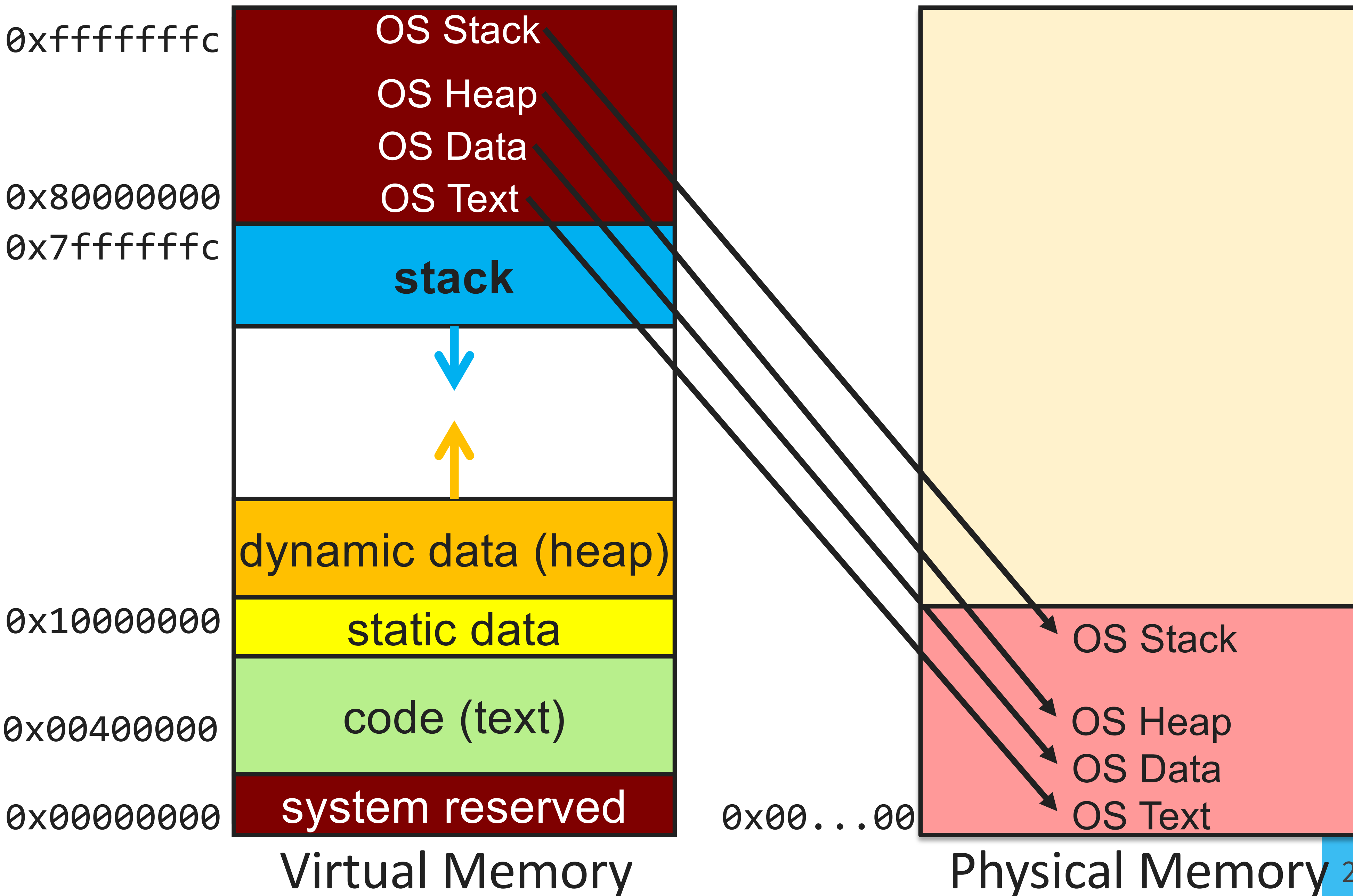
OS is omnipresent, available to help user-level applications

- Typically in high memory

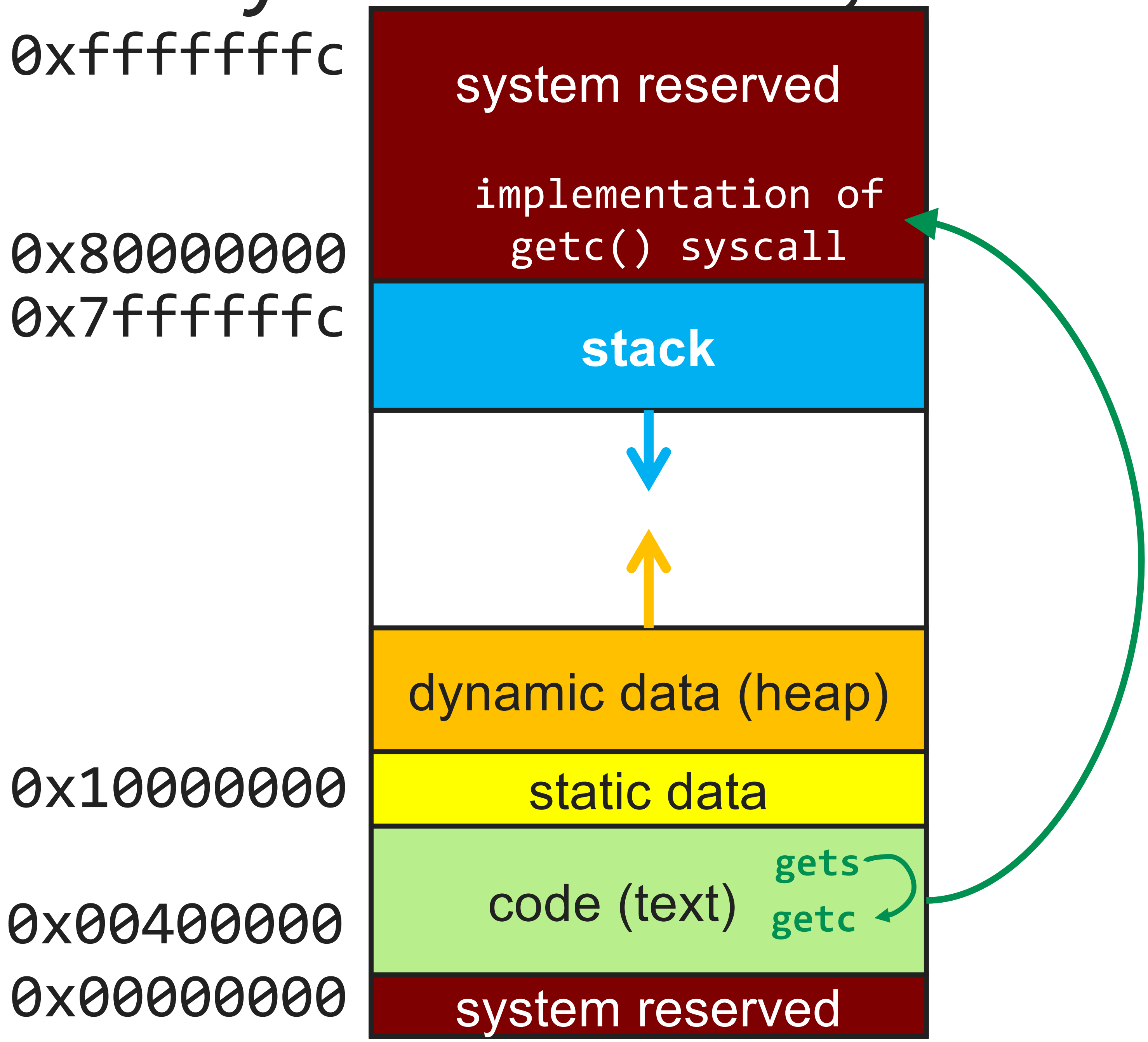


Virtual Memory

Full System Layout



Anatomy of a Process, v2



Clicker Question

Which statement is FALSE?

A) OS manages the CPU, Memory, Devices, and Storage.
B) OS provides a consistent API to be used by other processes.
C) The OS kernel is always present on Disk.
D) The OS kernel is always present in Memory.
E) Any process can fetch and execute OS code in user mode.

Clicker Question

Which one of the following statements is true?

A. Multiple copies of OS code reside in physical memory because every process keeps a copy of the kernel in its reserved address space.
B. A programmer can invoke the operating system by using an instruction that will trigger an interrupt.
C. The OS uses its own stack when executing a system call on behalf of user code.
D. The OS can interrupt user code via a system call.
E. The OS is always actively running on the CPU.

Inside the SYSCALL instruction

SYSCALL instruction does an atomic jump to a controlled location (*i.e.*, MIPS 0x8000 0180)

- Saves the old (user) SP value
- Switches the SP to the kernel stack
- Saves the old (user) PC value (= return addr)
- Saves the old privilege mode
- Sets the new privilege mode to 1
- Sets the new PC to the kernel syscall handler

Inside the SYSCALL **implementation**

Kernel system call handler carries out the desired system call

- Saves callee-save registers
- Examines the syscall number
- Checks arguments for sanity
- Performs operation
- Stores result in v0
- Restores callee-save registers
- Performs a “return from syscall” (ERET) instruction, which restores the privilege mode, SP and PC

Exceptional Control Flow

Anything that *isn't* a user program executing its own user-level instructions.

System Calls:

- just one type of exceptional control flow
- Process requesting a service from the OS
- Intentional – *it's in the executable!*

Software Exceptions

Trap

Intentional

Examples:

System call

(OS performs service*)*

Breakpoint traps

Privileged instructions

Fault

Unintentional but

Possibly recoverable

Examples:

Division by zero

Page fault

Abort

Unintentional

Not recoverable

Examples:

Parity error

*One of **many** ontology / terminology trees*

Hardware support for exceptions

Exception program counter (EPC)

- 32-bit register, holds addr of affected instruction
- Syscall case: Address of SYSCALL

Cause register

- Register to hold the cause of the exception
- Syscall case: 8, Sys

Special instructions to load TLB

- Only do-able by kernel

Exceptional Control Flow

AKA Exceptions

Hardware interrupts

Asynchronous

= caused by events external to CPU

Maskable

Can be turned off by CPU

Example: alert from network device that a packet just arrived, clock notifying CPU of clock tick

Unmaskable

Cannot be ignored

Example: alert from the power supply that electricity is about to go out

Software exceptions

Synchronous

= caused by CPU executing an instruction

Clicker Q

Which sequence best describes a:

1) System Call
2) Page Fault
3) Interrupt

Sequence A:

- current instruction (at PC) triggers handler
- control passes to handler
- execution returns to user process
- current instruction (at PC) executes once more

Sequence B:

- current instruction (at PC) triggers handler
- control passes to handler
- execution returns to user process
- next instruction (at PC+4) executes

Sequence C:

- current instruction (at PC) completes
- control passes to handler
- execution returns to user process
- next instruction (at PC+4) executes

Sequence D:

- current instruction (at PC) triggers handler
- control passes to handler
- execution never returns to the user process

Interrupts & Unanticipated Exceptions

No SYSCALL instruction. Hardware steps in:

- Saves PC of exception instruction (EPC)
- Saves cause of the interrupt/privilege (Cause register)
- Switches the sp to the kernel stack
- Saves the old (user) SP value
- Saves the old (user) PC value
- Saves the old privilege mode
- Sets the new privilege mode to 1
- Sets the new PC to the kernel ~~syscall hander~~ interrupt/exception handler

SYSCALL

Inside Interrupts & Unanticipated Exceptions

interrupt/exception handler handles event

Kernel ~~system call handler carries out system call~~

all

- Saves ~~callee-save~~ registers
- Examines the ~~syscall number~~ cause
- ~~Checks arguments for sanity~~
- ~~Performs operat~~ion
- Stores result in v0
- Restores ~~callee-save~~ all registers
- Performs a ERET instruction (restores the privilege mode, SP and PC)

Clicker Question

What other task requires both Hardware and Software?

A) Virtual to Physical Address Translation
B) Branching and Jumping
C) Clearing the contents of a register
D) Pipelining instructions in the CPU
E) What are we even talking about?

Address Translation: HW/SW Division of Labor

Virtual → physical address translation!

Hardware

- has a concept of operating in physical or virtual mode
- helps manage the TLB
- raises page faults
- keeps Page Table Base Register (PTBR) and ProcessID

Software/OS

- manages Page Table storage
- handles Page Faults
- updates Dirty and Reference bits in the Page Tables
- keeps TLB valid on context switch:
  - Flush TLB when new process runs (x86)
  - Store process id (MIPS)

Demand Paging on MIPS

1. TLB miss
2. Trap to kernel
3. Walk Page Table
4. Find page is invalid
5. Convert virtual address to file + offset
6. Allocate page frame
   - Evict page if needed
7. Initiate disk block read into page frame
8. Disk interrupt when DMA complete
9. Mark page as valid
10. Load TLB entry
11. Resume process at faulting instruction
12. Execute instruction