CS162
Operating Systems and Systems Programming
Lecture 2

Protection: Processes and Kernels

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https://cs162.org/

Slides based on prior slide decks from David Culler, Ion Stoica, John Kubiatowicz, Alison Norman and Lorenzo Alvisi

Admistratrivia

Homework and Early Drop Deadline

HW0 Due 31/8

Should be working on Homework 0 already!

- cs162-xx account, Github accountVagrant and VirtualBox – VM environment for the course
  - » Consistent, managed environment on your machine
- Get familiar with all the cs162 tools, submit to autograder via git

Homework and Early Drop Deadline

HW0 Due 1/9 (Same Day as Early Drop Deadline)

Should be working on Homework 0 already!

- Get familiar with all the cs162 tools, submit to autograder via git

HW1 will be released on 2/9

Projects are looming

Group Formation Form (Link on EdStem) is due 2/9.

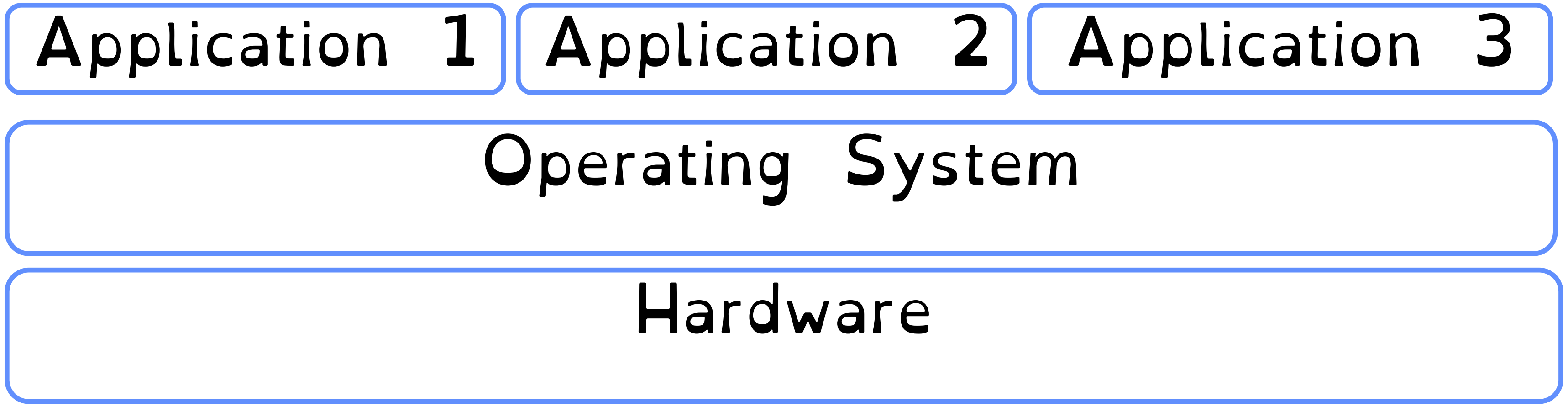
There is a teammate search functionality on EdStem.

Discussions are starting! First 2 optional but mandatory afterwards

Project 0 will be released on 9/4

Recall: Operating System

An operating system implements a virtual machine for the application whose interface is more convenient than the raw hardware interface
(convenient = security, reliability, portability)



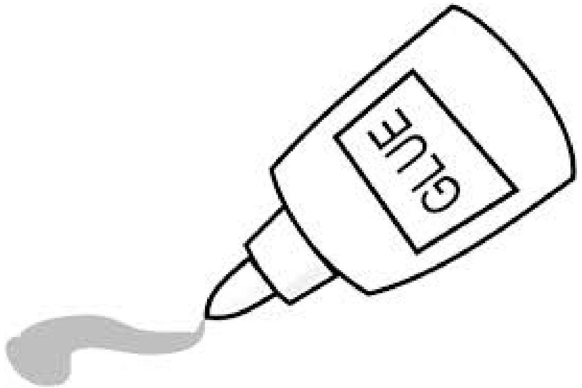
Recall: Three main hats

Referee

Manage protection, isolation, and sharing of resources

Illusionist

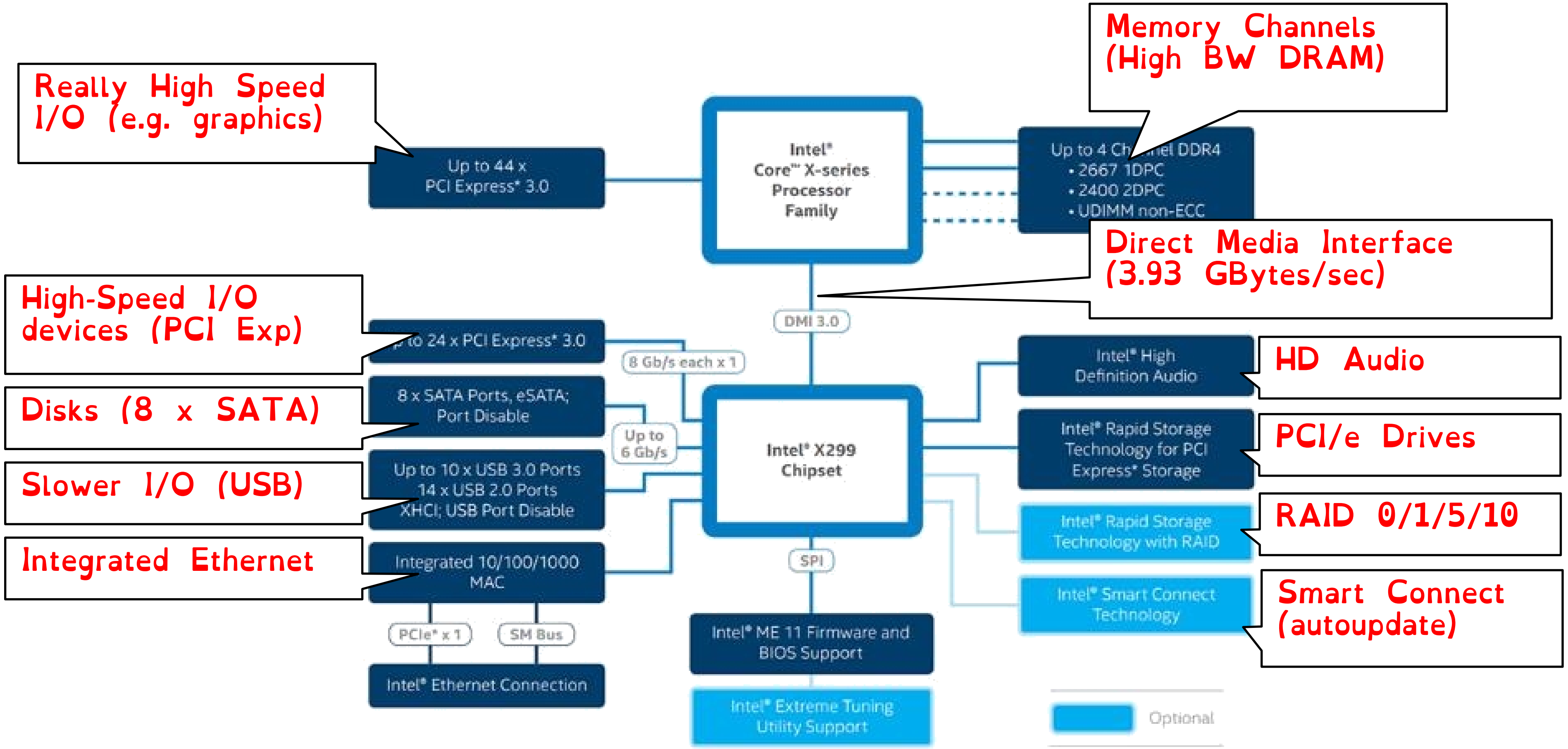
Provide clean, easy-to-use abstractions of physical resources



Glue

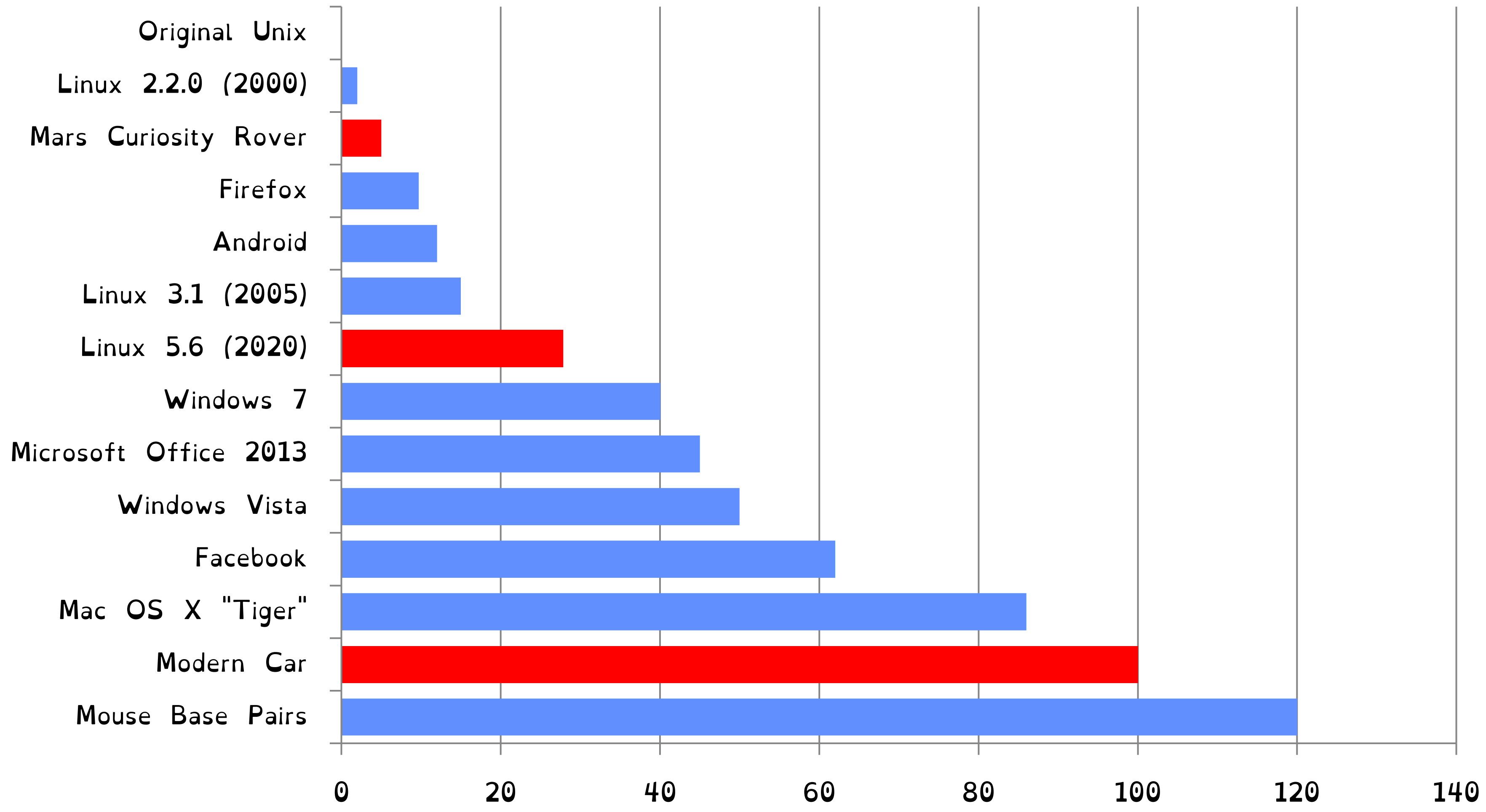
Provides a set of common services

Recall: HW Complex



Intel Skylake-X I/O Configuration

Recall: Increasing Software Complexity



Topic Breakdown

Virtualizing the CPU	Process Abstraction and API
	Threads and Concurrency
	Scheduling
Virtualizing Memory	Virtual Memory
	Paging
Persistence	IO devices
	File Systems
Distributed Systems	Challenges with distribution
	Data Processing & Storage

Mechanisms vs Policy

Mechanism

Low-level methods or protocols that implement a needed piece of functionality

A Brake Pedal!

Policy

Algorithms for making decisions within the OS. Use the mechanism.

"I break when I see a stop sign"

Goals for Today

- What are the requirements of a good VM abstraction?
- What is a process?
- How does the kernel use processes to enforce protection?
- When does one switch from kernel to user mode and back?

Goal 1: Requirements for Virtualization

The OS will protect you

Protection is necessary to preserve the virtualization abstraction

Protect applications from other application's code (reliability, security, privacy)

Protect OS from the application

Protect applications against inequitable resource utilisation (memory, CPU time)

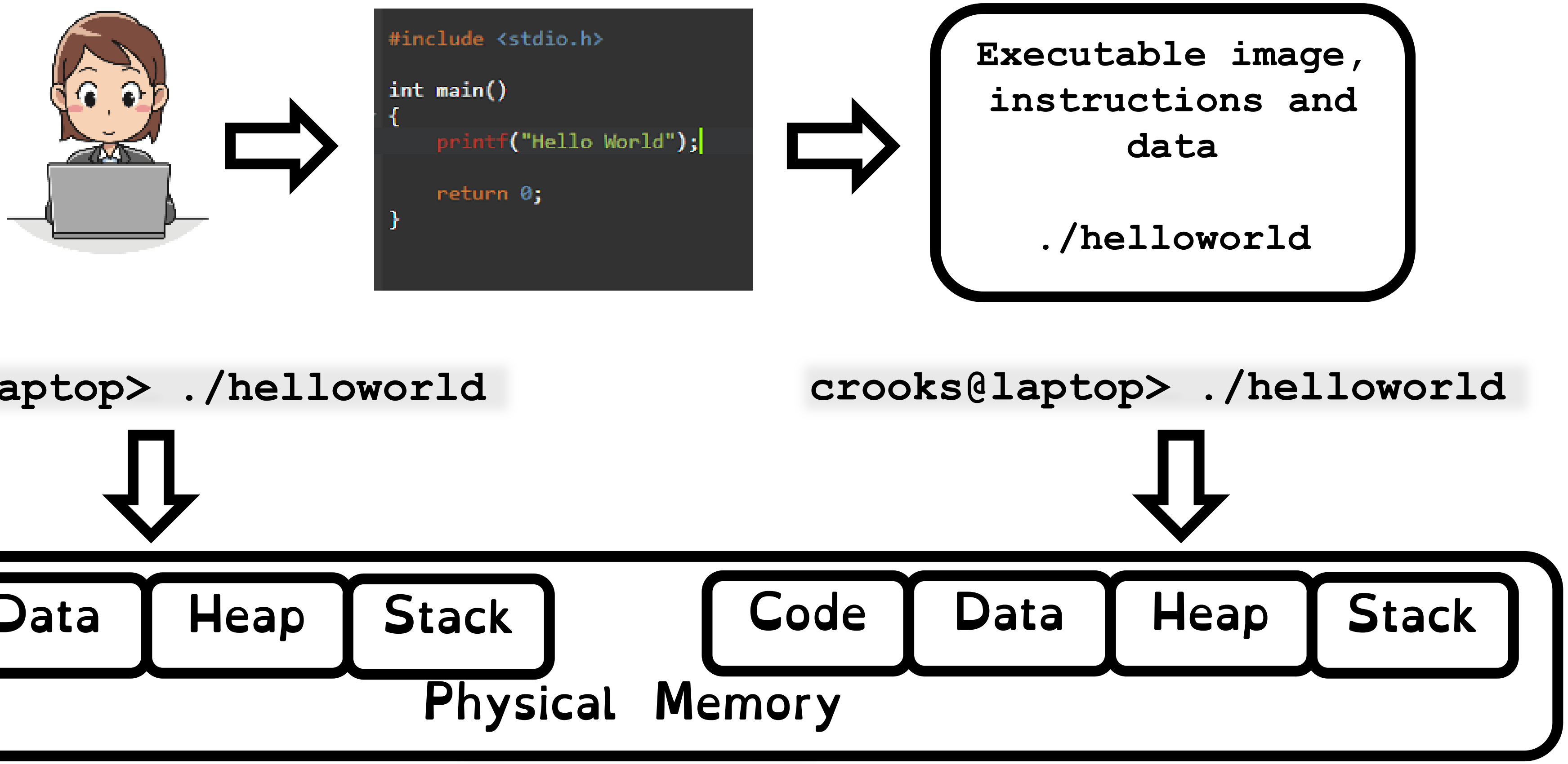
Goal 2: What is a Process?

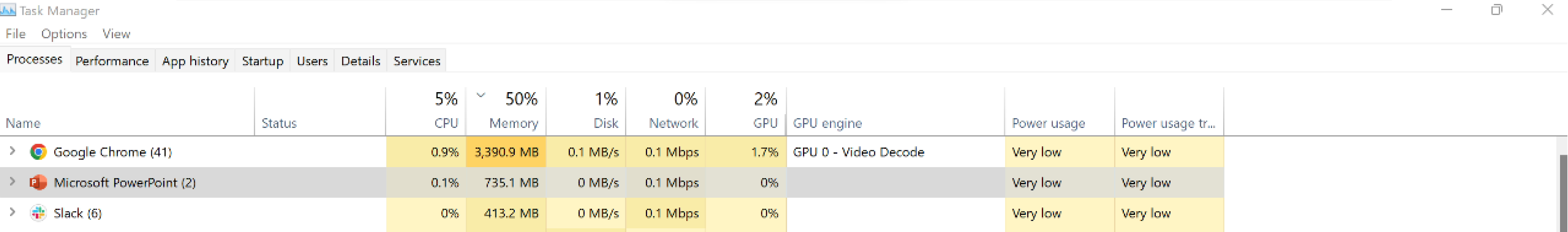
A process (simplified)

A process is an instance of a running program

CPU	Memory (address space)	Registers	IO information
	Store code, data, stack, heap	Program Counter, Stack Pointer Regular registers	Open files (and others)

From program to process

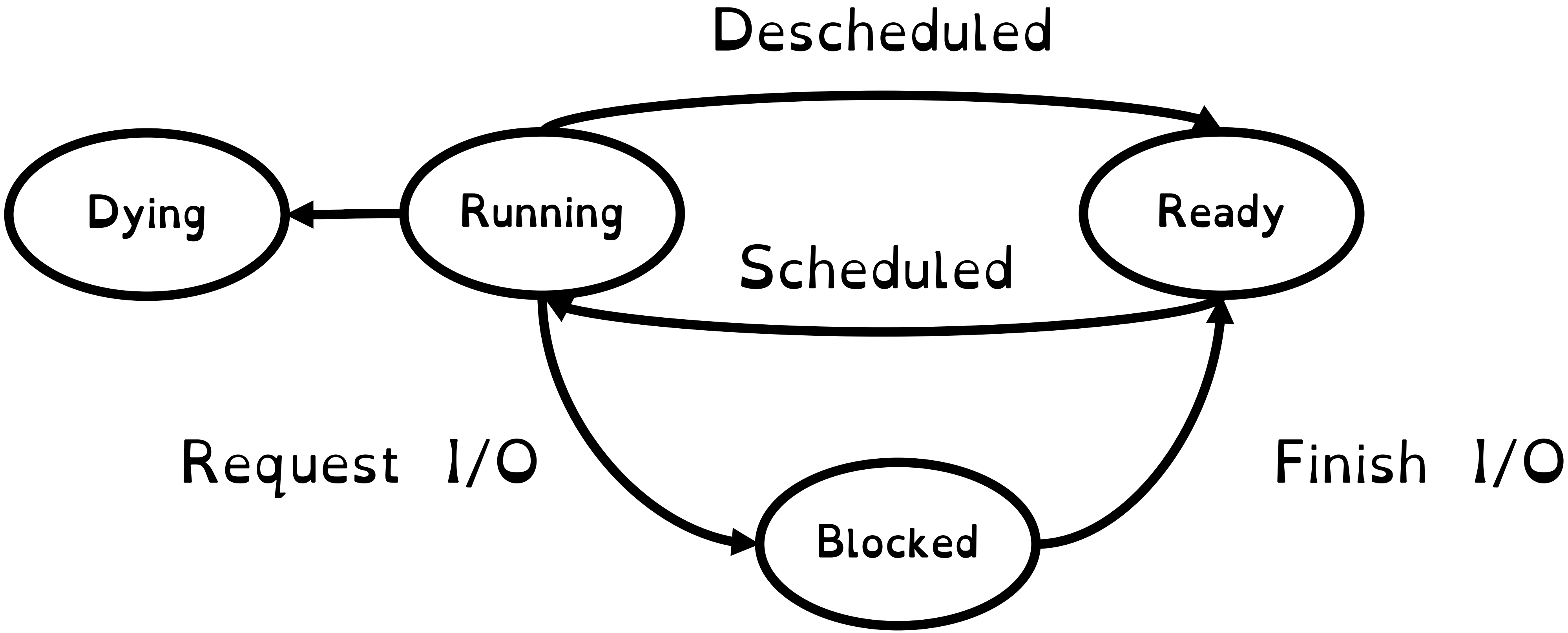



Task Manager
File Options View
Processes | Performance | App history | Startup | Users | Details | Services

Name	Status	5% CPU	50% Memory	1% Disk	0% Network	2% GPU	GPU engine	Power usage	Power usage tr...
Google Chrome (41)		0.9%	3,390.9 MB	0.1 MB/s	0.1 Mbps	1.7%	GPU 0 - Video Decode	Very low	Very low
Microsoft PowerPoint (2)		0.1%	735.1 MB	0 MB/s	0.1 Mbps	0%		Very low	Very low
Slack (6)		0%	413.2 MB	0 MB/s	0.1 Mbps	0%		Very low	Very low

Process Life Cycle

A process can be in one of several states:
(real OSes have additional variants)



Process Management by the OS

Process Control Block (or process descriptor) in OS stores necessary metadata

PC
Stack Ptr
Registers
PID
UID
List of open files
Process State
...

Three "Prongs" for the Class

Understanding OS principles

System Programming

Map Concepts to Real Code

Processes in the wild (well, in the kernel)

```
enum procstate { UNUSED, EMBRYO, SLEEPING, RUNNABLE, RUNNING, ZOMBIE };

// Per-process state
struct proc {
  uint sz;                     // Size of process memory (bytes)
  pde_t* pgdir;                // Page table
  char *kstack;                // Bottom of kernel stack for this process
  enum procstate state;        // Process state
  int pid;                     // Process ID
  struct proc *parent;         // Parent process
  struct trapframe *tf;        // Trap frame for current syscall
  struct context *context;     // swtch() here to run process
  void *chan;                  // If non-zero, sleeping on chan
  int killed;                  // If non-zero, have been killed
  struct file *ofile[NOFILE];  // Open files
  struct inode *cwd;           // Current directory
  char name[16];               // Process name (debugging)
};
```

In Linux: `task_struct` defined in `<linux/sched.h>`

Xv6 Kernel (proc.h)

Processes in Pintos

```
struct process {
  /* Owned by process.c. */
  uint32_t* pagedir;           /* Page directory. */
  char process_name[16];       /* Name of the main thread */
  struct thread* main_thread;  /* Pointer to main thread */

  /* All the fun data structures you're going to add */
};
```

Pintos
(userprog/process.h)

Many Processes

Process List stores all processes

```
struct {
  struct spinlock lock;
  struct proc proc[NPROC];
} ptable;
```

Xv6 Kernel (proc.c)

Run Queues

Lists all PCBs in **READY** state

Wait Queues

Lists all PCBs in **BLOCKED** state

The Illusionist and the Referee are Back

Illusionist	Referee
Give every process the illusion of running on a private CPU	Manage resources to allocate to each process
Give every process the illusion of running on private memory	Isolate process from all other processes and protect OS

Operating System Kernel

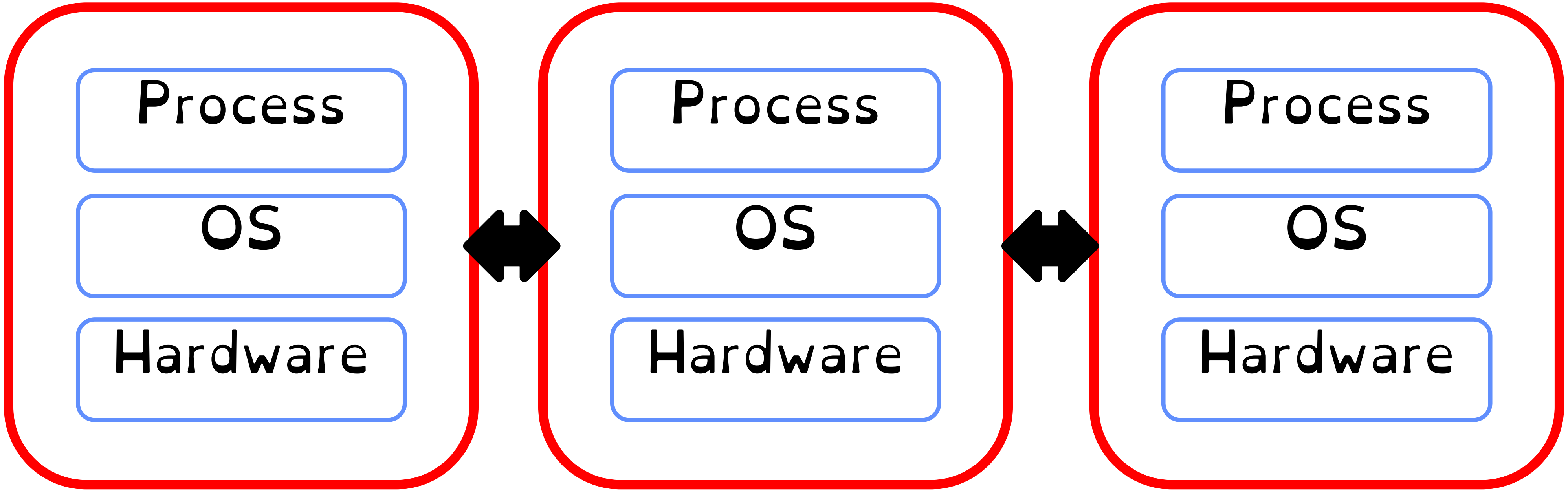
Lowest level of OS running on system.
Kernel is trusted with full access to all hardware capabilities

All other software (OS or applications) is considered untrusted

Untrusted	Applications Rest of OS
Trusted	Operating System Kernel
Untrusted	Hardware

The Process, Refined

A executing program with restricted rights



Enforcing mechanism must not hinder functionality or hurt performance

User vs Kernel: Dr Jekyll and Mr Hyde

Application/User Code (Untrusted)

Run all the processor with all potentially dangerous operations disabled

Kernel Code (Trusted)

Runs directly on processor with unlimited rights

Performs any hardware operations

But run on the same machine!

How can the kernel enforce restricted rights?

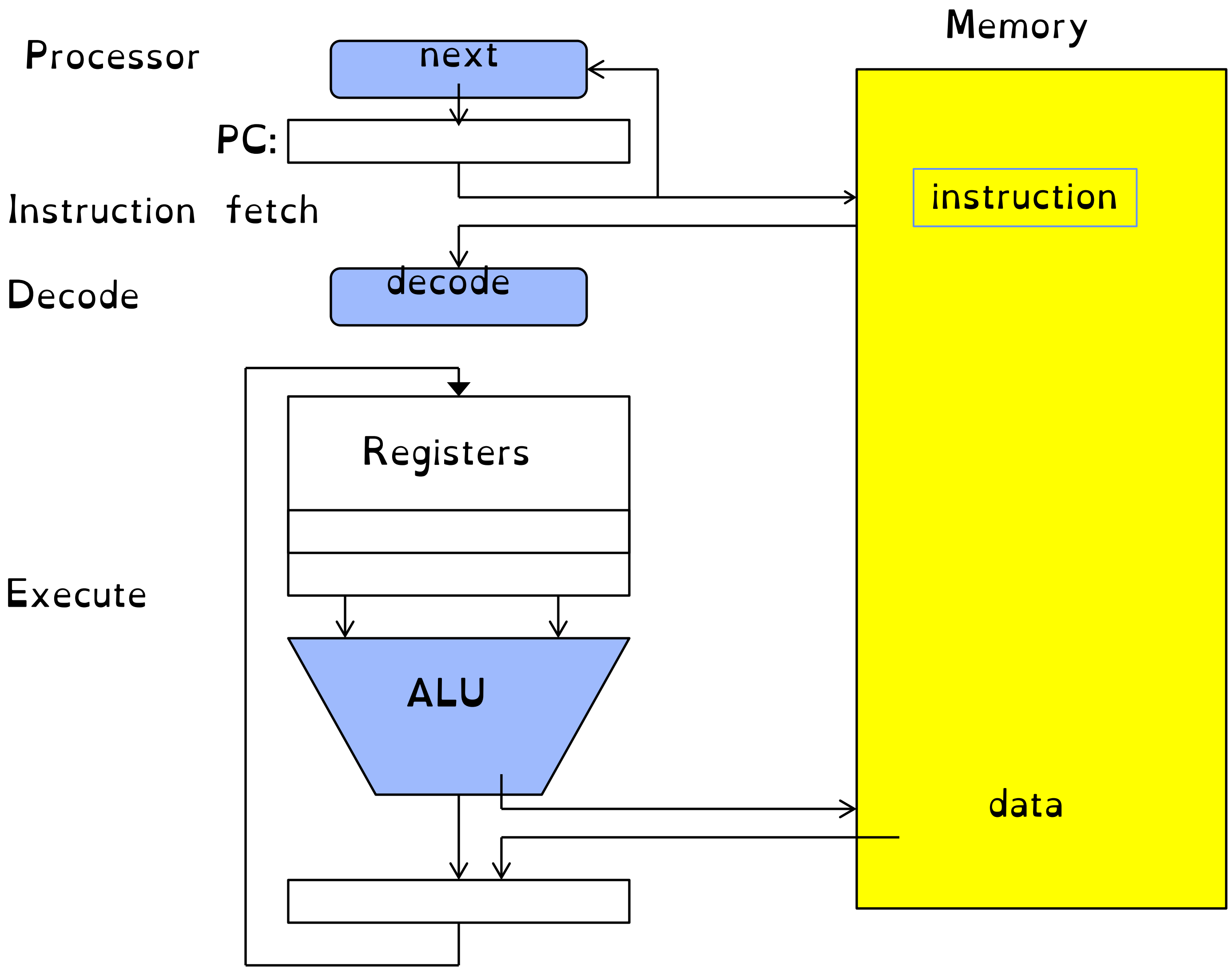
1) While preserving functionality

2) While preserving performance

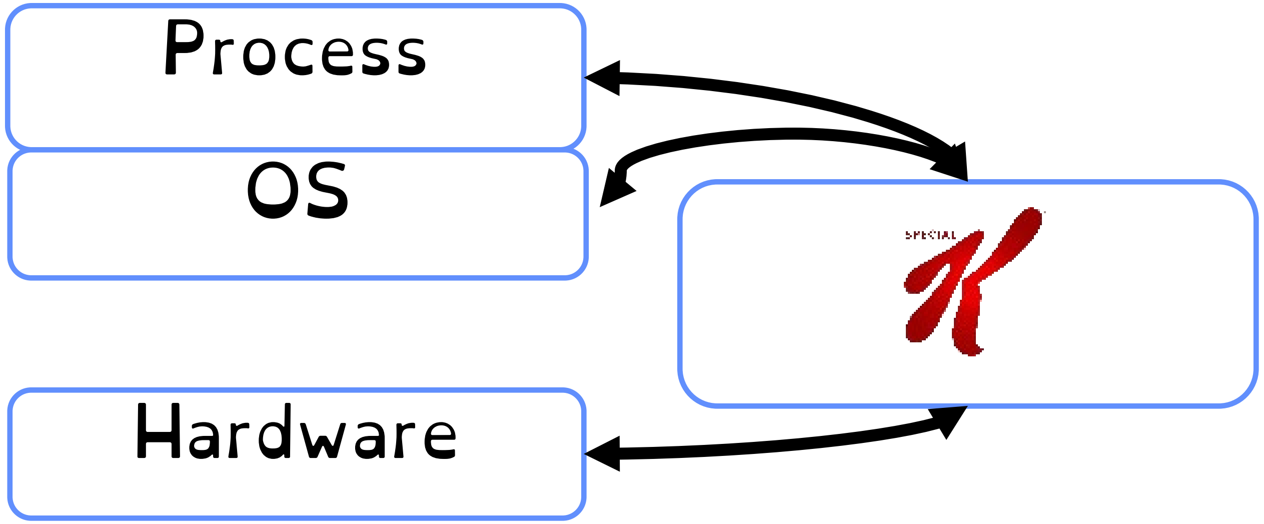
3) While preserving control

Attempt 1: Simulation

Recall: CPU Instruction Cycle (from CS61c)



Attempt 1: Simulation



Have the Kernel interpret and check every instruction!

Potential Issues:

Extremely slow! Would have to cycle through all operations, switch into the kernel, etc.

Unnecessary. Most operations are perfectly safe!

Attempt 2: Dual Mode Operation

Hardware to the rescue!
Use a bit to enable two modes of execution

In User Mode

Processor checks each instruction before executing it

Executes a limited (safe) set of instructions

In Kernel Mode

OS executes with protection checks off

Can execute any instructions

Hardware must support

1) Privileged Instructions

Unsafe instructions cannot be executed in user mode

2) Memory Isolation

Memory accesses outside a process's address space prohibited

3) Interrupts

Ensure kernel can regain control from running process

4) Safe Transfers

Correctly transfer control from user-mode to kernel-mode and back

Req 1/4: Privileged Instructions

Cannot change privilege level (set mode bit)

Cannot change address space

Cannot disable interrupts

Cannot perform IO operations

Cannot halt the processor

How can an application do anything useful ...

Asks for permission to access kernel mode!

System calls Transition from user to kernel mode only at specific locations specified by the OS

Exceptions User mode code attempts to execute a privileged exception. Generates a processor exception which passes control to kernel at specific locations

More on safe control transfers later

Hardware must support

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Req 2/4: Memory Protection

OS and applications both resident in memory

Application should not read/write kernel memory
(or other apps memory)

A Bug's Tail

The character could leave the game area and start overwriting other running programs and kernel memory.

One of the worst bugs I ever had to deal with was in this game. Once the game player made it to the Colony, every so often the system would crash and burn at totally random times. You might be playing for ten minutes when it happened or ten hours, but it would just die in a totally random way

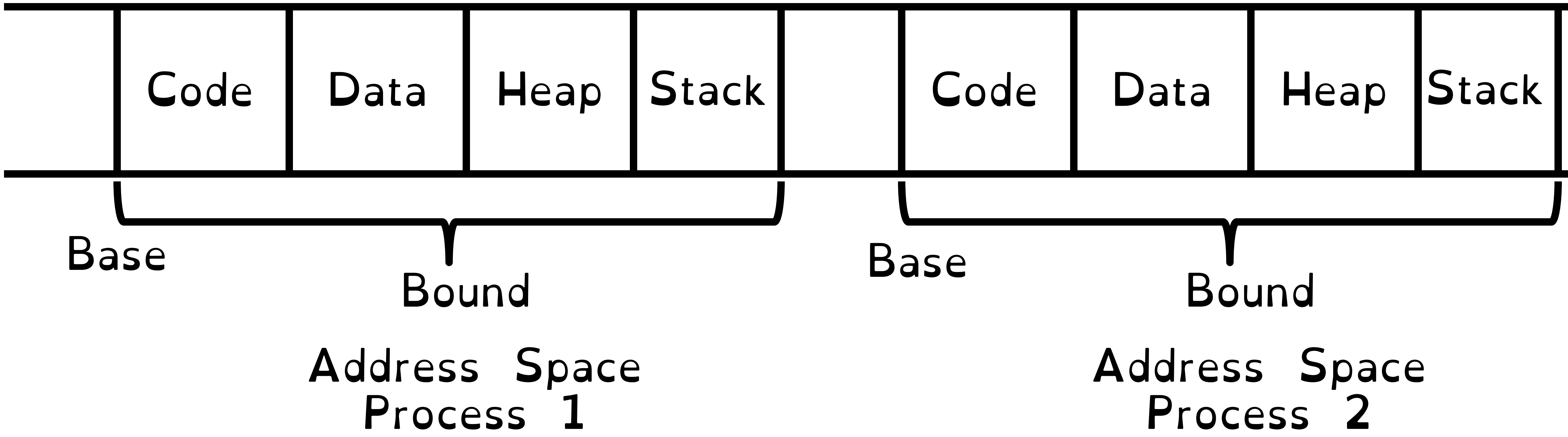
There was a slow-moving slug like creature that knew how to follow the game player's trail. When it came across another creature, rather than bouncing off and risk losing the trail, I made it so that it would destroy the other creature and stay on target to find you. This worked great, except that on some rare occasions, this slug could do to a wall what it did to the other creatures. That is, it could delete it. This meant that the virtual door was now open for this creature to explore the rest of the RAM on the Macintosh, deleting and modifying it as it went along. Of course, it was just a matter of time before it found some juicy code. In other words, the bug was a REAL bug.

Super Mario Land 2

Mario could exit a level and explore the entire memory of the system

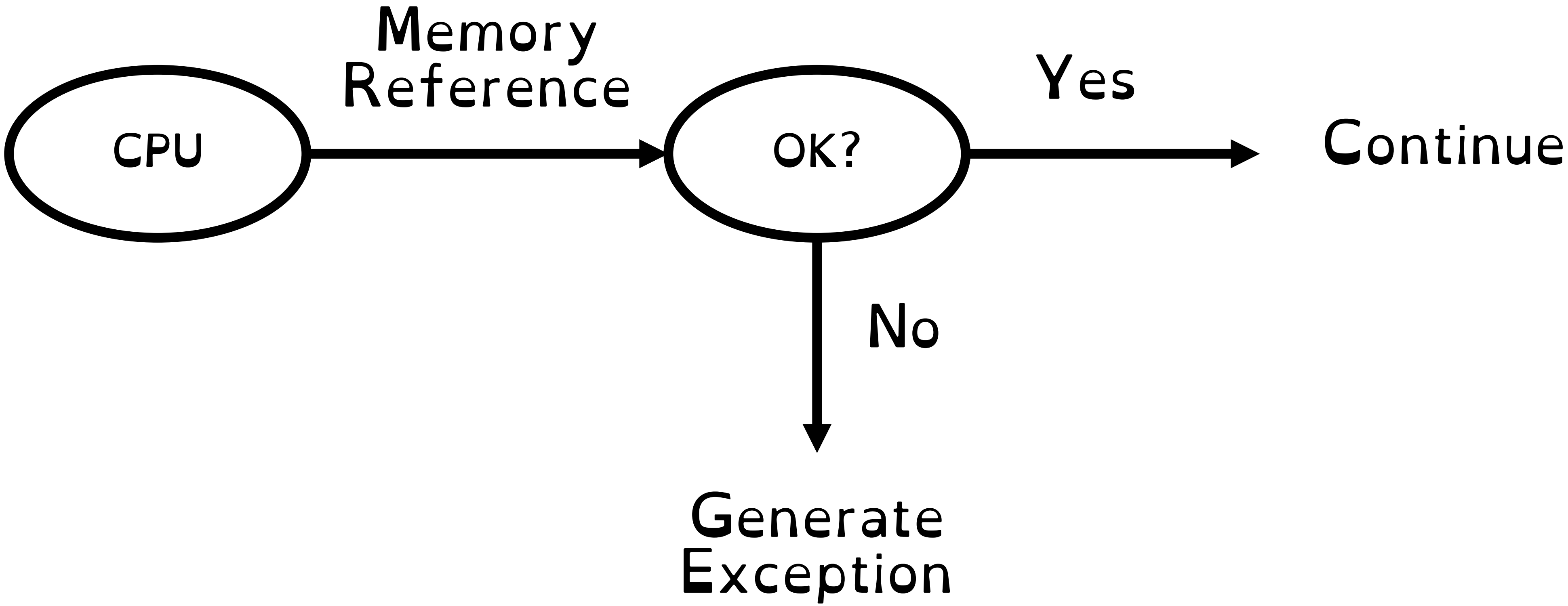
Attempt 1: Isolation

Hardware to the rescue! (Again)
Base and Bound registers



Attempt 1: Isolation

Hardware to the rescue! (Again)
Base and Bound registers



Attempt 1: Isolation

Kernel Mode executes without
Base and Bound registers

What can the Kernel see?

a) Kernel memory only
b) Kernel memory + application memory of app that "invoked" kernel
c) Everything

Limitations of Isolation

1) Expandable memory

Static memory allocation

2) Memory Sharing

Cannot share memory between processes

3) Non-Relative Memory Addresses

Location of code & data determined at runtime

4) Fragmentation

Cannot relocate/move programs. Leads to fragmentation

Attempt 2: Virtualization

Virtual address space

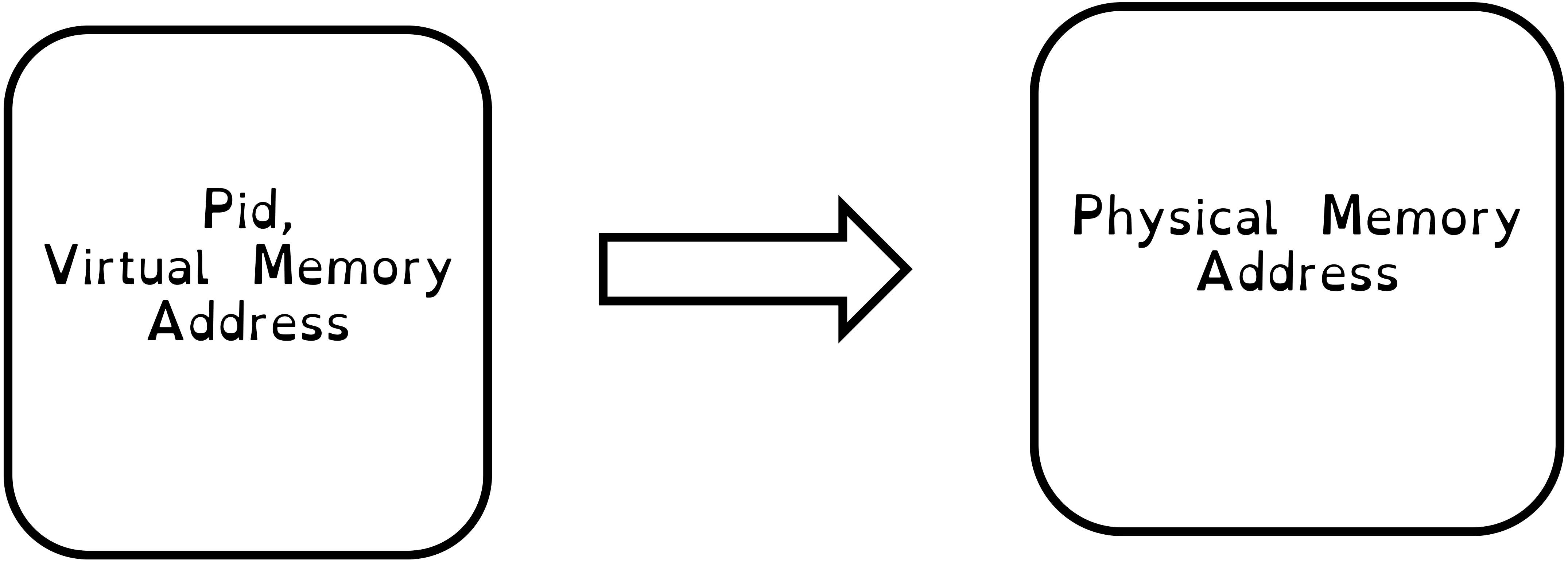
Set of memory addresses that process can “touch”

Physical address space

Set of memory addresses supported by hardware

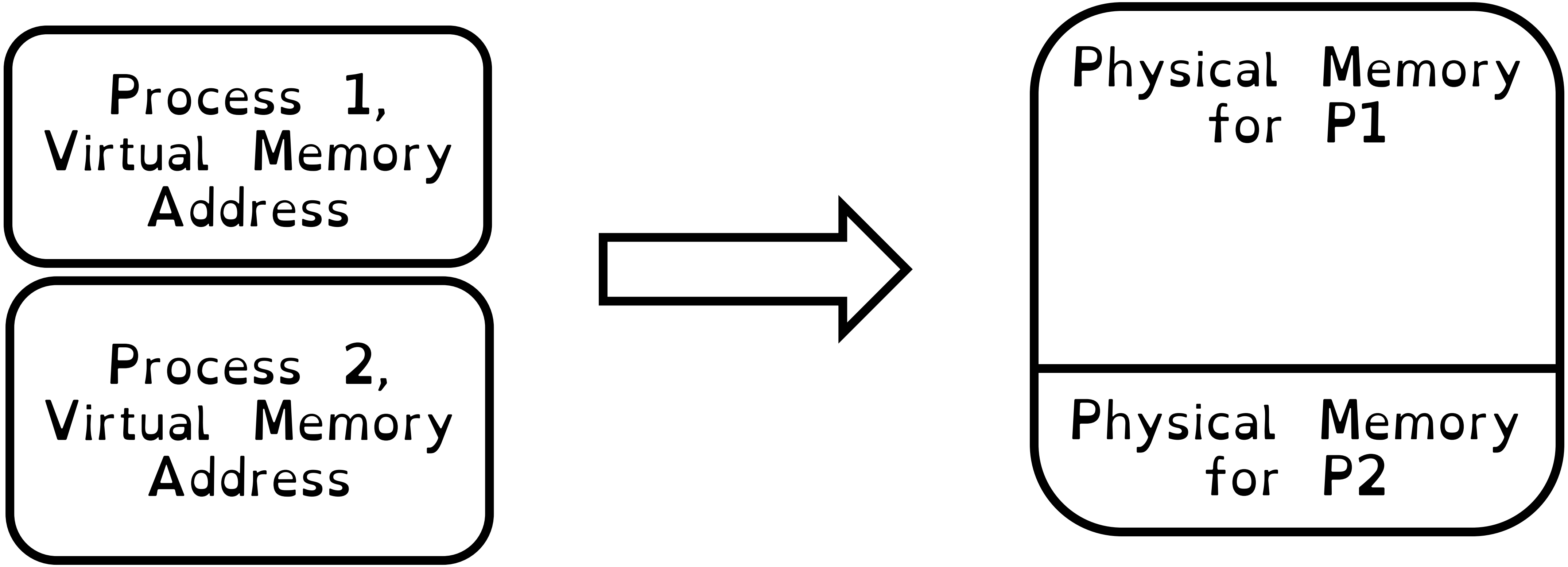
Attempt 2: Virtualization

Map from virtual addresses to physical addresses through address translation



Attempt 2: Virtualization

Continues to provide isolation



Benefits of Virtualization

1) Expandable memory

Whole space of virtual address space! Even physical address not resident in memory

2) Memory Sharing

Same virtual address can map to same physical address

3) Relative Memory Addresses

Every process's memory always starts at 0

4) Fragmentation

Can dynamically change mapping of virtual to physical addresses

What does this program do? (CS61C)

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>

int main(int argc, char *argv[]){
  int *p = malloc(sizeof(int));
  printf("(%d) p: %p\n", getpid(), p);
  *p = 0;
  while (1) {
    *p = *p + 1;
    printf("(%d) p: %d\n", getpid(), *p);
  }
  return 0;
}
```

```
crooks@laptop> gcc -o memory memory.c -Wall
crooks@laptop> ./memory
(120) p: 0x200000
(120) p: 1
(120) p: 2
(120) p: 3
(120) p: 4
crooks@laptop> ./memory & ./memory
(120) p: 0x200000
(254) p: 0x200000
```

Are these virtual or physical addresses?

Virtual memory provides each process with illusion of own complete (and infinite) memory

Virtual Memory is Hard!

- Virtualizing the CPU
  - Process Abstraction and API
  - Threads and Concurrency
  - Scheduling
- Virtualizing Memory
  - Virtual Memory
  - Paging
- Persistence
  - IO devices
  - File Systems
- Distributed Systems
  - Challenges with distribution
  - Data Processing & Storage

Hardware must support

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Unsafe instructions cannot be executed in user mode

2) Memory Isolation

Memory accesses outside a process's address space prohibited

3) Interrupts

Ensure kernel can regain control from running process

4) Safe Transfers

Correctly transfer control from user-mode to kernel-mode and back

Req 3/4: Interrupts

Kernel must be able to regain control of the processor

Hardware to the rescue! (Again x 2)
Hardware Interrupts

Set to interrupt processor after a specified delay or specified event and transfer control to (specific locations) in Kernel.

Resetting timer is a privileged operation

Hardware must support

1) Privileged Instructions

Unsafe instructions cannot be executed in user mode

2) Memory Isolation

Memory accesses outside a process's address space prohibited

3) Interrupts

Ensure kernel can regain control from running process

4) Safe Transfers

Correctly transfer control from user-mode to kernel-mode and back

Req 4/4: Safe Control Transfer

How do safely/correctly transition from executing user process to executing the kernel?

1) System Calls

2) Exceptions

3) Interrupts

Synchronous Events (trapping)

Asynchronous

Can be maskable or non-maskable

Safe Control Transfer: System Calls

User program requests OS service
Transfers to kernel at well-defined location

Synchronous/non-maskable

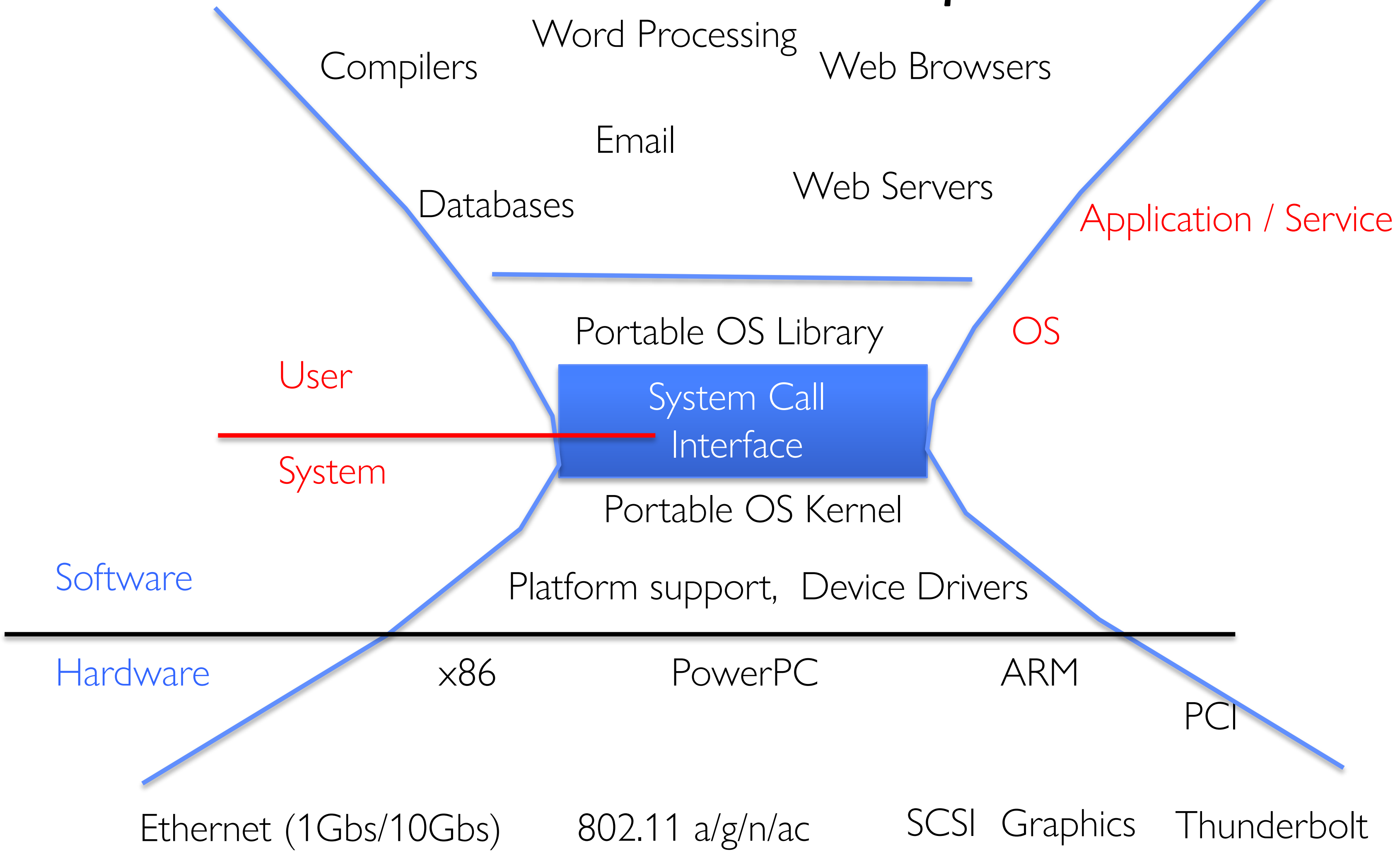
Read input/write to screen, to files, create new processes, send network packets, get time, etc.

How many system calls in Linux 3.0 ?
a) 15 b) 336 c) 1021 d) 21121

https://man7.org/linux/man-pages/man2/syscalls.2.html

System Calls are the "Narrow Waste"

Simple and powerful interface allows separation of concern
Eases innovation in user space and HW



System Calls in the Wild (In Linux)

torvalds / linux Public

Notifications | Fork 44.2k | Star 137k

Code | Pull requests 313 | Actions | Projects | Security | Insights

v4.17 linux / arch / x86 / entry / syscalls / syscall_64.tbl

Go to file ...

Dominik Brodowski syscalls/core, syscalls/x86: Rename struct pt_regs-based sys_*() to ... ...

Latest commit d5a0052 on Apr 9, 2018 History

7 contributors

386 lines (385 sloc) | 15.2 KB

Raw | Blame

```
#
# 64-bit system call numbers and entry vectors
#
# The format is:
# <number> <abi> <name> <entry point>
#
# The __x64_sys_*() stubs are created on-the-fly for sys_*() system calls
#
# The abi is "common", "64" or "x32" for this file.
#
0       common  read                    __x64_sys_read
1       common  write                   __x64_sys_write
2       common  open                    __x64_sys_open
3       common  close                   __x64_sys_close
4       common  stat                    __x64_sys_newstat
5       common  fstat                   __x64_sys_newfstat
6       common  lstat                   __x64_sys_newlstat
7       common  poll                    __x64_sys_poll
8       common  lseek                   __x64_sys_lseek
```

Safe Control Transfer: Exceptions

Any unexpected condition caused by user program behaviour

Stop executing process and enter kernel at specific exception handler

Synchronous and non-maskable

Process missteps (division by zero, writing read-only memory)
Attempts to execute a privileged instruction in user mode
Debugger breakpoints!

Exceptions in the Wild (In Linux)

torvalds / linux Public

Notifications | Fork 44.3k | Star 137k

Code | Pull requests 313 | Actions | Projects | Security | Insights

master | linux / arch / x86 / include / asm / trapnr.h | Go to file

joergroedel x86/boot/compressed/64: Add stage1 #VC handler ... Latest commit 29dcc60 on Sep 7, 2020 History

1 contributor

32 lines (29 sloc) | 1.29 KB

Raw | Blame

```
/* SPDX-License-Identifier: GPL-2.0 */
#ifndef _ASM_X86_TRAPNR_H
#define _ASM_X86_TRAPNR_H

/* Interrupts/Exceptions */

#define X86_TRAP_DE            0     /* Divide-by-zero */
#define X86_TRAP_DB            1     /* Debug */
#define X86_TRAP_NMI           2     /* Non-maskable Interrupt */
#define X86_TRAP_BP            3     /* Breakpoint */
#define X86_TRAP_OF            4     /* Overflow */
#define X86_TRAP_BR            5     /* Bound Range Exceeded */
#define X86_TRAP_UD            6     /* Invalid Opcode */
#define X86_TRAP_NM            7     /* Device Not Available */
#define X86_TRAP_DF            8     /* Double Fault */
#define X86_TRAP_OLD_MF        9     /* Coprocessor Segment Overrun */
#define X86_TRAP_TS           10     /* Invalid TSS */
#define X86_TRAP_NP           11     /* Segment Not Present */
#define X86_TRAP_SS           12     /* Stack Segment Fault */
#define X86_TRAP_GP           13     /* General Protection Fault */
#define X86_TRAP_PF           14     /* Page Fault */
```

Safe Control Transfer: Interrupts

Asynchronous signal to the processor that some external event has occurred and may require attention

When process interrupt, stop current process and enter kernel at designated interrupt handler

Timer Interrupts, IO Interrupts, Interprocessor Interrupts

Safe Control Transfer: Kernel->User

New Process Creation

Kernel instantiates datastructures, sets registers, switches to user mode

Resume after an exception/interrupt/syscall

Resume execution by restoring PC, registers, and unsetting mode

Switching to a different process

Save old process state. Load new process state (restore PC, registers). Unset mode.

Summary: Goals for today

- What are the requirements of a good VM abstraction?
- What is a process?
- How does the kernel use processes to enforce protection?
- When does one switch from kernel to user mode and back?

Summary: Goals for today

- What are the requirements of a good VM abstraction?

Protection while preserving functionality and performance

- What is a process?

Program execution with restricted rights

- How does the kernel use processes to enforce protection?

Dual-Mode operation: privileged instructions, memory protection, control, interrupts, safe control transfer

- When does one switch from kernel to user mode and back?

System Calls, Interrupts, Exceptions