# CS162
# Operating Systems and Systems Programming
# Lecture 2

## Protection: Processes and Kernels

Professor Natacha Crooks

https://cs162.org/

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

# Admistratrivia

# Homework and Early Drop Deadline

Both on Friday Sept 2nd

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

# Projects are looming

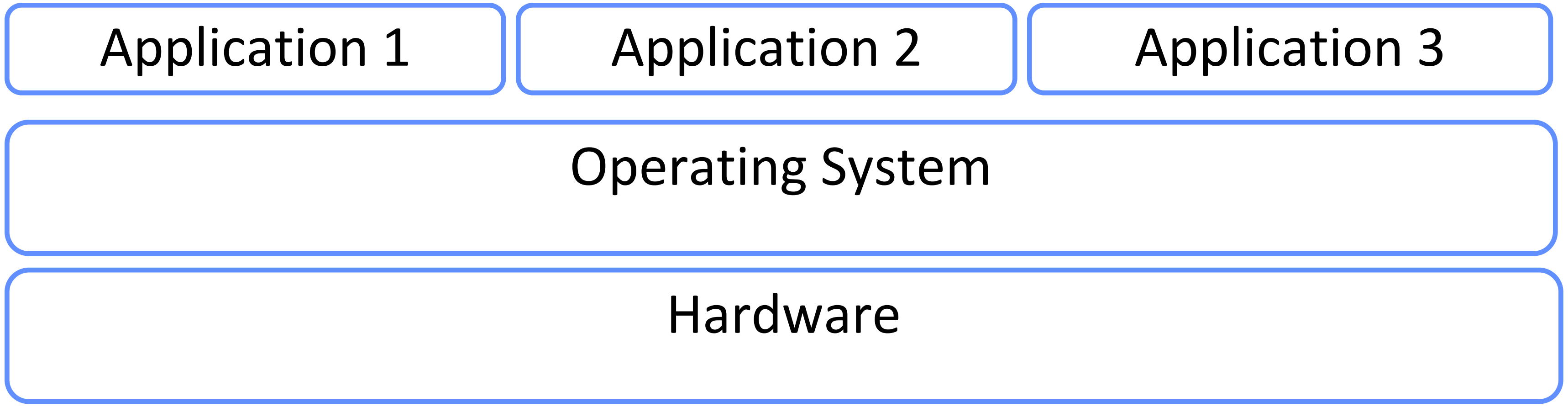
Group Formation Form (Link on EdStem) is due 4/9.

There is a teammate search functionality on EdStem.

Discussions are starting! First 2 optional but mandatory afterwards

# 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)



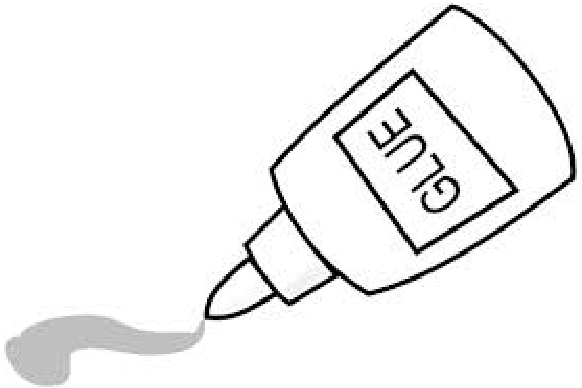
# Recall: Three main hats

**Referee**

Manage protection, isolation, and sharing of resources

**Illusionist**

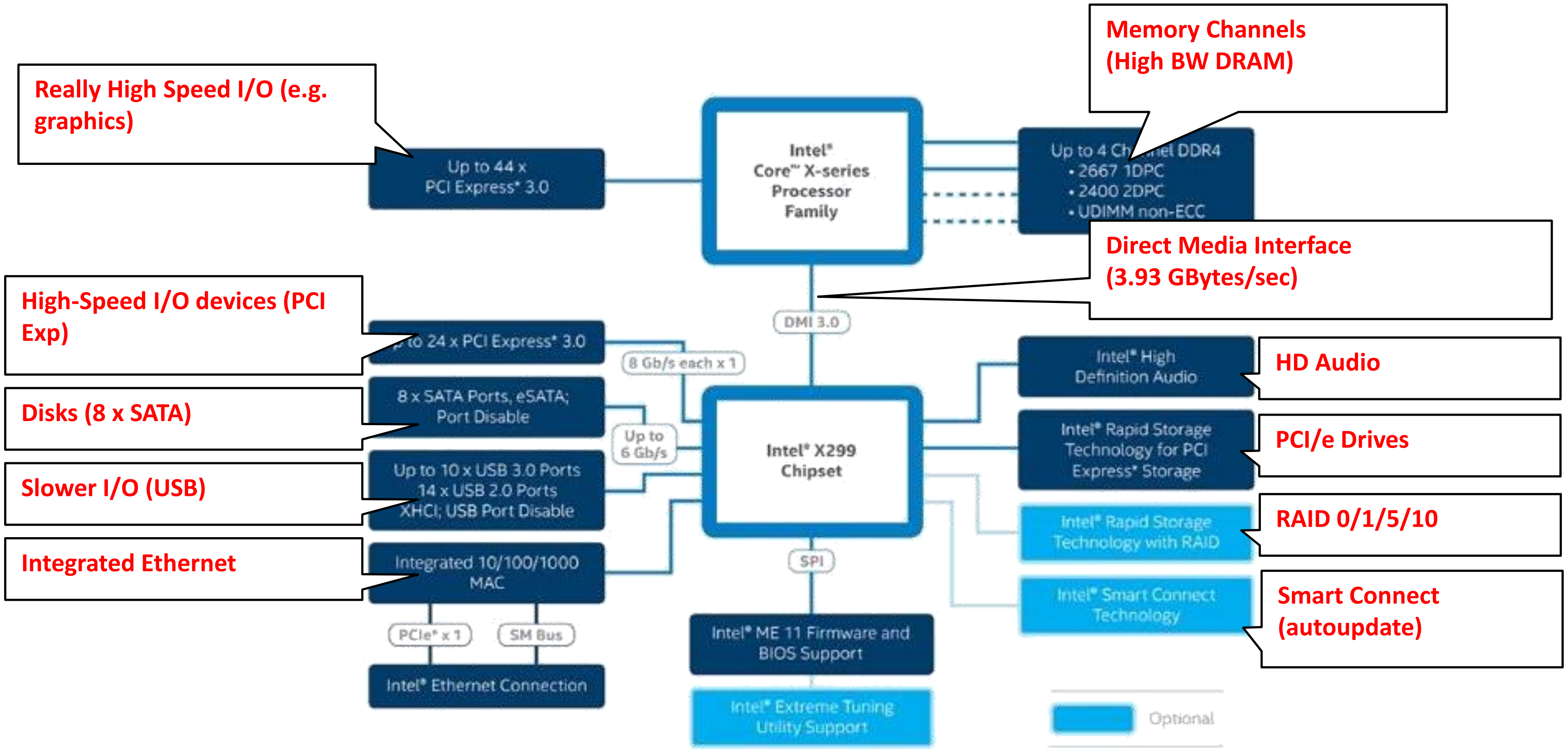
Provide clean, easy-to-use abstractions of physical resources




**Glue**

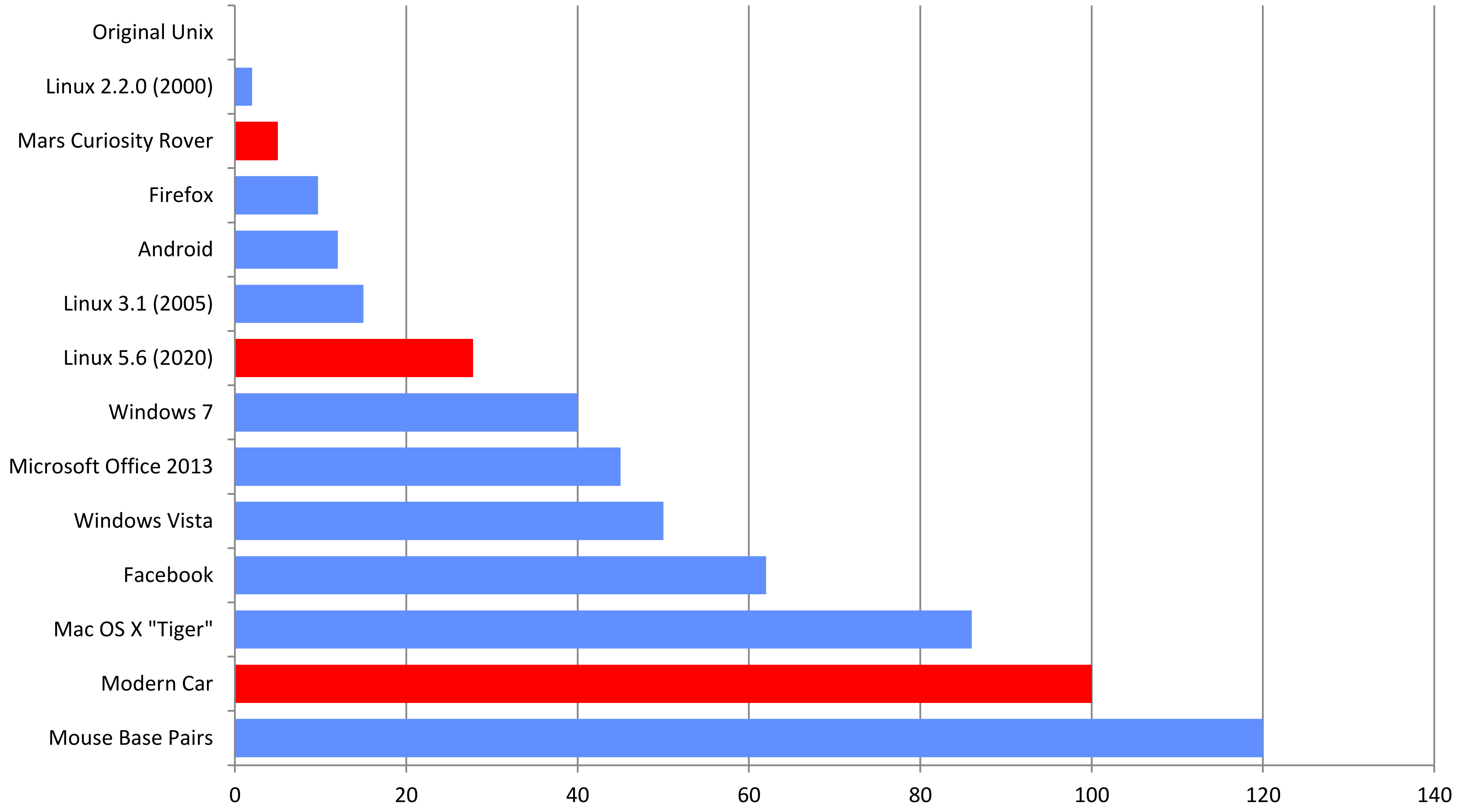
Provides a set of common services

# 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

## Policy

Algorithms for making decisions within the OS.

Use the mechanism.

**A Brake Pedal!**

**“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<br>Regular registers | Open files (and others) |

# From program to process

```c
#include <stdio.h>

int main()
{
    printf("Hello World");

    return 0;
}
```

Executable image, instructions and data

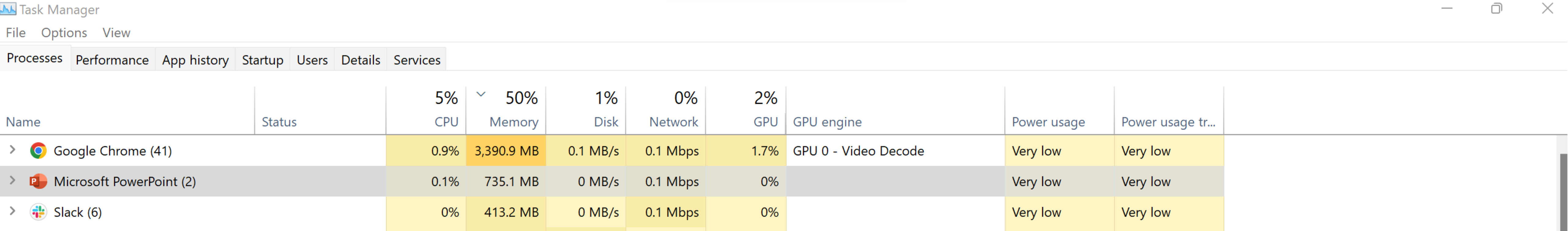
./helloworld

crooks@laptop> ./helloworld

crooks@laptop> ./helloworld

| Code | Data | Heap | Stack | Code | Data | Heap | Stack |
|---|---|---|---|---|---|---|---|

Physical Memory



Task Manager

File Options View

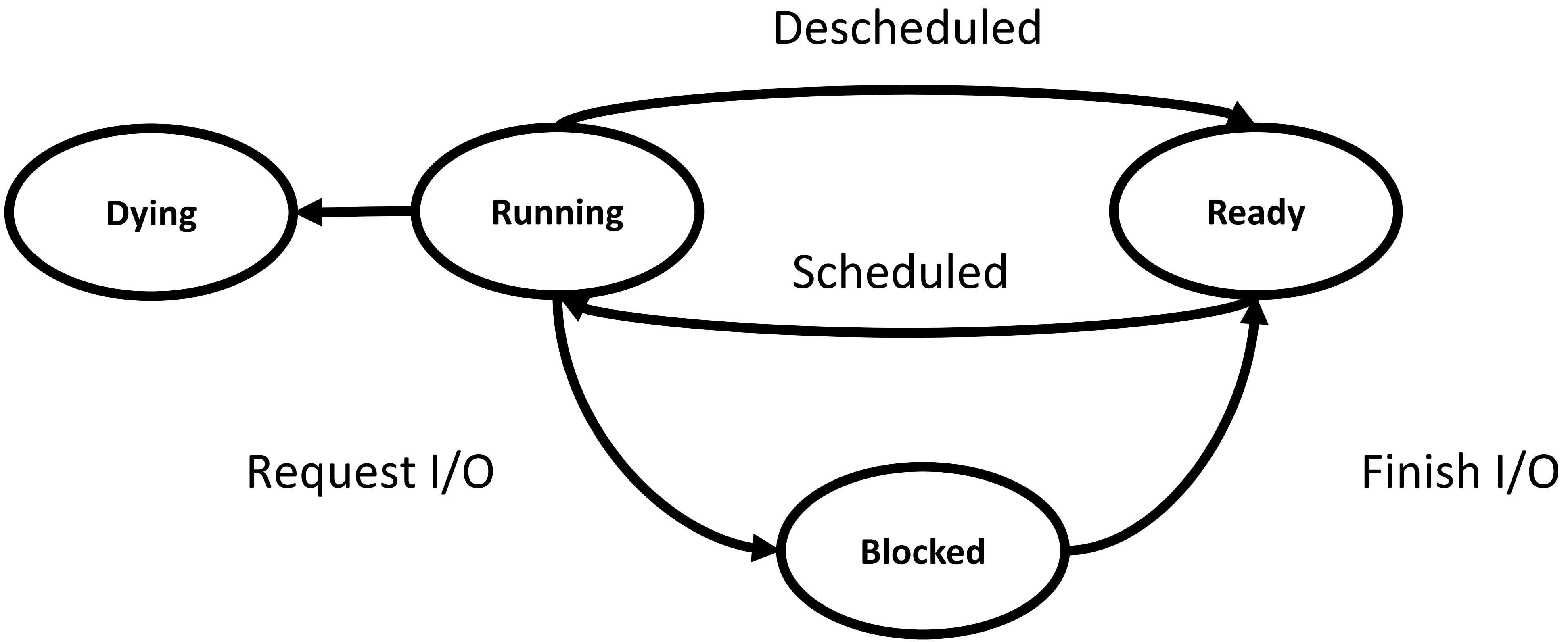
Processes | Performance | App history | Startup | Users | Details | Services

| 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)

# 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.

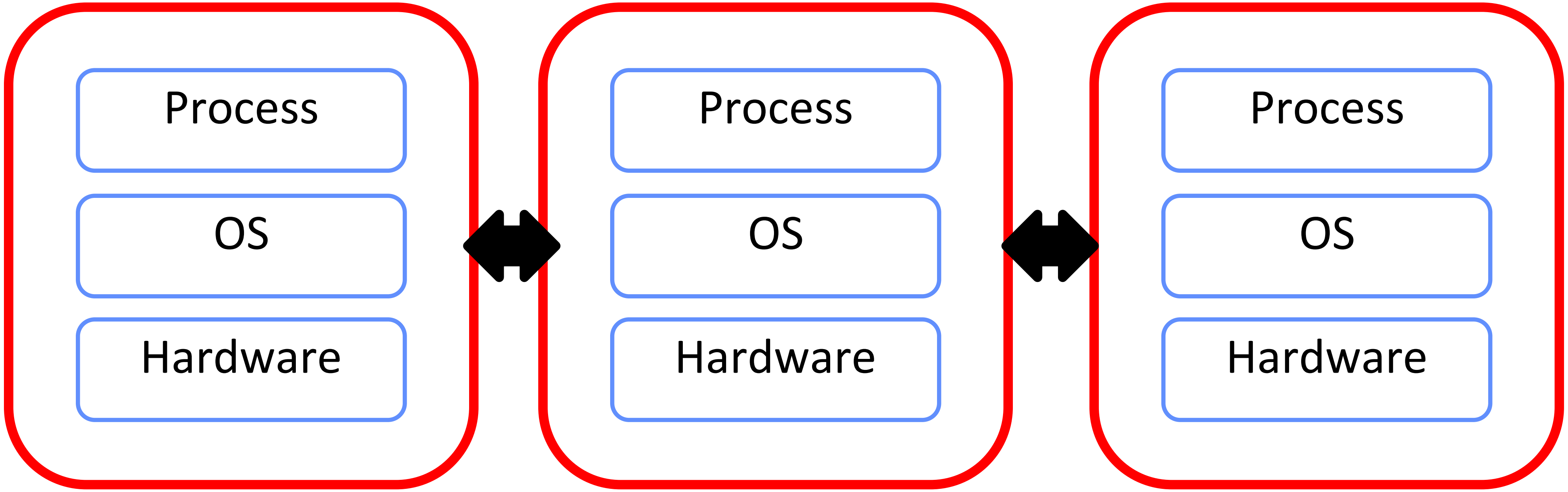
Kernel is trusted with full access to all hardware capabilities

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

<u>Application/User Code (Untrusted)</u>

Run all the processor with all potentially dangerous operations disabled

<u>Kernel Code (Trusted)</u>

Runs directly on processor with unlimited rights

Performs any hardware operations

But run on the same machine!

# How can the kernel enforce restricted rights?

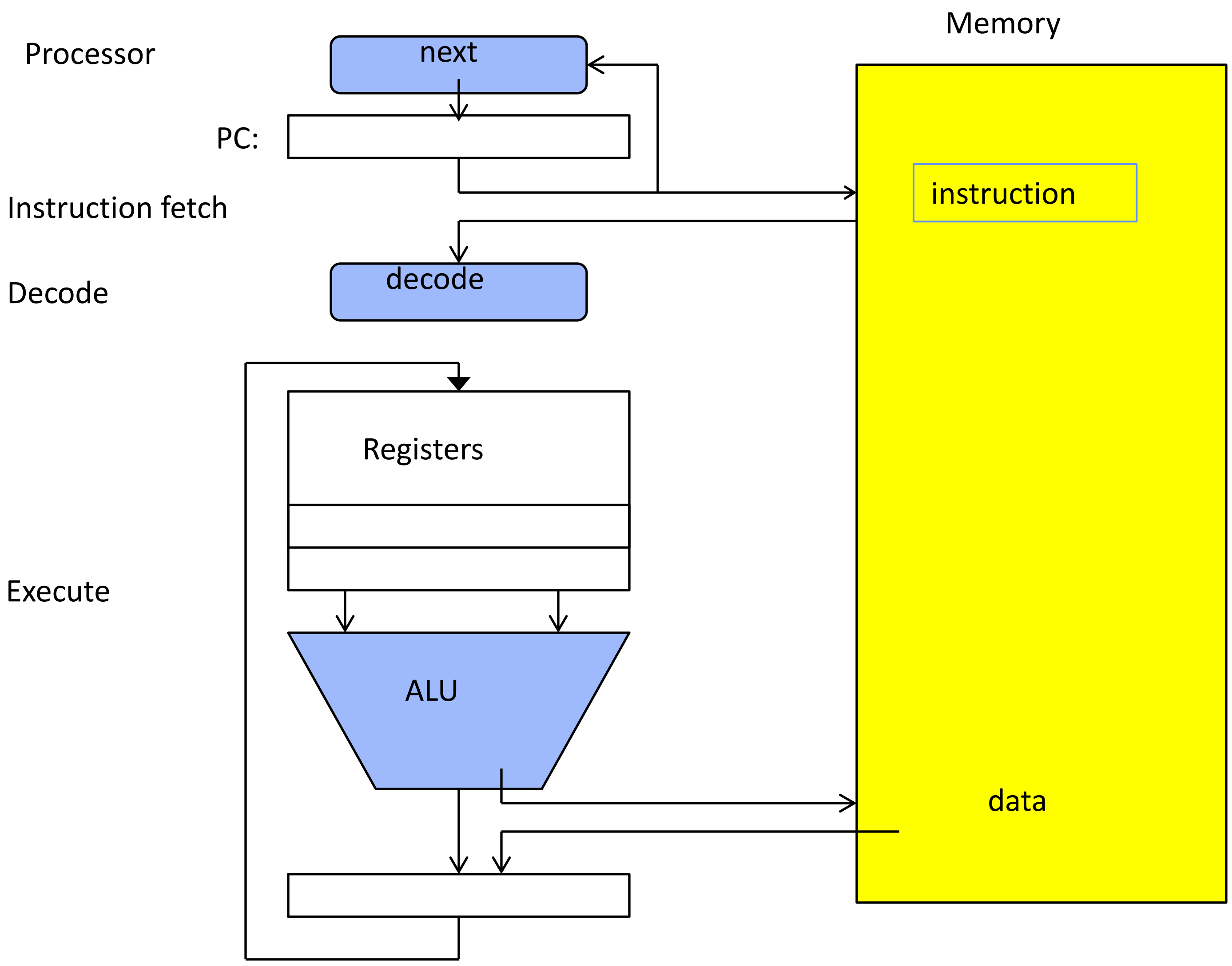
**1) While preserving functionality**

**2) While preserving performance**

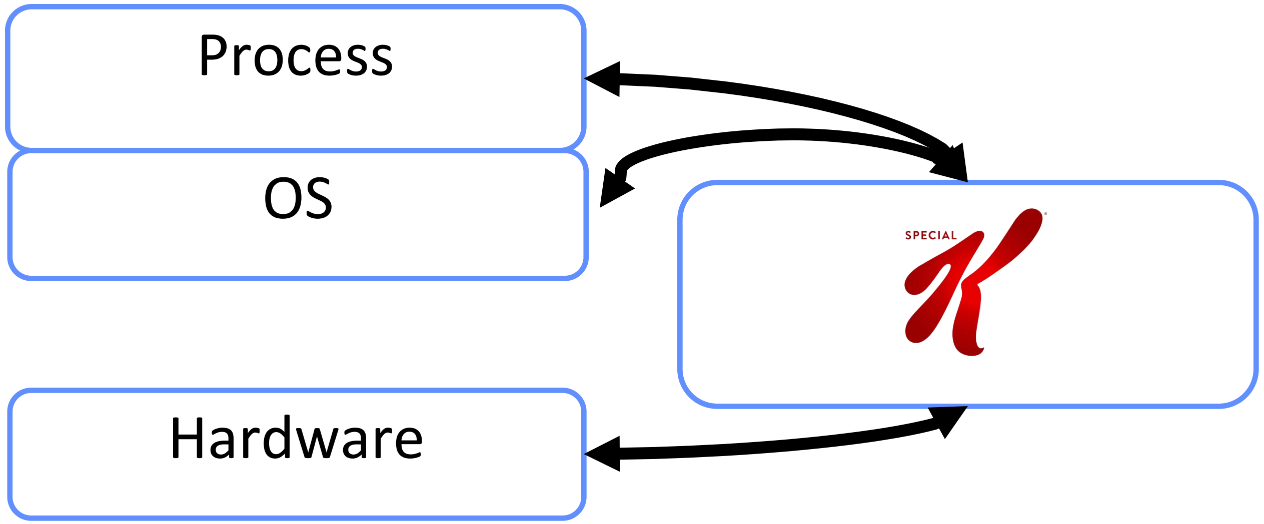
**3) While preserving control**

# 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.

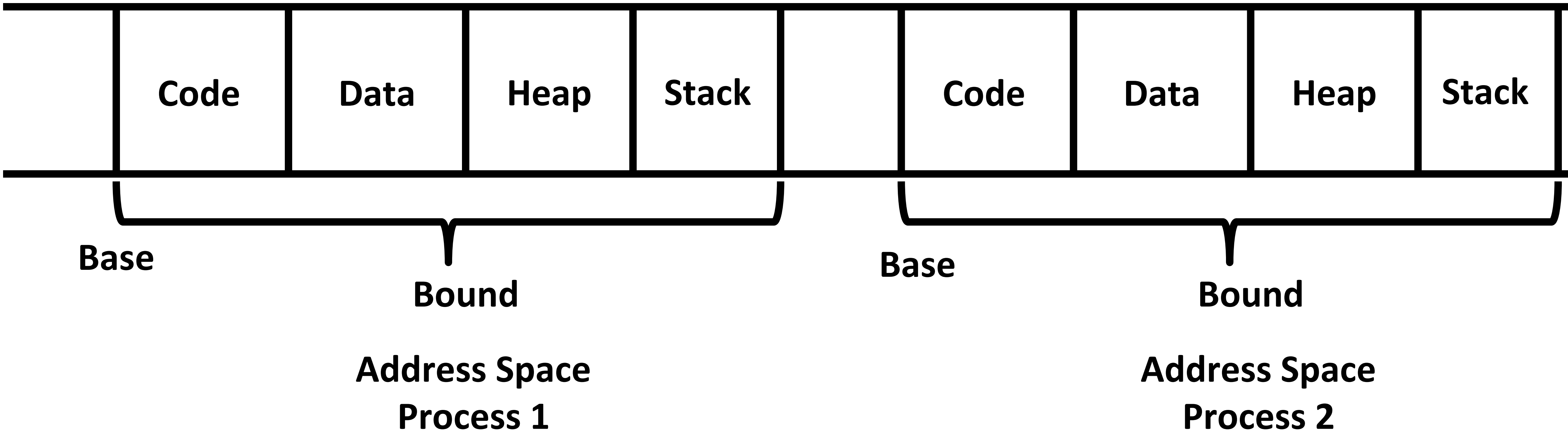
# Super Mario Land 2

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

# Attempt 1: Isolation

**Hardware to the rescue! (Again)**

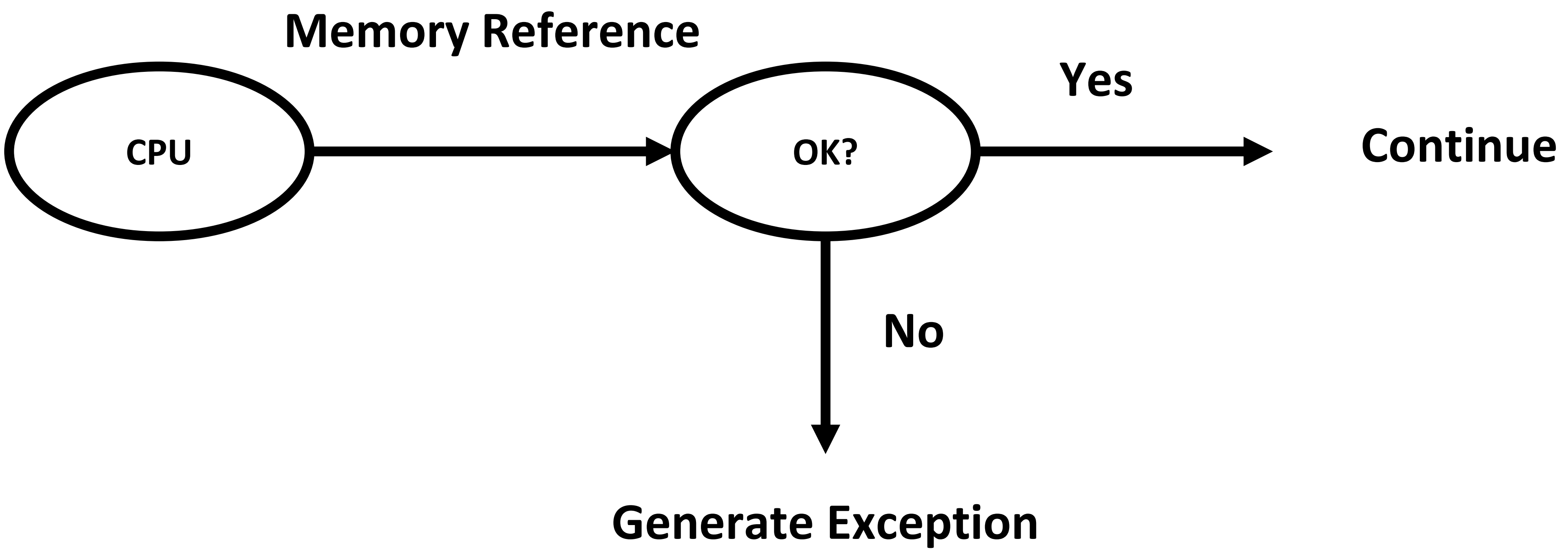
**Base and Bound registers**



# 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**

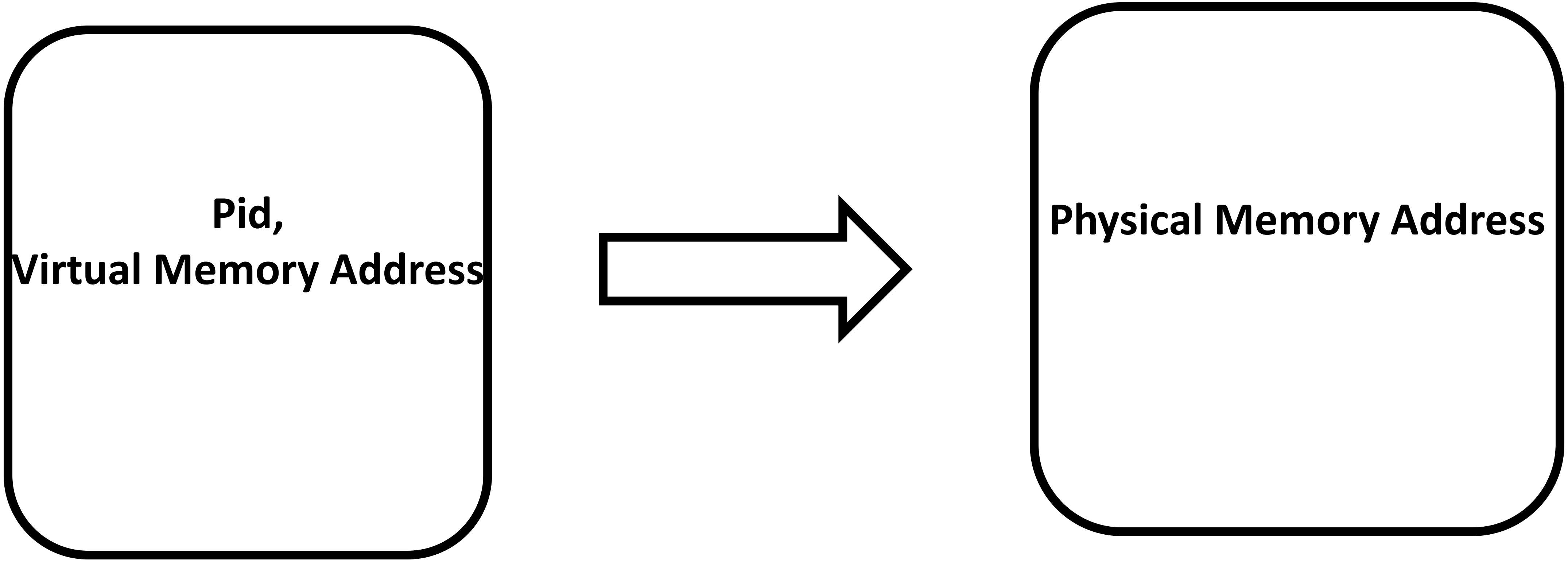
**Set of memory addresses that process can “touch”**

**Physical address space**

**Set of memory addresses supported by hardware**

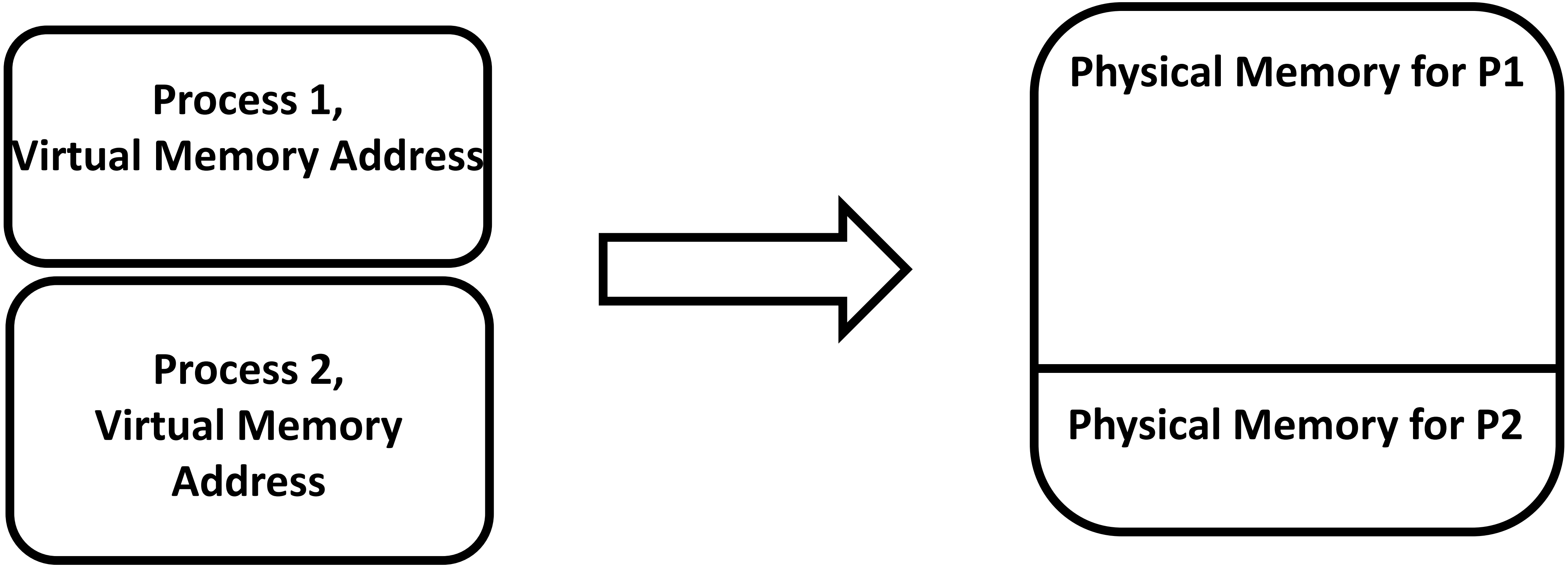
# Attempt 2: Virtualization

**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)

```c
#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 |
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| Distributed Systems | Challenges with distribution |
| | Data Processing & Storage |

# Hardware must support

## 1) Privileged Instructions

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## 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**

**Synchronous Events (trapping)**

3) **Interrupts**

**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.**

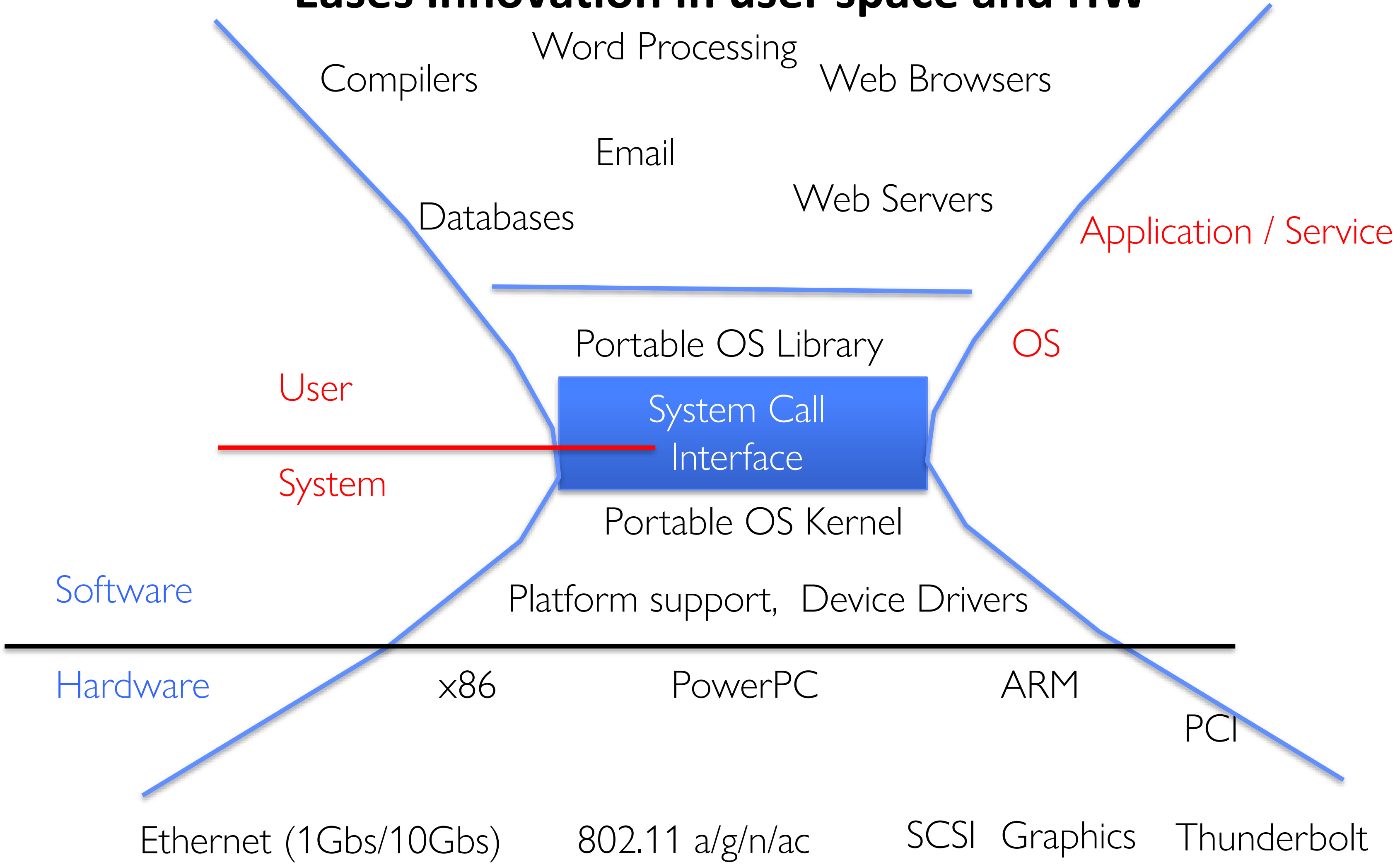
**How many system calls in Linux 3.0 ?**
**a) 15 b) 336 c) 1021 d) 21121**

**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-maskeable**

**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

```c
/* 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