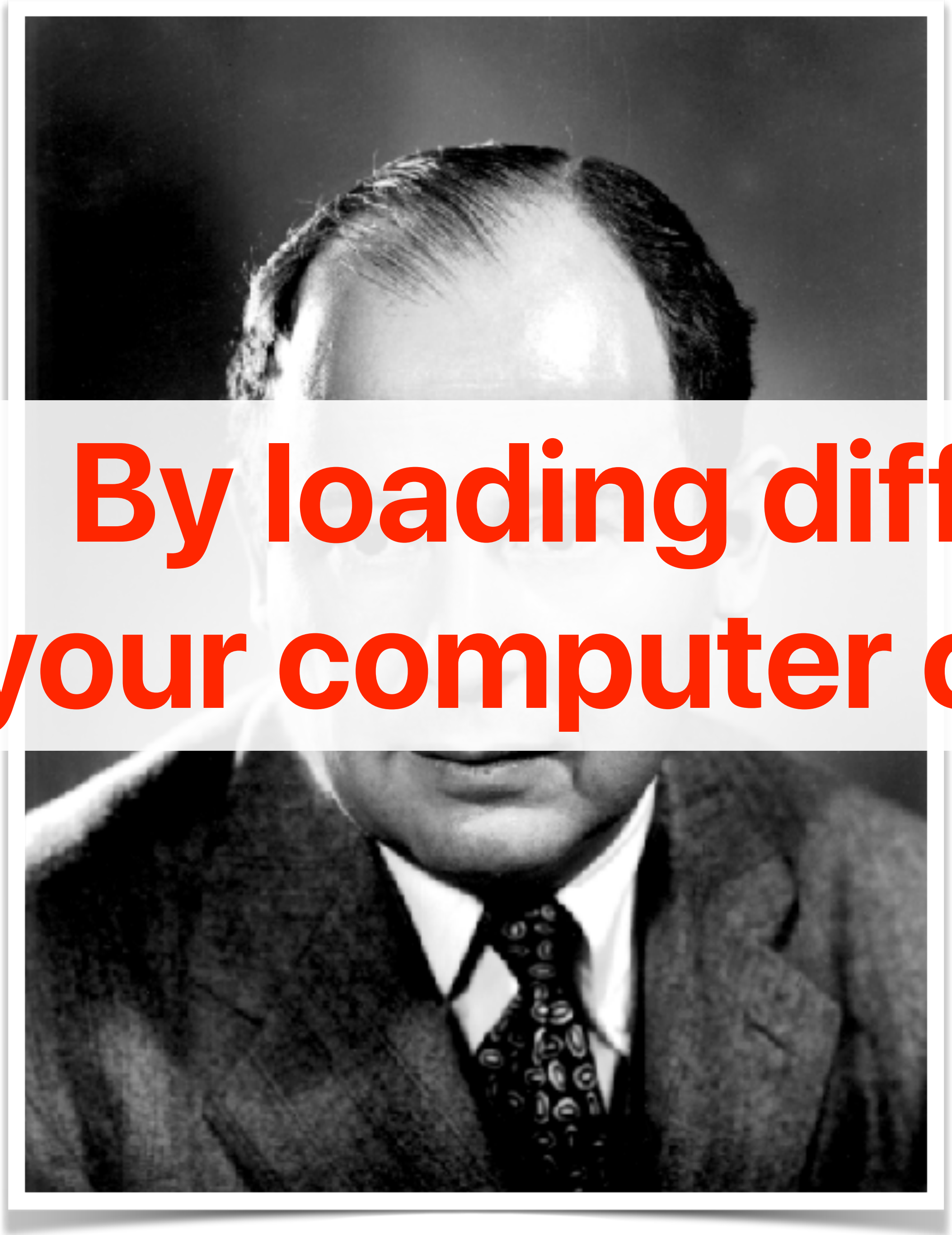
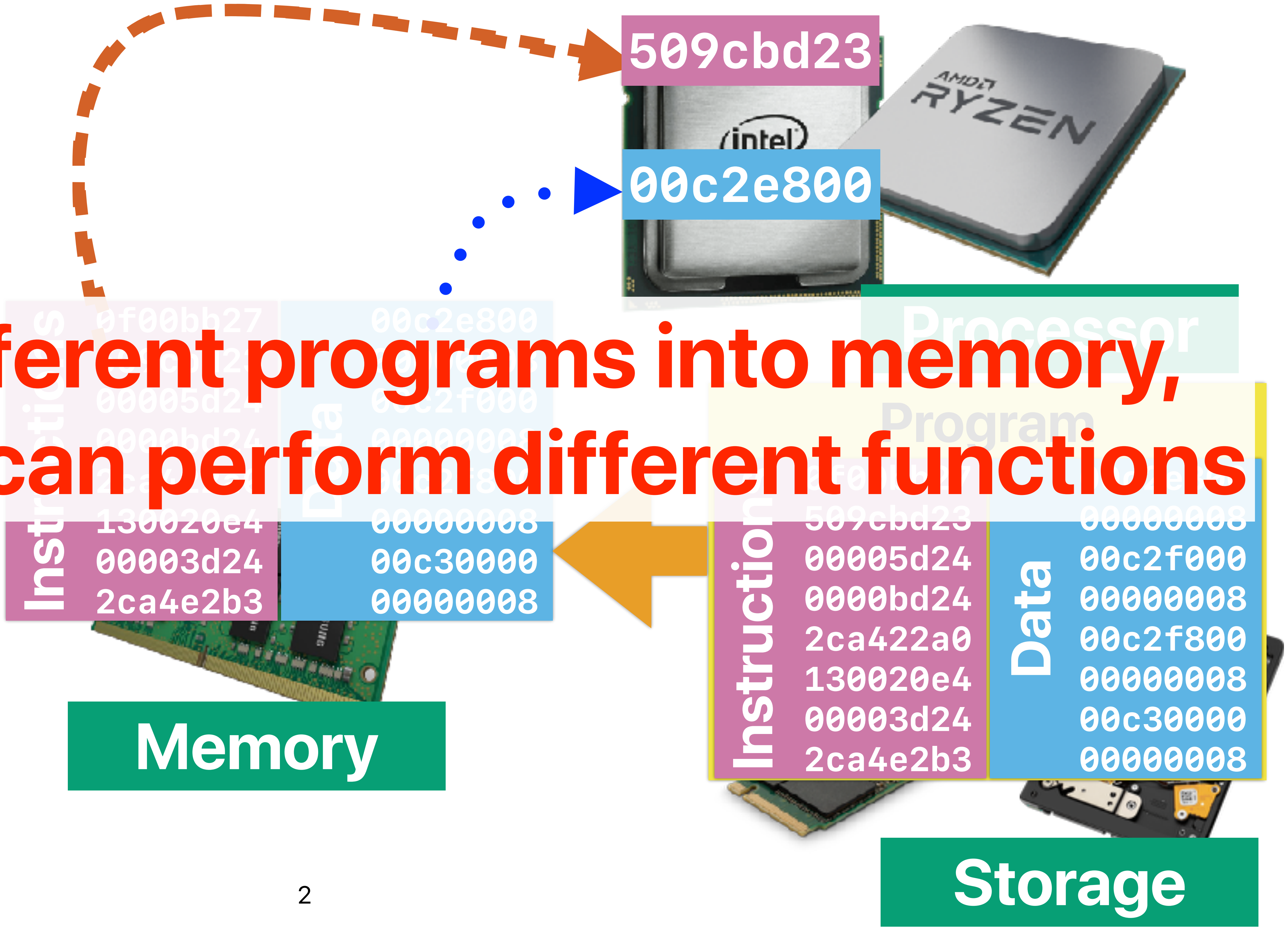
The Fundamentals of Operating Systems

Hung-Wei Tseng

Recap: von Neumman Architecture

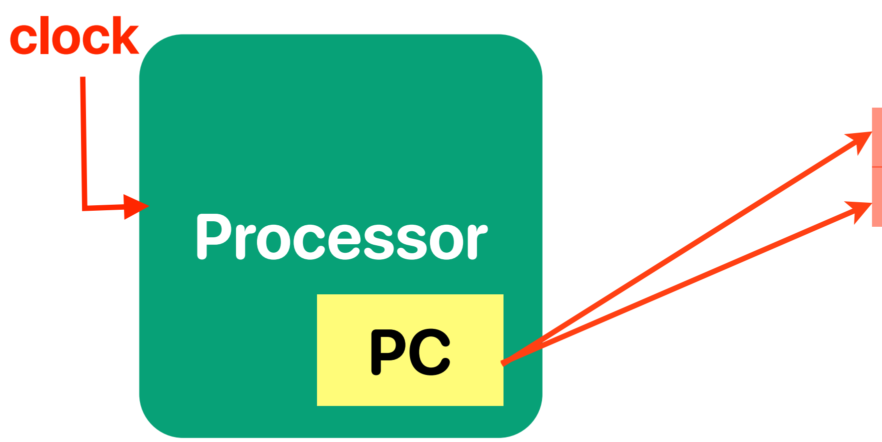




By loading different programs into memory, your computer can perform different functions

Recap: How processor executes a program

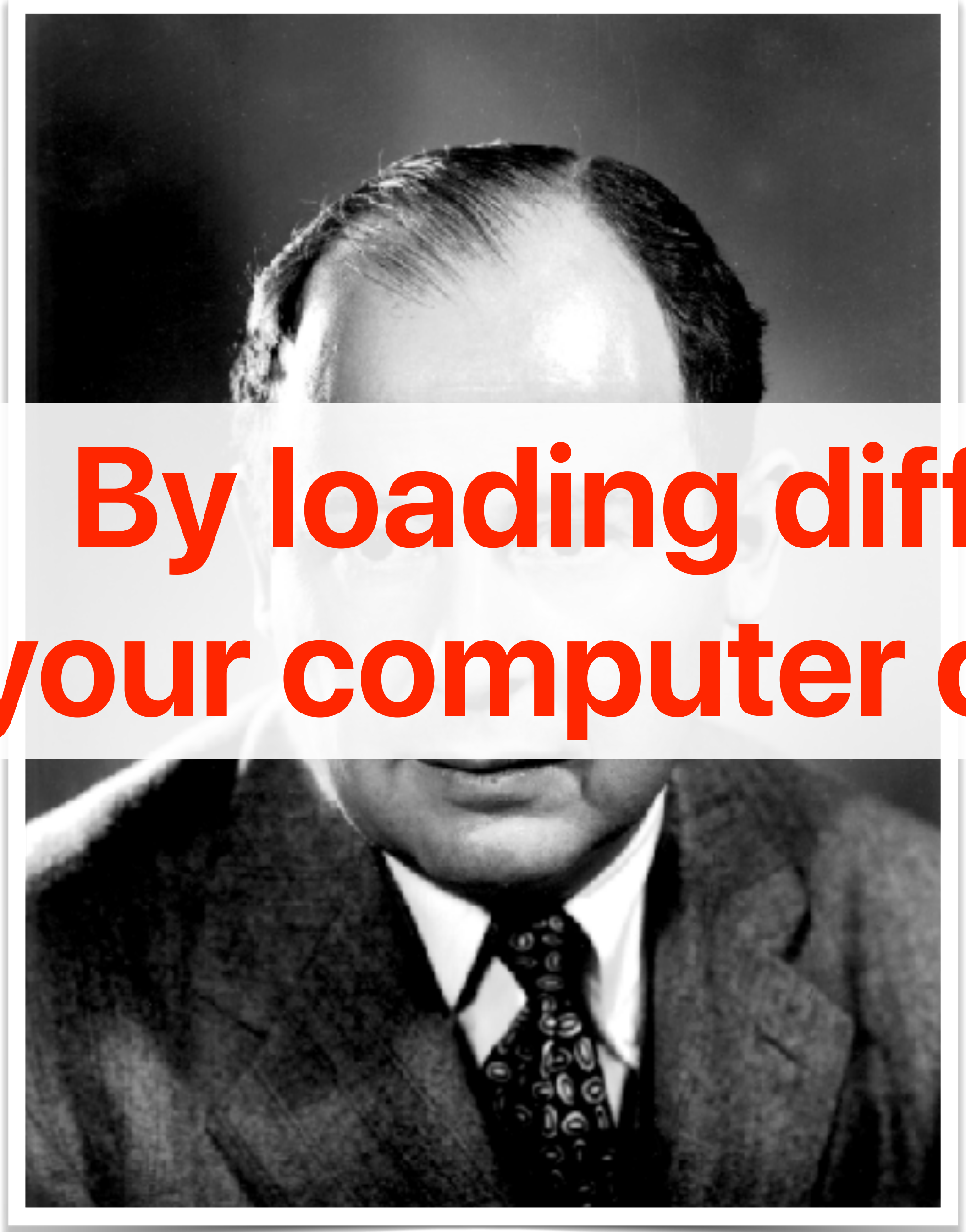
- The program counter (PC) tells where the upcoming instruction is in the memory
- Processor fetches the instruction, decode the instruction, execute the instruction, present the instruction results according to clock signals
- The processor fetches the next instruction whenever it’s safe to do so



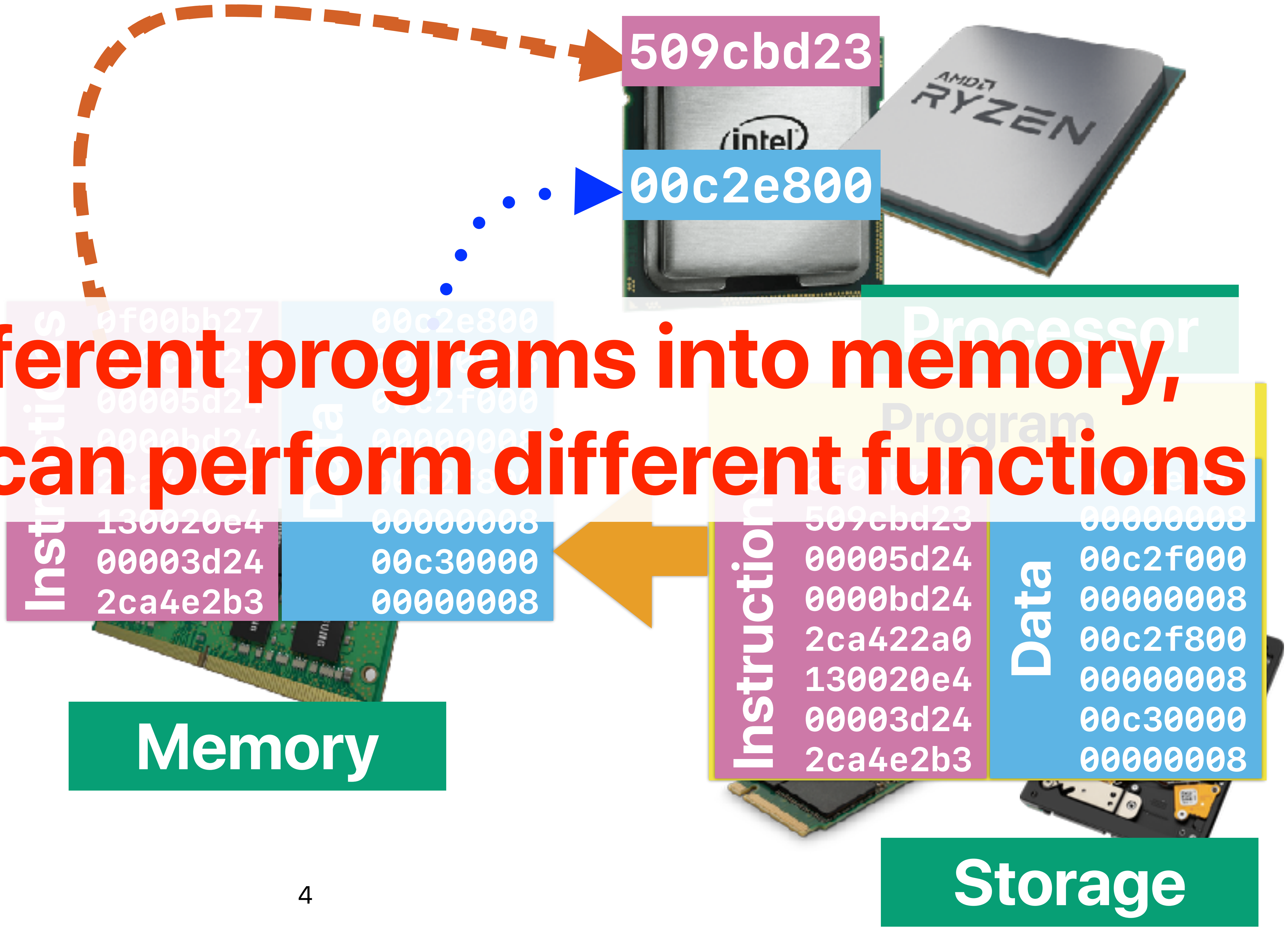
instruction memory

```
120007a30:  0f00bb27  ldah  gp,15(t12)
120007a34:  509cbd23  lda   gp,-25520(gp)
120007a38:  00005d24  ldah  t1,0(gp)
120007a3c:  0000bd24  ldah  t4,0(gp)
120007a40:  2ca422a0  ldl   t0,-23508(t1)
120007a44:  130020e4  beq   t0,120007a94
120007a48:  00003d24  ldah  t0,0(gp)
120007a4c:  2ca4e2b3  stl   zero,-23508(t1)
120007a50:  0004ff47  clr   v0
120007a54:  28a4e5b3  stl   zero,-23512(t4)
120007a58:  20a421a4  ldq   t0,-23520(t0)
120007a5c:  0e0020e4  beq   t0,120007a98
120007a60:  0204e147  mov   t0,t1
120007a64:  0304ff47  clr   t2
120007a68:  0500e0c3  br    120007a80
```

Recap: von Neumman Architecture



By loading different programs into memory, your computer can perform different functions

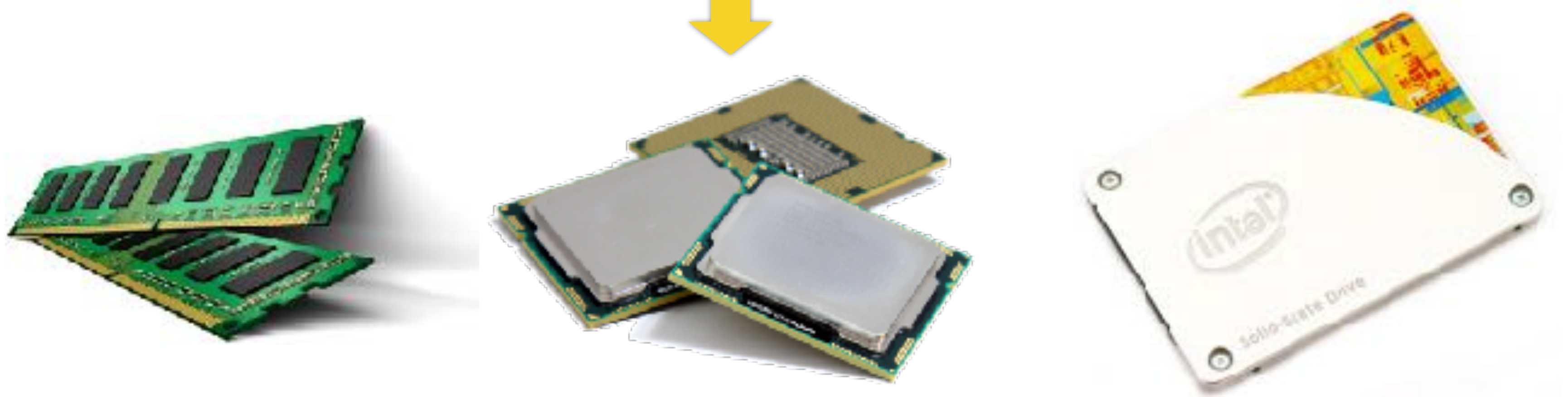


Without OSs...

https://az-eandt-live-legacy.azureedge.net/news/2013/apr/images/640_edsac-web.jpg

Without an OS: Direct Execution

Only one at a time, no way to interrupt a running task, and etc...



The goal of an OS

Recap: What modern operating systems support?

- **Virtualize** hardware/architectural resources
  - Easy for programs to interact with hardware resources
  - Share hardware resource among programs
  - Protect programs from each other (security)
- Execute multithreaded programs **concurrently**
  - Support multithreaded programming model
  - Execute multithreaded programs efficiently
- Store data **persistently**
  - Store data safely
  - Secure

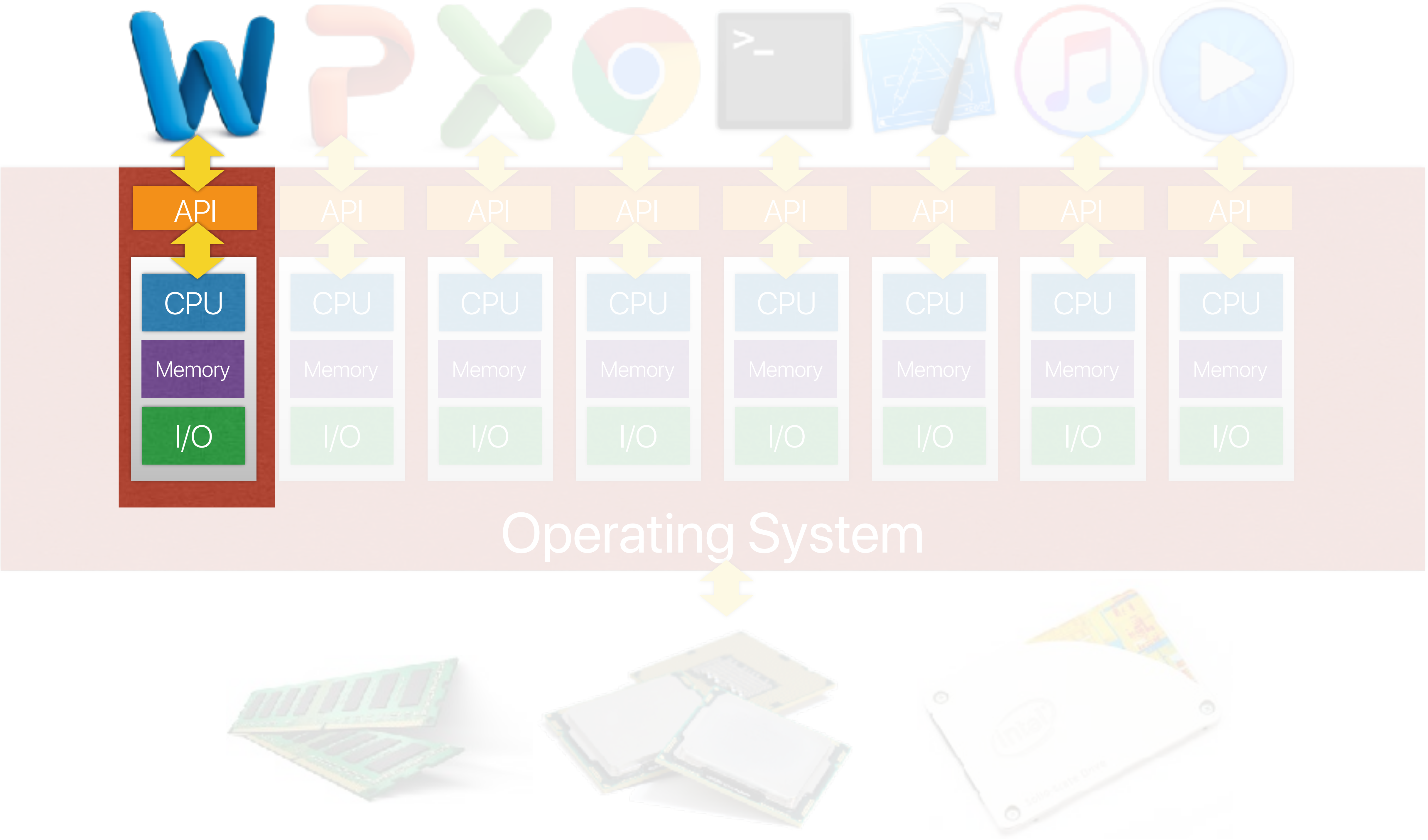
Outline

- Operating systems: virtualizing computers
- Process: the most important abstraction in modern OSs
- Restricted operations: kernel and user modes

Operating systems: virtualizing computers

The goal of an OS

The idea of an OS: virtualization



The idea: virtualization

- The operating system presents an illusion of a virtual machine to each running program and maintains architectural states of a von Neumann machine
    - Processor
    - Memory
    - I/O
- Each virtualized environment accesses architectural facilities through some sort of application programming interface (API)
- Dynamically map those virtualized resources into physical resources

Demo: Virtualization

```
double a;

int main(int argc, char *argv[])
{
    int cpu, status, i;
    int *address_from_malloc;
    cpu_set_t my_set;         // Define your cpu_set bit mask.
    CPU_ZERO(&my_set);        // Initialize it all to 0, i.e. no CPUs selected.
    CPU_SET(4, &my_set);      // set the bit that represents core 7.
    sched_setaffinity(0, sizeof(cpu_set_t), &my_set); // Set affinity of this process to the defined mask, i.e. only 7.
    status = syscall(SYS_getcpu, &cpu, NULL, NULL);
```

getcpu system call to retrieve the executing CPU ID

```
    if(argc < 2)
    {
        fprintf(stderr, "Usage: %s process_nickname\n",argv[0]);
        exit(1);
    }

    srand((int)time(NULL)+(int)getpid());
    a = rand();
```

create a random number

```
    fprintf(stderr, "\nProcess %s is using CPU: %d. Value of a is %lf and address of a is %p\n",argv[1], cpu, a, &a);
    sleep(1);
```

print the value of a and address of a

```
    fprintf(stderr, "\nProcess %s is using CPU: %d. Value of a is %lf and address of a is %p\n",argv[1], cpu, a, &a);
    sleep(3);
```

print the value of a and address of a again after sleep

```
    return 0;
}
```

```
Process C is using CPU: 4. Value of a is 685161796.000000 and address of a is 0x6010b0
Process A is using CPU: 4. Value of a is 217757257.000000 and address of a is 0x6010b0
Process B is using CPU: 4. Value of a is 2057721479.000000 and address of a is 0x6010b0
Process D is using CPU: 4. Value of a is 1457934803.000000 and address of a is 0x6010b0
Process C is using CPU: 4. Value of a is 685161796.000000 and address of a is 0x6010b0
Process A is using CPU: 4. Value of a is 217757257.000000 and address of a is 0x6010b0
Process B is using CPU: 4. Value of a is 2057721479.000000 and address of a is 0x6010b0
Process D is using CPU: 4. Value of a is 1457934803.000000 and address of a is 0x6010b0
```

Different values

The same processor!

Different values are preserved

The same memory address!

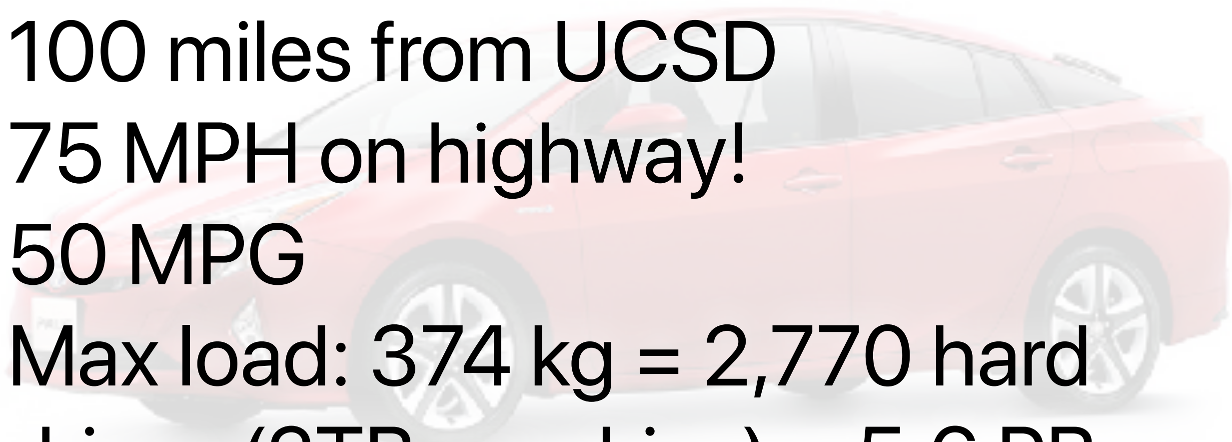
Demo: Virtualization

- Some processes may use the same processor
- Each process has the same address for variable a, but different values.
- You may see the content of a compiled program using objdump

Latency v.s. Throughput

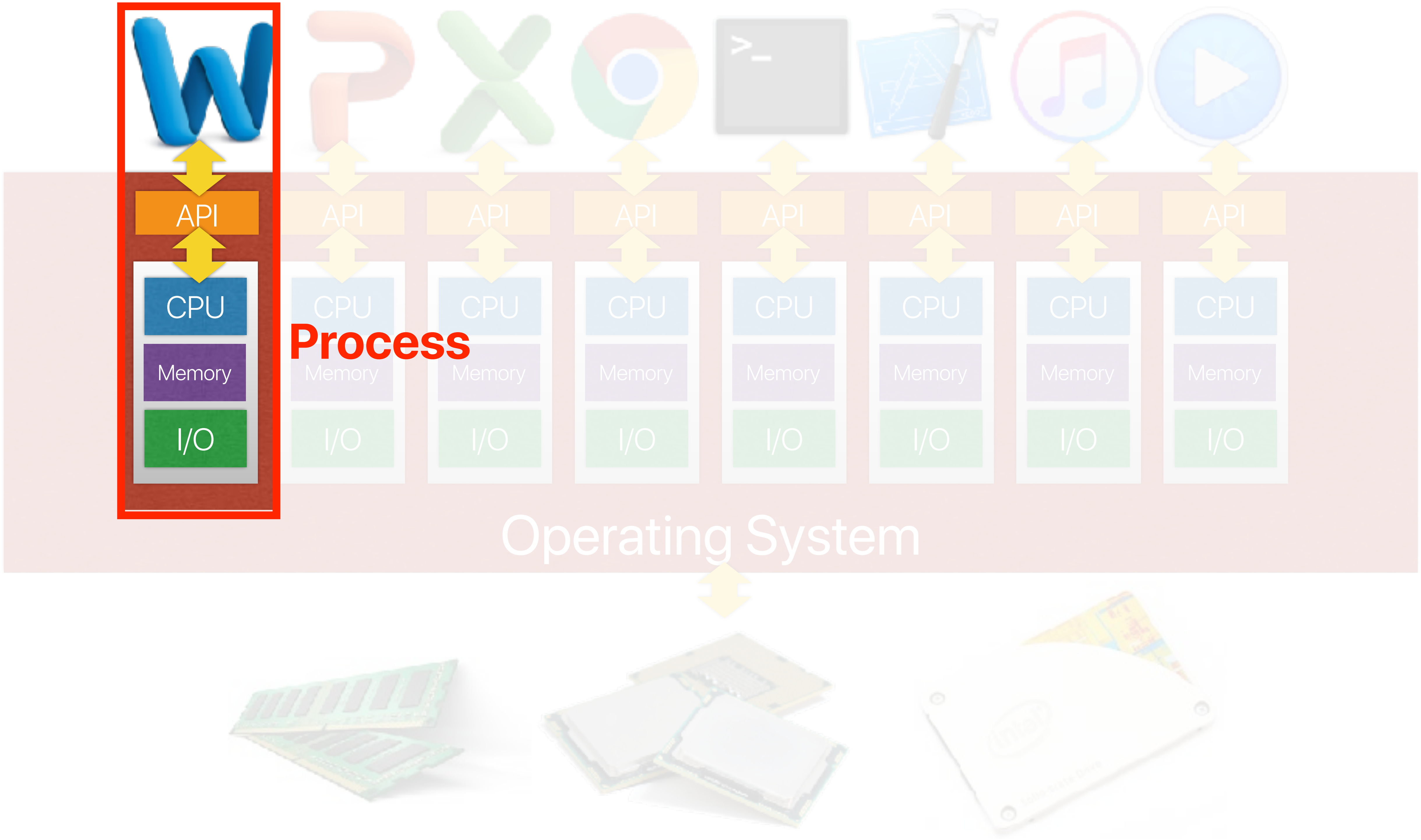
- A 4K movie clip using H.265 coding takes **70GB** in storage
- If you want to transfer a total of 2 Peta-Byte video clips (roughly 29959 movies) from UCSD
  - 100 miles from UCR
  - Assume that you have a **100Gbps** ethernet
    - Throughput: 100 Gbits per second
    - 2 Peta-byte (16 Peta-bits) over 167772 seconds = 1.94 Days
    - Latency: first 70GB (first movie) in 6 seconds

Or ...

	Toyota Prius	10Gb Ethernet
	 100 miles from UCSD 75 MPH on highway! 50 MPG Max load: 374 kg = 2,770 hard drives (2TB per drive) = 5.6 PB	
Throughput/ bandwidth	**450GB/sec**	100 Gb/s or 12.5GB/sec
latency	3.5 hours	2 Peta-byte over 167772 seconds = 1.94 Days
response time	You see **nothing** in the first 3.5 hours	You can start watching the first movie as soon as you get a frame!

Process: the most important abstraction in modern operating systems

The idea of an OS: virtualization



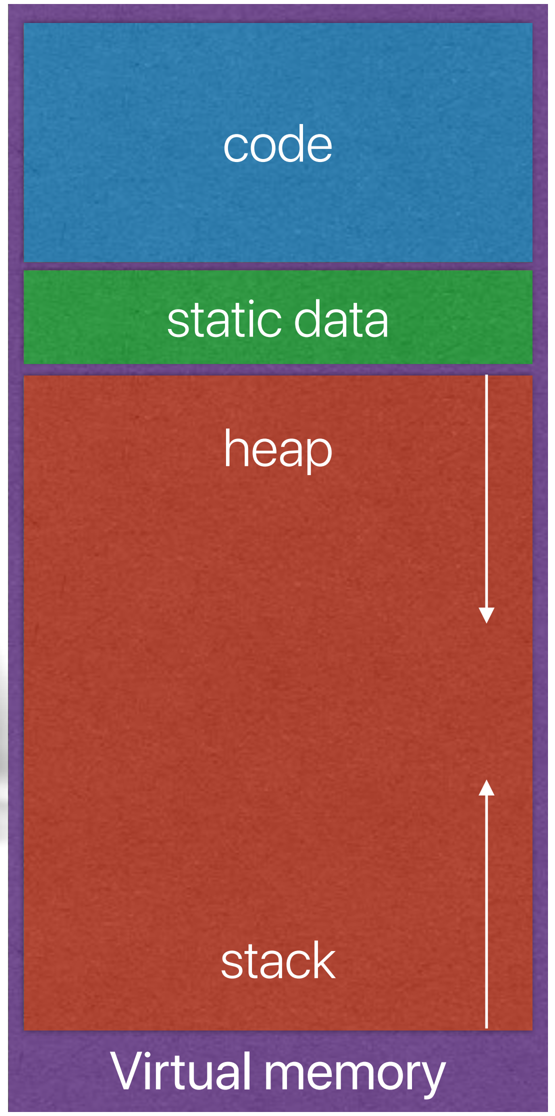
Processes

- The **most important abstraction** in modern operating systems.
- A process abstracts the underlying computer.
- A process is a **running program —** a dynamic entity of a program.
  - Program is a static file/combination of instructions
  - Process = program + states
  - The states evolves over time
- A process may be dynamically switched out/back during the execution

Virtualization

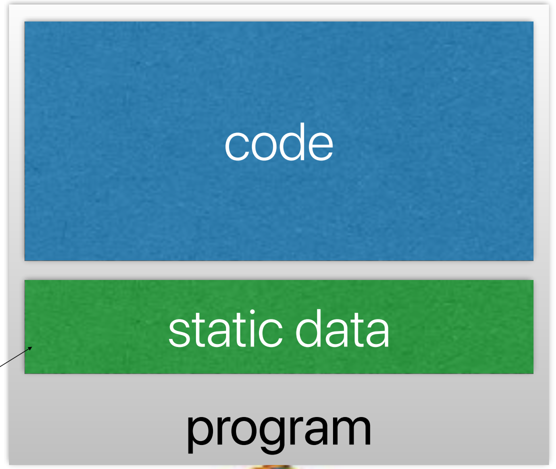
- The operating system presents an **illusion** of a **virtual machine** to each running program — **process**
  - Each virtual machine contains architectural states of a von Neumann machine
    - Processor
    - Memory
    - I/O
- Each virtualized environment accesses architectural facilities through some sort of application programming interface (API) — **system calls**
- Dynamically map those virtualized resources into physical resources — **policies, mechanisms**

What happens when creating a process



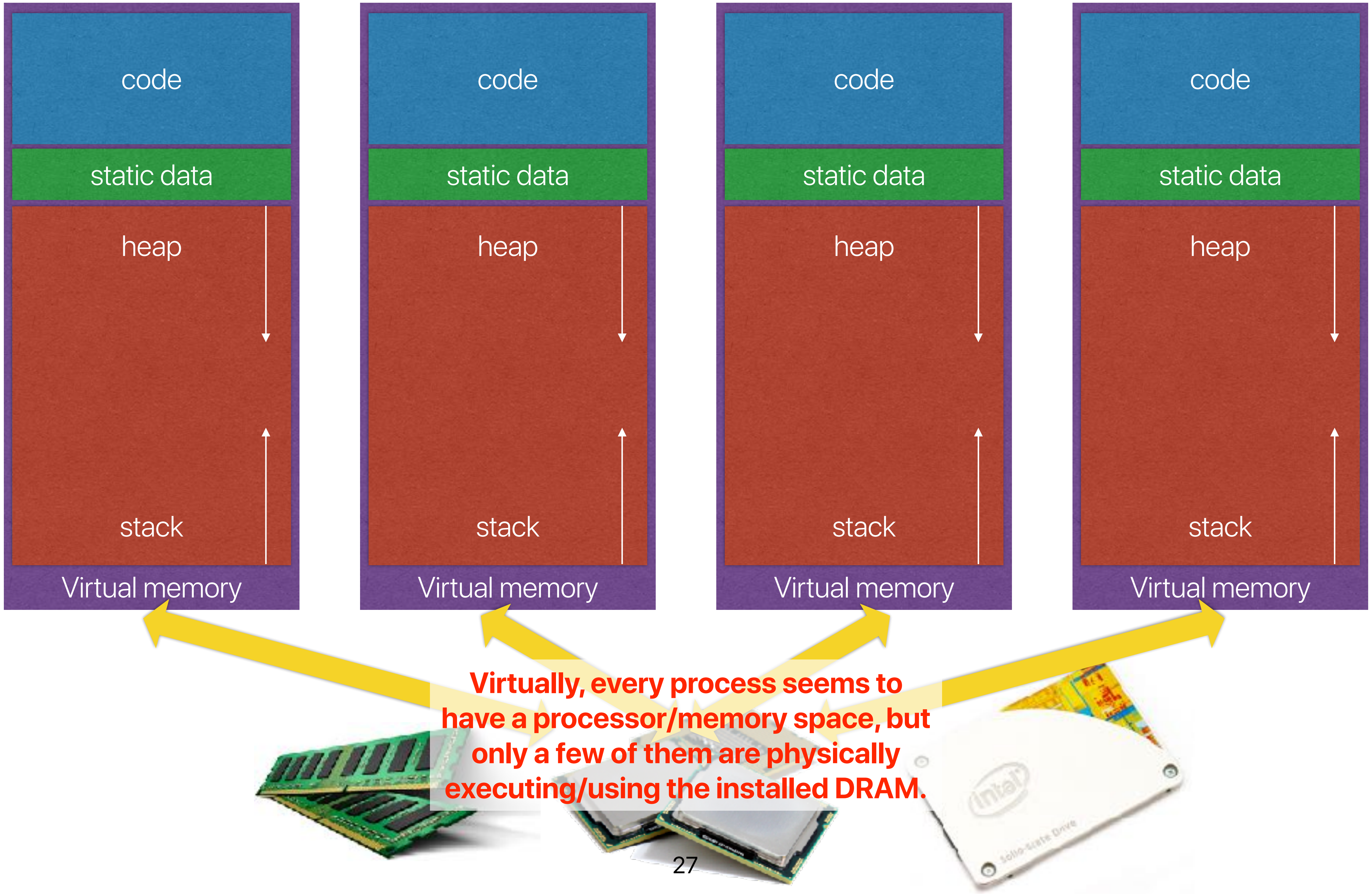
Dynamic allocated data: `malloc()`

Local variables,
arguments



Linux contains a .bss section
for uninitialized global variables

The illusion provided by processes



Virtually, every process seems to have a processor/memory space, but only a few of them are physically executing/using the installed DRAM.

Process control block

- OS has a PCB for each process
- Sometimes called Task Controlling Block, Task Struct, or Switchframe
- The data structure in the operating system kernel containing the information needed to manage a particular process.
- The PCB is the manifestation of a process in an operating system

Example: `struct task_struct` in Linux

```
struct task_struct {
        volatile long state;    /* -1 unrunnable, 0 runnable, >0 stopped */
        void *stack;
        atomic_t usage;
        unsigned int flags;     /* per process flags, defined below */
        unsigned int ptrace;
        int on_rq;
        int prio, static_prio, normal_prio;
        const struct sched_class *sched_class;
        struct sched_entity se;
        struct sched_rt_entity rt;
        unsigned int policy;
        int nr_cpus_allowed;
        cpumask_t cpus_allowed;
        pid_t pid;
        struct task_struct __rcu *real_parent;
        struct task_struct __rcu *parent;
        struct list_head children;
        struct list_head sibling;
        ……
        struct list_head tasks;
        ……
        struct mm_struct *mm, *active_mm;
        ……
/* CPU-specific state of this task */
        struct thread_struct thread;
}
```

Process state

Process ID

Virtual memory pointers

Low-level architectural states

- You may find this struct in /usr/src/linux-headers-x.x.x-xx/include/linux/sched.h

Memory pointers in `struct mm_struct`

```
struct mm_struct {
        struct vm_area_struct * mmap;           /* list of VMAs */
        ...
        unsigned long start_code, end_code, start_data, end_data;
        unsigned long start_brk, brk, start_stack;
        ...
};
```

start of heap

end of heap

current stack pointer

Processor states in `struct thread_struct`

```
struct thread_struct {
        struct desc_struct tls_array[GDT_ENTRY_TLS_ENTRIES];
        unsigned long           sp0;
        unsigned long           sp;
#ifdef CONFIG_X86_32
        unsigned long           sysenter_cs;
#else
        unsigned short          es;
        unsigned short          ds;
        unsigned short          fsindex;
        unsigned short          gsindex;
#endif
#ifdef CONFIG_X86_32
        unsigned long           ip;
#endif
#ifdef CONFIG_X86_64
        unsigned long           fs;
#endif
        unsigned long           gs;
        struct perf_event       *ptrace_bps[HBP_NUM];
        unsigned long           debugreg6;
        unsigned long           ptrace_dr7;
        unsigned long           cr2;
        unsigned long           trap_nr;
        unsigned long           error_code;
#ifdef CONFIG_VM86
        struct vm86             *vm86;
#endif
        unsigned long           *io_bitmap_ptr;
        unsigned long           iopl;
        unsigned                io_bitmap_max;
        struct fpu              fpu;
    };
```

Some x86 Register values

Program counter

Virtualization

However, we don't want everything to pass through this API!

Too slow!!!

Do you really need to track all intermediate states?

Solution — hardware support

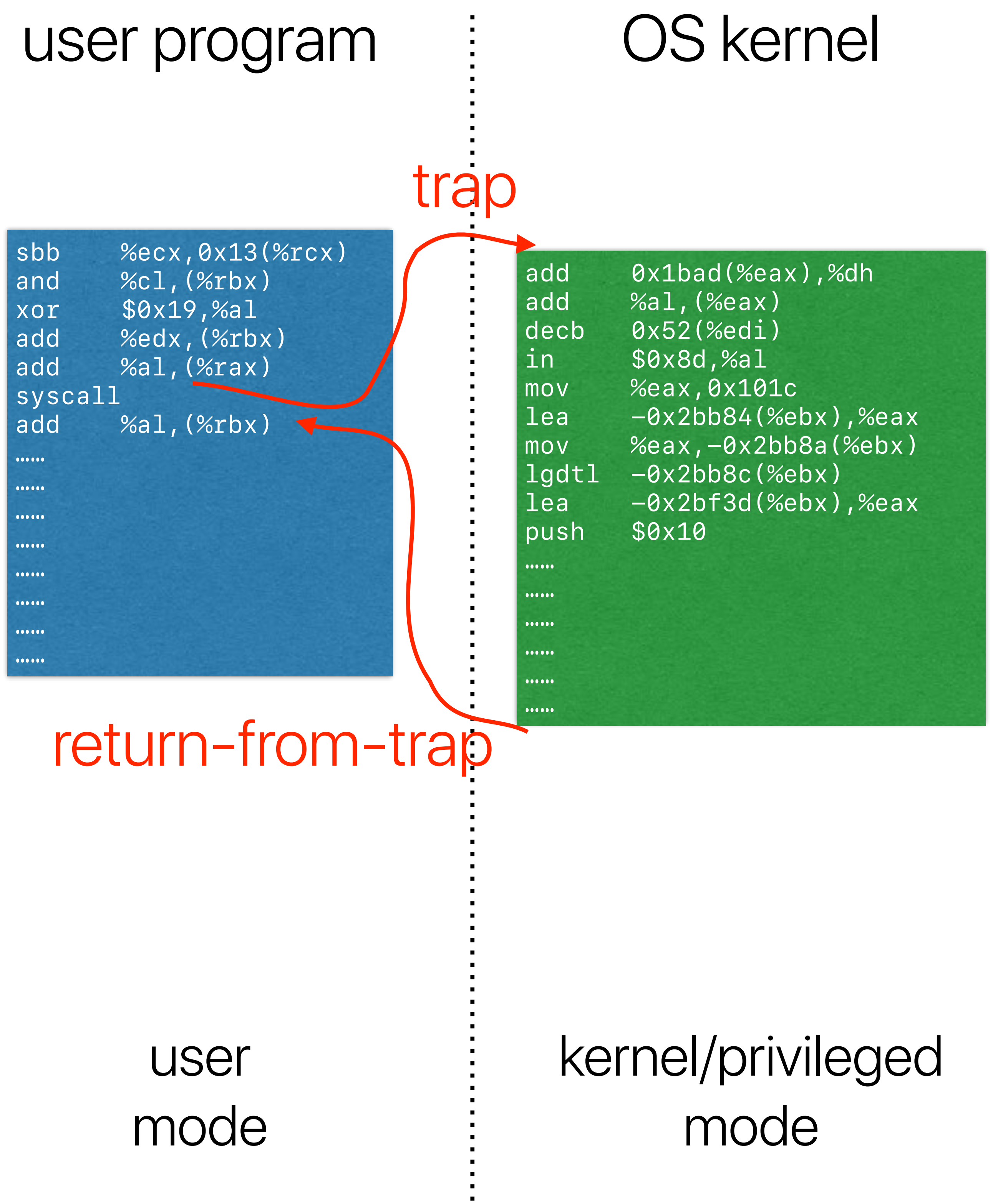
Restricted operations: kernel and user modes

Restricted operations

- Most operations can directly execute on the processor without OS's intervention
- The OS only takes care of protected resources, change running processes or anything that the user program cannot handle properly
- Divide operations into two modes
  - User mode
    - Restricted operations
    - User processes
  - Kernel mode
    - Can perform privileged operations
    - The operating system kernel
- Requires architectural/hardware supports

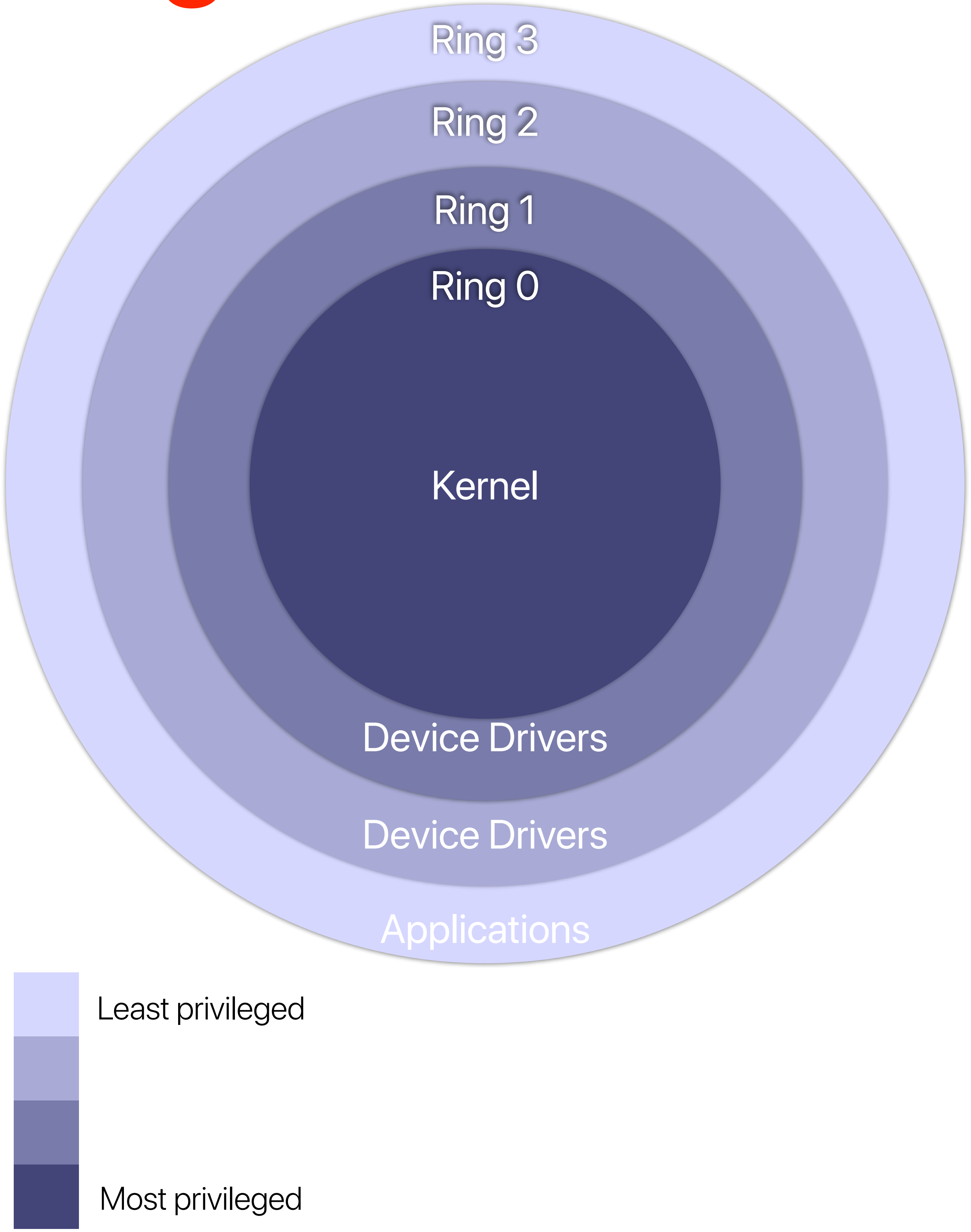
How applications can use privileged operations?

- Through the API: **System calls**
- Implemented in "trap" instructions
  - Raise an exception in the processor
  - The processor saves the exception PC and jumps to the corresponding exception handler in the OS kernel



Architectural support: privileged instructions

- The processor provides **normal** instructions and **privileged** instructions
  - Normal instructions: ADD, SUB, MUL, and etc ...
  - Privileged instructions: HLT, CLTS, LIDT, LMSW, SIDT, ARPL, and etc...
- The processor provides different modes
  - User processes can use normal instructions
  - Privileged instruction can only be used if the processor is in proper mode



Interrupts, system calls, exceptions

- All of them will trap to kernel mode
- Interrupts: raised by hardware
  - Keystroke, network packets
- System calls: raised by applications
  - Display images, play sounds
- Exceptions: raised by processor itself
  - Divided by zero, unknown memory addresses

"A lie doesn't become truth, wrong doesn't become right and evil doesn't become good, just because it is accepted by a majority."

–RICK WARREN

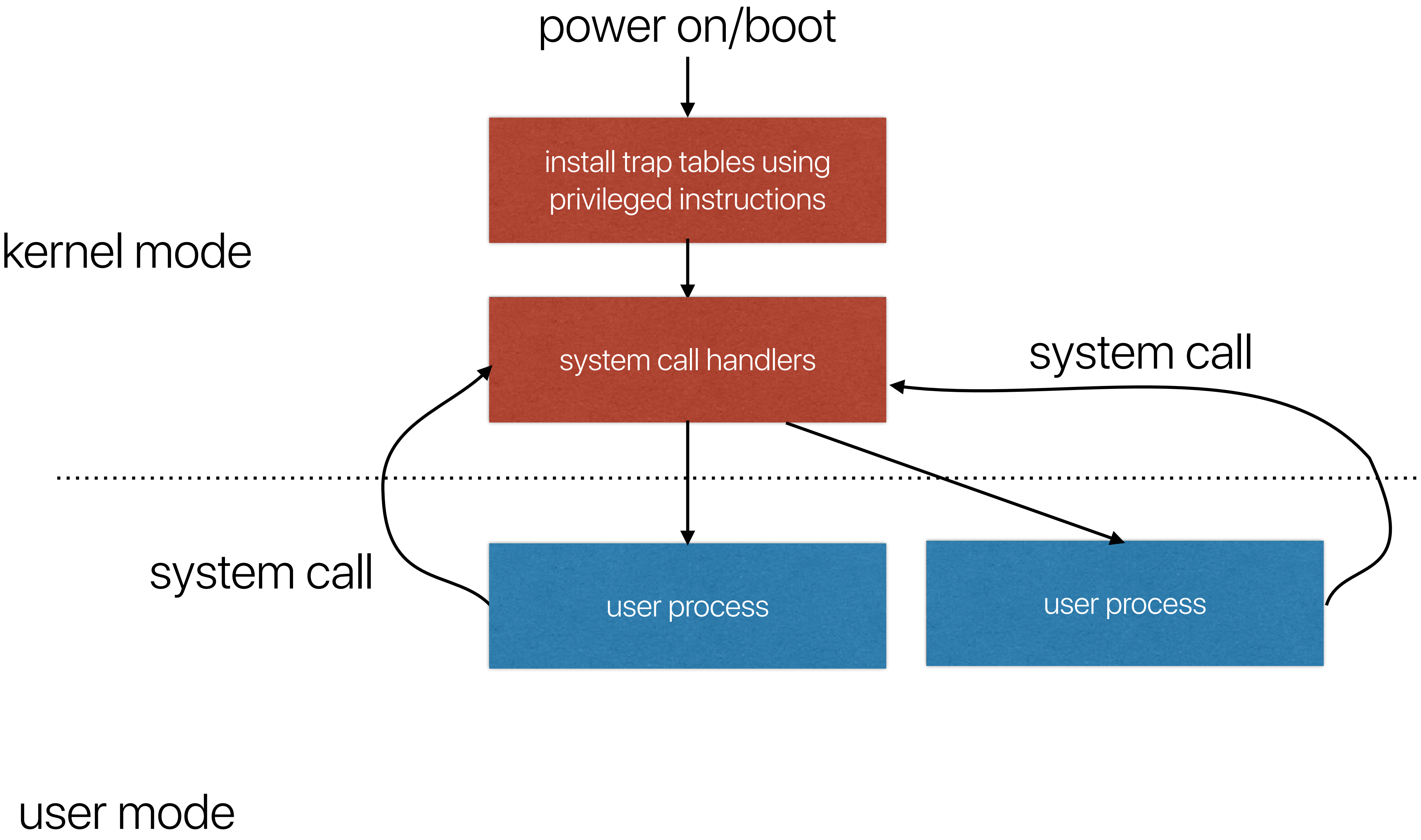
Latency Numbers Every Programmer Should Know

Operations	Latency (ns)	Latency (us)	Latency (ms)	
L1 cache reference	0.5 ns			~ 1 CPU cycle
Branch mispredict	5 ns			
L2 cache reference	7 ns			14x L1 cache
Mutex lock/unlock	25 ns			
Main memory reference	100 ns			20x L2 cache, 200x L1 cache
Compress 1K bytes with Zippy	3,000 ns	3 us		
Send 1K bytes over 1 Gbps network	10,000 ns	10 us		
Read 4K randomly from SSD*	150,000 ns	150 us		~1GB/sec SSD
Read 1 MB sequentially from memory	250,000 ns	250 us		
Round trip within same datacenter	500,000 ns	500 us		
Read 1 MB sequentially from SSD*	1,000,000 ns	1,000 us	1 ms	~1GB/sec SSD, 4X memory
Disk seek	10,000,000 ns	10,000 us	10 ms	20x datacenter roundtrip
Read 1 MB sequentially from disk	20,000,000 ns	20,000 us	20 ms	80x memory, 20X SSD
Send packet CA-Netherlands-CA	150,000,000 ns	150,000 us	150 ms	

Demo: Kernel Switch Overhead

- Measure kernel switch overhead using lmbench http://www.bitmover.com/lmbench/

How does the processor knows where to jump to?



Context Switch

- The process of changing the running program on a processor
- What happen during context switches:
  - Save the current architectural context in the memory
    - Execute machine dependent assembly code to save register values to memory
  - Restore the architectural context for the new running process
    - Execute machine dependent assembly code to load register values to memory
    - Jump to the PC of the new running process

Latency Numbers Every Programmer Should Know

Operations	Latency (ns)	Latency (us)	Latency (ms)	
L1 cache reference	0.5 ns			~ 1 CPU cycle
Branch mispredict	5 ns			
L2 cache reference	7 ns			14x L1 cache
Mutex lock/unlock	25 ns			
Main memory reference	100 ns			20x L2 cache, 200x L1 cache
Compress 1K bytes with Zippy	3,000 ns	3 us		
Send 1K bytes over 1 Gbps network	10,000 ns	10 us		
Read 4K randomly from SSD*	150,000 ns	150 us		~1GB/sec SSD
Read 1 MB sequentially from memory	250,000 ns	250 us		
Round trip within same datacenter	500,000 ns	500 us		
Read 1 MB sequentially from SSD*	1,000,000 ns	1,000 us	1 ms	~1GB/sec SSD, 4X memory
Disk seek	10,000,000 ns	10,000 us	10 ms	20x datacenter roundtrip
Read 1 MB sequentially from disk	20,000,000 ns	20,000 us	20 ms	80x memory, 20X SSD
Send packet CA-Netherlands-CA	150,000,000 ns	150,000 us	150 ms	

Announcement

- Two reading quizzes next week
  - We will discuss **4 papers** next week
  - We split them into two since that's probably the first you read papers