The Kernel

ICS332
Operating Systems

Henri Casanova (henric@hawaii.edu)

What is the Kernel

- The OS is **software**, and it has many components:
  - User interface (graphical, terminal)
  - File system
  - Device drivers (code that knows how to “speak” to all kinds of external devices)
  - System utilities to manage the system (think the “control panel”)
  - Libraries (to make software development easier)
  - **The Kernel**
- There is some debate about what’s “in the OS” and what’s not
- But everybody agrees about the kernel
- The kernel is the core component of the OS in charge of resource virtualization and allocation
- It does all the special/dangerous things that we don’t want user programs to be able to do

The New York Times

The software patches could slow the performance of affected machines by 20 to 30 percent, said Andres Freund, an independent software developer who has tested the new Linux code. The researchers who discovered the flaws voiced similar concerns

What's a kernel?

PCWorld FROM IDG

The kernel inside a chip is basically an invisible process that facilitates the way apps and functions work on your computer. It has complete control over your operating system. Your PC needs to switch between user mode and kernel mode thousands of times a day, making sure instructions and data flow seamlessly and instantaneously. Here's how The Register puts it: "Think

The Register® Biting the hand that feeds IT

Think of the kernel as God sitting on a cloud, looking down on Earth. It's there, and no normal being can see it, yet they can pray to it.

These KPTI patches move the kernel into a completely separate address space, so it's not just invisible to a running process, it's not even there at all. Really, this shouldn't be needed, but clearly there is a flaw in Intel's silicon that allows kernel access protections to be bypassed in some way.

THE VERGE

THURSDAY, JANUARY 4, 2018 | CHIPOCALYPSE NOW

FLAW IS RELATED TO KERNEL MEMORY ACCESS

The exact bug is related to the way that regular apps and programs can discover the contents of protect kernel memory areas. Kernels in operating systems have complete control over the entire system, and connect applications to the processor, memory, and other hardware inside a computer. There appears to be a flaw in Intel's processors that lets attackers bypass kernel access protections so that regular apps can read the contents of kernel memory. To protect against this, Linux programmers have been separating the kernel's memory away from user processes in what's being called "Kernel Page Table Isolation."

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...ELATED TO KERNEL ...ACCESS

The kernel is NOT a process (i.e., a running program)

Also, it's not "inside a chip" :)

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Better, but it's not "looking" or doing anything actively…

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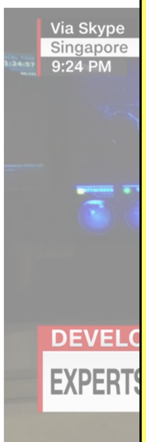

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…TO KERNEL

The kernel is code and data that always reside in RAM

- It is not a running program
- But its code can be invoked when various events occur

Kernels in operating systems have complete control over the entire system, and connect applications to the processor, memory, and other hardware inside a computer. There appears to be a flaw in Intel's processors that lets attackers bypass kernel access protections so that regular apps can read the contents of kernel memory. To protect against this, Linux programmers have been separating the kernel's memory away from user processes in what's being called "Kernel Page Table Isolation."

Who Writes the Kernel?

- Kernel Developers :)
- Initially, kernels were written in assembly only (yikes!)
- Since 1960s: written in high-level languages (MS-DOS being an exception)
- Usually with a language in the C-language family
  - C-like languages are “close” to the hardware and make it easy for developers to play “tricks” to make the code space- and time-efficient
  - Compilers for these languages are really good at making fast executables for our CPUs
- Windows, Linux, iOS, MacOS kernels have been written mostly in C/C++
  - With parts still in assembly (e.g., for calling specific CPU instructions)
- In late 2022, Rust has become an official language for Linux Kernel development, in addition to C, and Rust kernel code is being developed (e.g., device drivers)

Kernel Development

- OS kernels are among the most impressive/challenging software development endeavors
  - Good news: a lot of very smart people have already written the critical parts of kernels
- As a kernel developer a constant concern is to not use too much memory so as to reduce memory footprint
  - Hence the need to write lean and mean code and data structures
  - Hence the struggle about whether to add new features
- Another constant concern is speed
- You cannot use standard libraries
  - Since you're writing the kernel, which sits below the libraries
- Nobody is watching over you, and bugs lead to crashes
- Let's look at some examples from the Linux kernel code...
  - You're not in ICS212 anymore!

Non-portable intrinsics

Faster conditional with a gcc directive

```
if (__builtin_expect(n == 0, 0)) {
  return NULL;
}
```

- In kernel code you often see things like the above
- The `__builtin_expect` keyword is a gcc directive where you get to indicate whether the condition is typically true or false
  - In the example above, the 0 second argument means “typically false”
- This is useful because then the compiler can generate faster code (by 1 or 2 cycles)
  - This has to do with pipelining and branch prediction (see a Computer Architecture course)

Bitwise operations and macros

Bitwise operations galore, often macroed

```
#define MODIFY_BITS(port, mask, dir)       \
        if (mask) {                        \
                val = sa1111_readl(port);  \
                val &= ~(mask);            \
                val |= (dir) & (mask);     \
                sa1111_writel(val, port);  \
        }

MODIFY_BITS(gpio + SA1111_GPIO_PADDR, bits & 15, dir);
MODIFY_BITS(gpio + SA1111_GPIO_PBDDR, (bits >> 8) & 255, dir >> 8);
MODIFY_BITS(gpio + SA1111_GPIO_PCDDR, (bits >> 16) & 255, dir >> 16);
```

- Bitwise operations are super fast/useful, and used a lot in Kernel code (due to having to encode information in as few bits as possible)

Macros, macros, ...

Bitwise operations galore, often macroed

```
#define DIV_ROUND_CLOSEST(x, divisor)({                 \
        typeof(x) __x = x;                              \
        typeof(divisor) __d = divisor;                  \
        (((typeof(x))-1) > 0 ||                         \
         ((typeof(divisor))-1) > 0 || (__x) > 0) ?      \
                (((__x) + ((__d) / 2)) / (__d)) :       \
                (((__x) - ((__d) / 2)) / (__d)); })

#define container_of(ptr, type, member) ({                            \
        void *__mptr = (void *)(ptr);                                 \
        BUILD_BUG_ON_MSG(!__same_type(*(ptr), ((type *)0)->member) && \
                         !__same_type(*(ptr), void),                  \
                         "pointer type mismatch in container_of()");  \
        ((type *)(__mptr - offsetof(type, member))); })
```

- Due in part to C’s limitations, kernel developers typical define many macros

In-line Assembly

Code fragment with in-line assembly

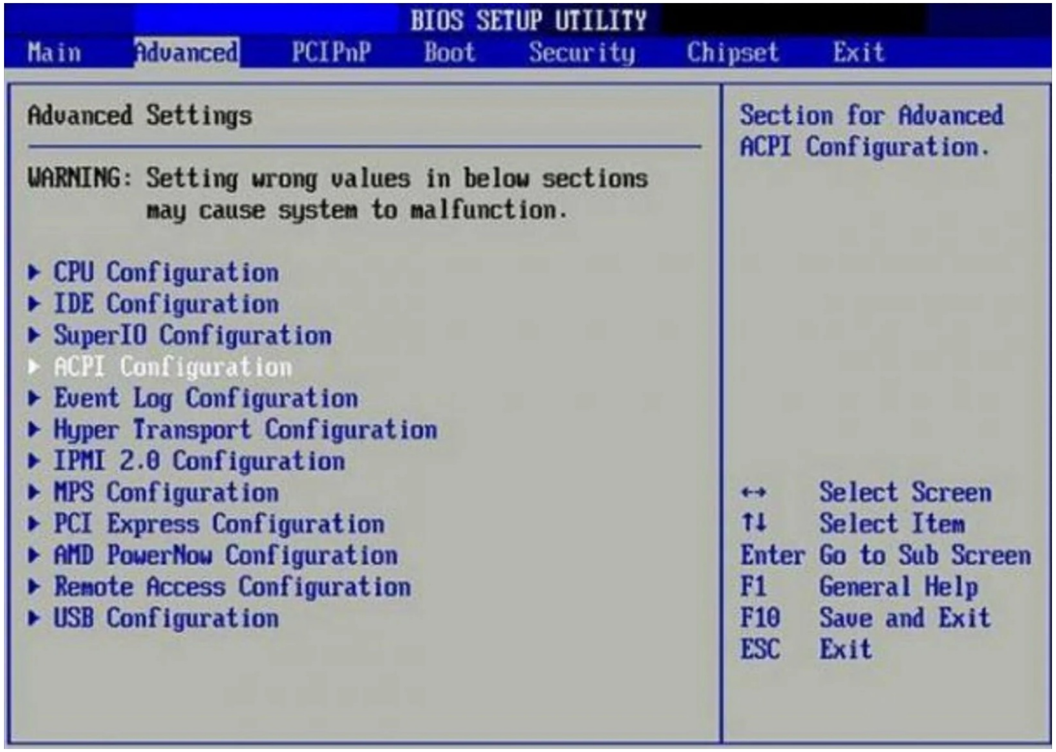
```
while (size >= 32) {
                asm("movq    (%0), %%r8\n" "movq   8(%0), %%r9\n"
                    "movq  16(%0), %%r10\n" "movq  24(%0), %%r11\n"
                    "movnti  %%r8,    (%1)\n" "movnti  %%r9,   8(%1)\n"
                    "movnti %%r10, 16(%1)\n" "movnti %%r11, 24(%1)\n"
                    :: "r" (source), "r" (dest)
                    : "memory", "r8", "r9", "r10", "r11");
                dest += 32;
                source += 32;
                size -= 32;
        }
```

- At many points in the kernel code there is inline assembly
- These are lines of assembly code that are spliced into the C code
- For speed or for doing things that would be difficult / impossible in C
  - The syntax above is x86 ATT syntax

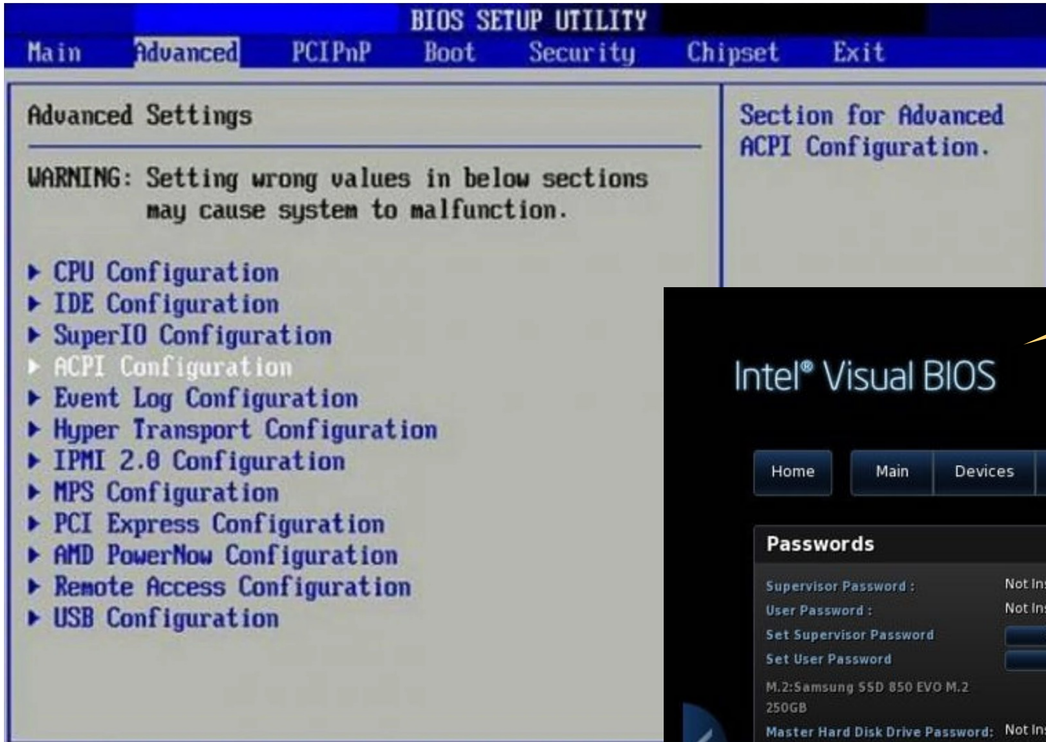
Who puts the Kernel in RAM?

- This happens during boot
  - Putting the kernel in RAM is the primary objective
- When you turn on your computer, POST (Power-On Self-Tests) are performed by the BIOS (Basic Input Output System)
  - Checks that RAM, disks, keyboard, etc. are all ok
  - Performs all kinds of initializations of registers and device controllers
- The BIOS is your computer’s firmware: stored in non-volatile memory (doesn’t need to be powered on to hold data)
- It used to be stored in a ROM chip (Read Only Memory), which means that a “firmware upgrade” would involved replacing the chip
- Nowadays it’s stored in EEPROM / flash memory, which can be rewritten to do a firmware upgrade
  - Which opens security issues, and the possibility of a bug in the BIOS, which could turn your machine into the proverbial “brick”
- People still say “BIOS” but there have been some changes….

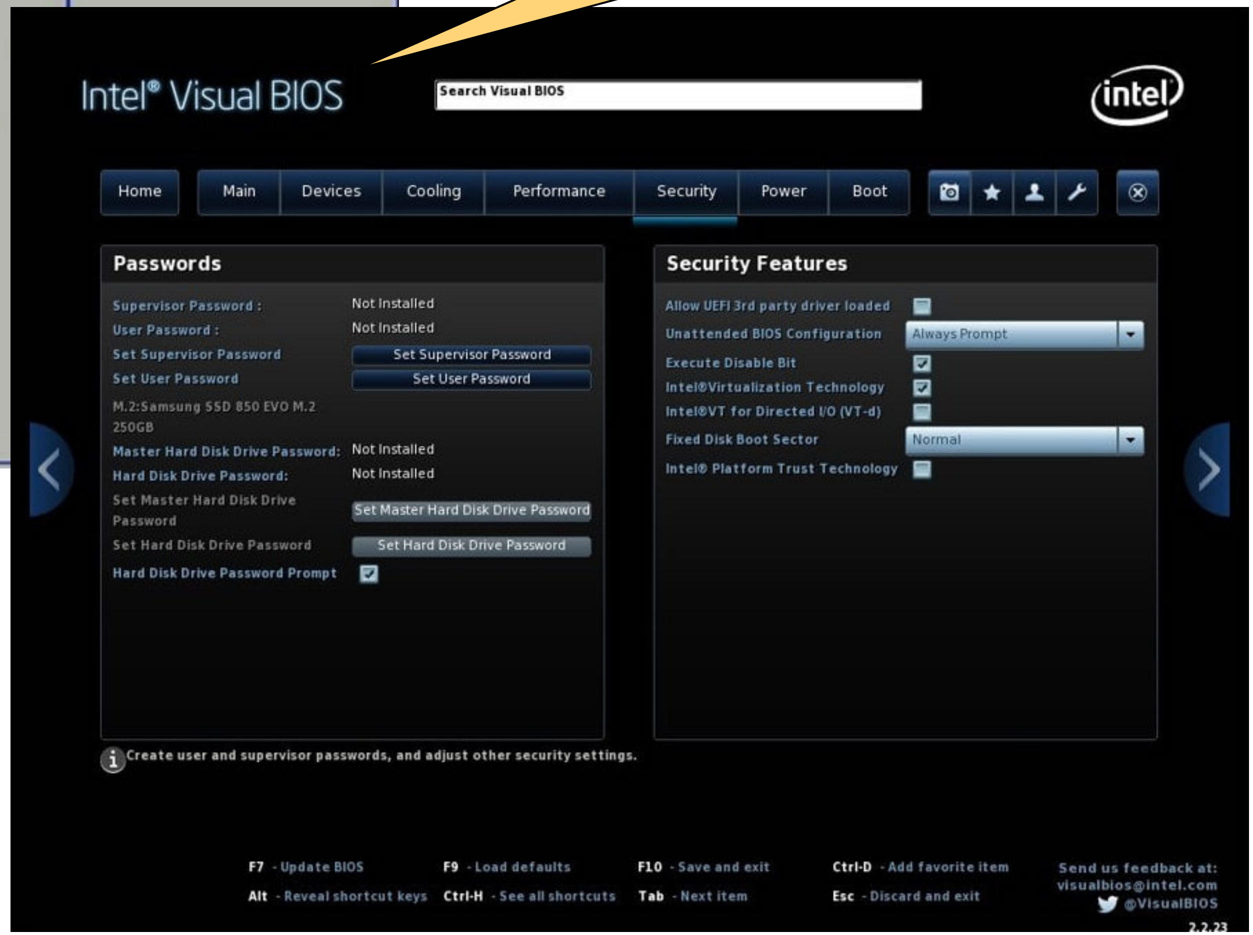
Basis Input Output System (BIOS)



Basis Input Output System (BIOS)



Still says BIOS



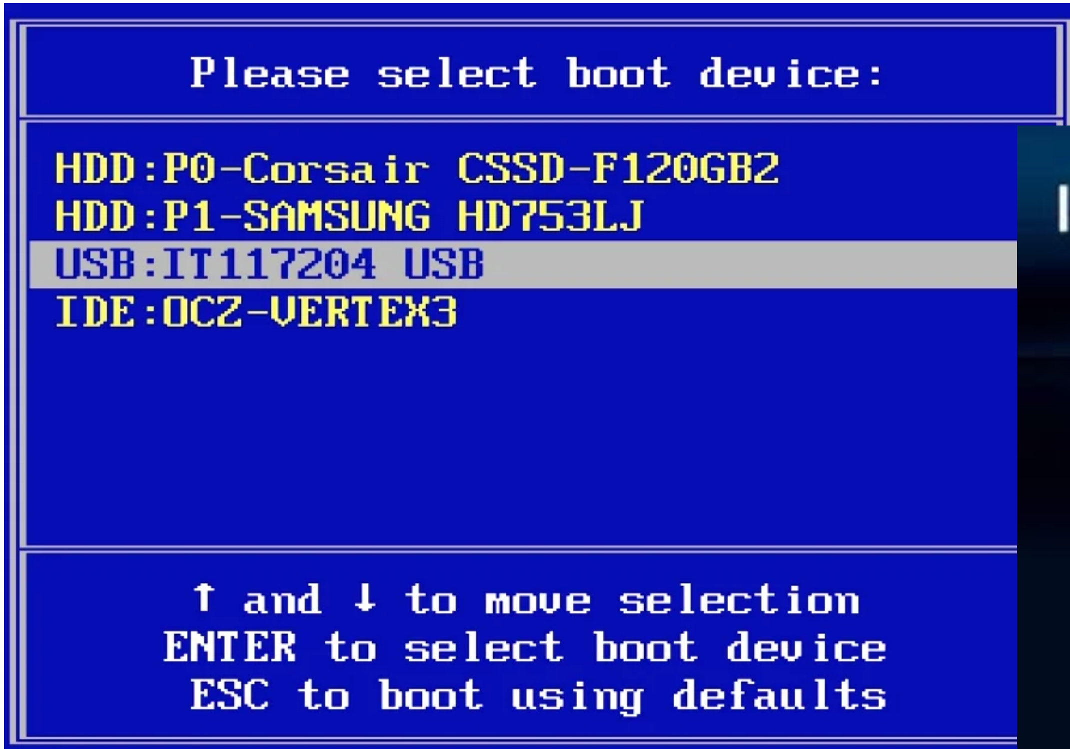
- Can do a lot more than the old BIOS
- Introduced in 2007
- Most computers today ship with UEFI instead of the old BIOS

Unified Extensible Firmware Interface (UEFI)

Finding a Bootable Device

- Configured in the BIOS is an ordered list of storage devices (disks, USB disks, CD-Rom, etc.)
  - This list is configurable in the BIOS
  - You may wonder how that works because the BIOS is stored in ROM!
    - Turns out, the list of bootable devices is stored in a small battery-powered CMOS memory, so that it keeps data even when the computer is powered off
    - And so the user can modify that list!
- The BIOS then goes through each device in order and determine whether it is bootable
  - It finds out whether the device contains a boot loader program
    - This is a program that knows how to load the kernel!
  - This is done in different ways (Master Boot Record, GUID Partition Table) and tons of technical details are available online
    - On my Mac: **`/System/Library/CoreServices/boot.efi`**

Selecting a bootable device



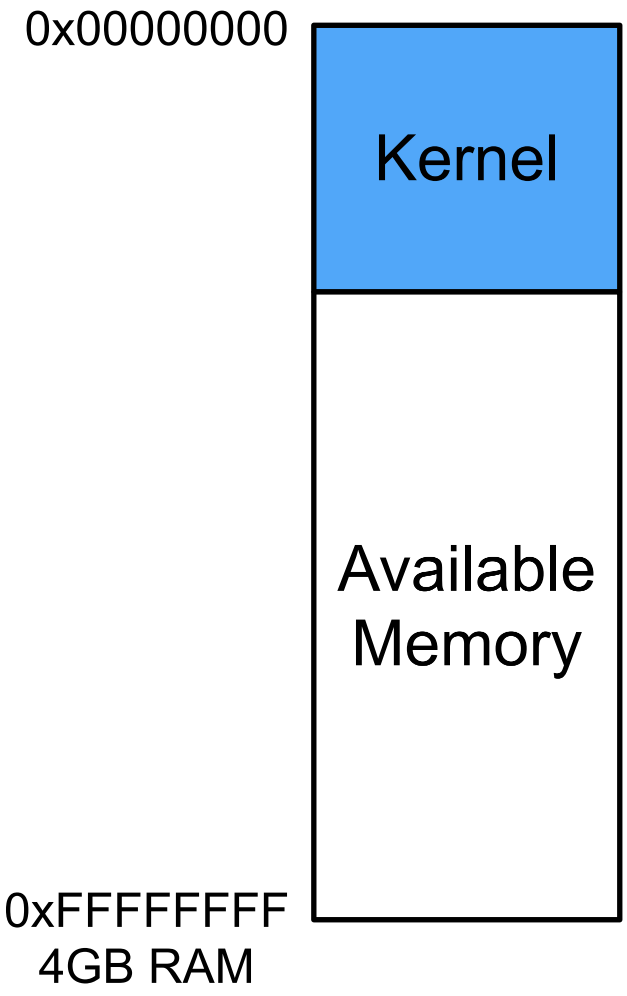
The Boot Loader Program

- The BIOS loads the boot loader program into RAM and hands over control to it (i.e., starts the fetch-execute-cycle from the boot loader program's first instruction)
- The boot loader program is the first program that runs on the machine
  - Linux: GRUB, LILO, etc.
  - Windows: WINLOAD. EXE
- The boot loader program does:
  - Perform some initializations to make sure the machine is ready for the kernel
  - Locates the kernel (code) on the bootable device and loads it into RAM and sets up data structures that the kernel will use
  - Then it hands off control to the bootstrap program…

The Bootstrap Program

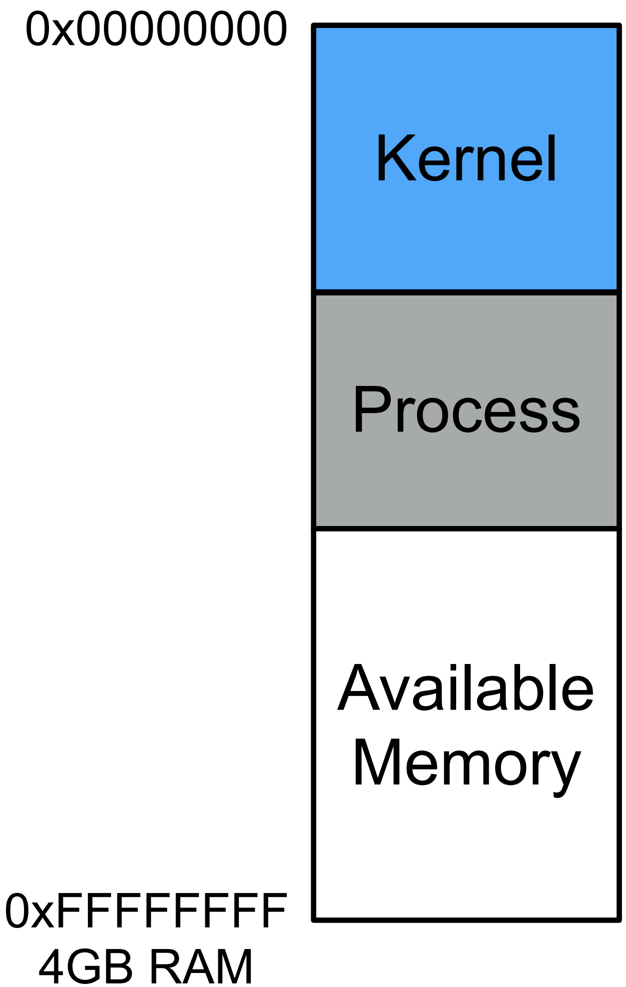
- The Bootstrap program is a program in Kernel code that
  - Does all “kernel initializations” (interrupt handles, timer, memory unit, etc.)
  - Configures and load all device drivers necessary for the detected attached devices
  - Starts system services (processes) that should be running
    - For instance, on Linux, the “init" process
  - Launches whatever application necessary for a user to start interacting with the OS
- Often this is done in a chain of loading/executing programs, each of them doing part of the work because loading/executing the next one

The Booted OS



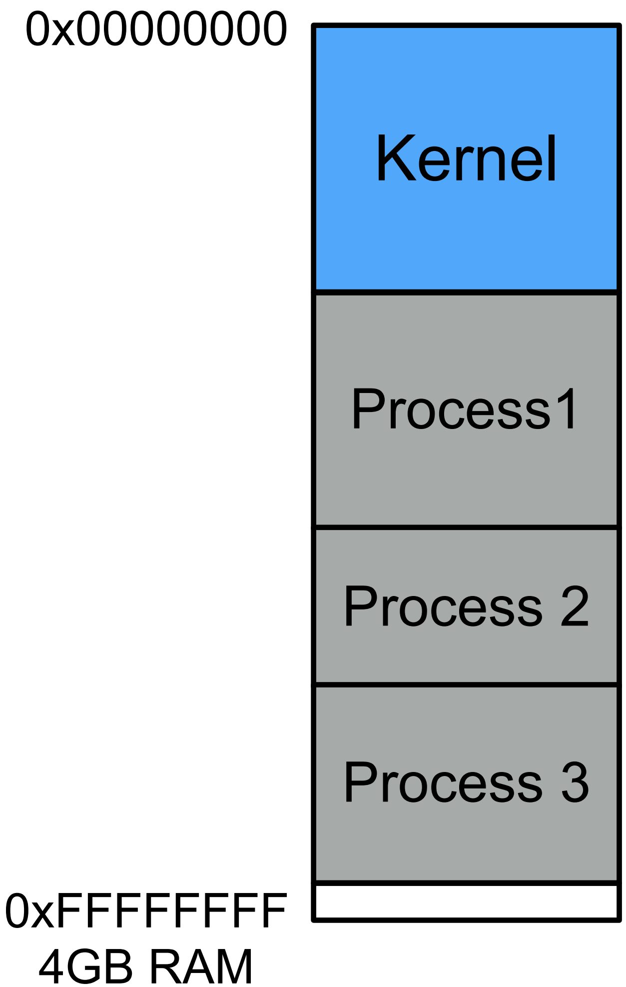
- The kernel code and data reside in memory at a specified address, as loaded by the bootstrap program(s)
- This picture is not to scale
- The kernel's memory footprint has to be small
  - This is memory the user cannot use

The Booted OS



- Each running program's code and data is then loaded into RAM
- A running program is called a process
- In RAM we thus have 2 kinds of code/data:
  - User code/data
  - Kernel code/data
- A process can run kernel code via system calls
  - Show of hands: who has heard that term before?

The Booted OS



- This figure shows 3 processes, occupying almost the full RAM
- Remember the OS illusion: each process thinks its alone, and processes never step on each other's toes in RAM (this is called memory protection)
- This figure makes drastic simplifications, and we'll see that the real picture is very different
  - But we can keep this simple picture in mind for a while
- If you want to know the list of processes running in your UNIX-ish machine: ps aux

The Kernel: An Event-Handler

- The Kernel is nothing but an event handler
  - After boot nothing happens until an event occurs!
- Once the system is booted, all entries into the kernel code occur as the result of an event
- The kernel defines a handler for each event type
- When an event occurs, the CPU stops what it was doing (i.e., going through the fetch-decode-execute cycle of some program), and instead starts running Kernel code
  - Just set the Instruction Counter register to the address of the first instruction in the appropriate event handler
- There are two kinds of events…

Interrupts and Traps

- **Interrupts**: Asynchronous events
  - Typically some device controller saying “something happened”
    - e.g., “incoming data on keyboard”
    - The kernel could then do: “great, I’ll write it somewhere in RAM and I’ll let some running program know about it”
  - ”Asynchronous” because generated in real time from the “outside world”
- **Traps**: Synchronous events (also called exceptions or faults)
  - Caused by an instruction executed by a running program
    - e.g.,“the running program tried to divide by 0”
    - The kernel could then do: “terminate the running program and print some error message to the terminal”
  - ”Synchronous" because generated as part of the fetch-decode-execute cycle from the “inside world”

- The two terms are often confused, even in textbooks…

The Kernel’s (unrealistic) pseudo-code

Event handling code

```
class Kernel {
  method waitEvent() {
    while (doNotShutdown) {
      event = sleepTillEventHappens();
      processEvent(event);
    }
  }
  method processEvent(Event event) {
    switch (event.type) {

    case MOUSE_CLICK:
       Kernel.MouseManager.handleClick(event.mouse_position); break;

    case NETWORK_COMMUNICATION:
       Kernel.NetworkManager.handleConnection(event.network_interface); break;

    case DIVISION_BY_ZERO:
       Kernel.ProcessManager.terminateProgram(“Can't divide by zero"); break;

  }
  return;
}
```

System Call: A Very Special Trap

- When a user program wants to do some “OS stuff”, we’ve said it places a system call
  - e.g., to open a file, to allocate some memory, to get input from the keyboard, etc.
  - Essentially, to do anything that’s not just “compute”
- A system call is really just a call to the kernel code
  - “Please kernel, run some of your code for me”
- We’ll see how they work later
- But for now we can just think of it as just another case in our pseudo-code...

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    case DIVISION_BY_ZERO:
      Kernel.ProcessManager.terminateProgram(“Can't divide by zero"); break;

    case SYSTEM_CALL:
      Kernel.doSystemCall(event); break;
  }
  return;
}
```

Conclusion

- The kernel is code and data that always resides in RAM
- Booting is the process by which the machine goes from “turned on” to “the kernel has been loaded”
- The kernel is not a running program but really just an event handler
  - When some event occurs, some kernel code runs
- There are two kinds of events: asynchronous interrupts and synchronous traps
- An important kind of trap are system calls, by which user programs ask the kernel to do some work on their behalf

- Onward to Operating System interfaces…