

cs5460/6460: Operating Systems

Lecture 07: System boot

Anton Burtsev

February, 2025

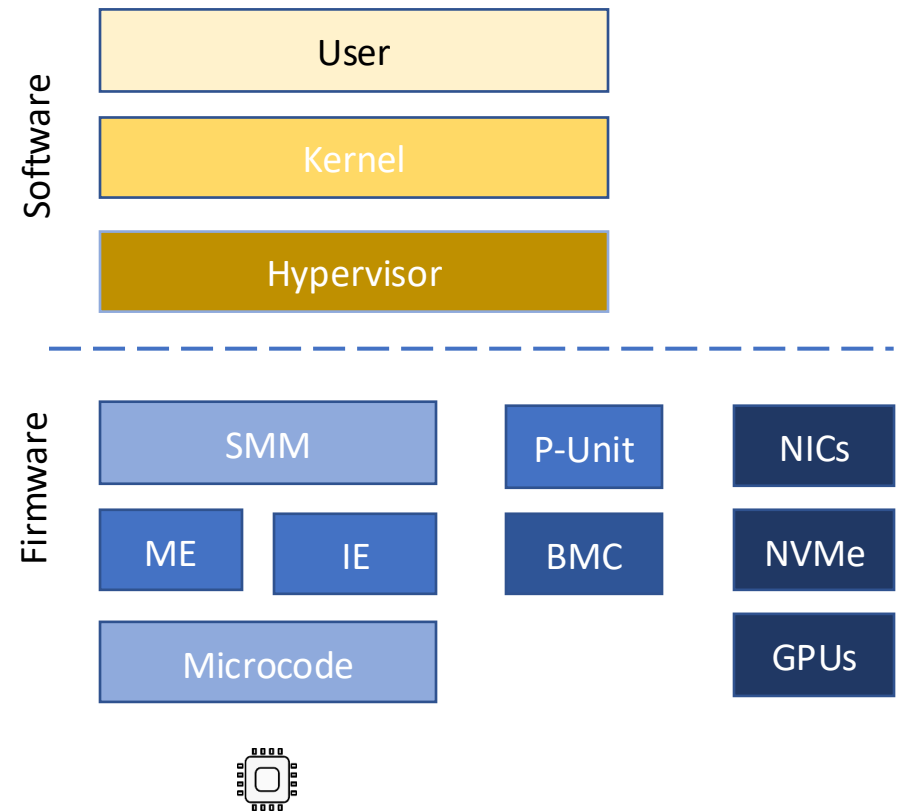
What happens when we turn on the power?

- Well it's complicated
 - Intel SGX Explained is a good start (Section 2.13 [1])
- At a high-level a sequence of software pieces initializes the platform
 - Management engine (ME), microcode, firmware (BIOS), bootloader

- The most important thing: the OS is not the only software running on the machine
 - And not the most privileged
- Today, at least two layers sit underneath the OS/hypervisor
- System Management Mode (SMM) (ring -2)
 - Runs below the hypervisor/OS
- Intel Management Engine and Intel Innovation Engine (ring -3)

Multiple layers of firmware

- Microcode
- BIOS
- Management and Innovation Engines (ME and IE)
- System Management Mode (SMM)
- Board Management Controller (BMC)
- Power microcontrollers (P-Unit and SCU)
- A ton more...
 - NICs, HDDs, NVMe, GPUs




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  </ProductInfo>

```



Mark Ermolov

@_markel

Follow

It's amazing how many heterogeneous CPU cores were integrated in Intel Silvermont's Moorefield SoC (ANN): x86, ARC, LMT, 8051, Audio DSP, each running own firmware and supporting JTAG interface

```

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InstanceNameSuffix="true">

InstanceSuffix="true">

InstanceNameSuffix="true">

InstanceSuffix="true">

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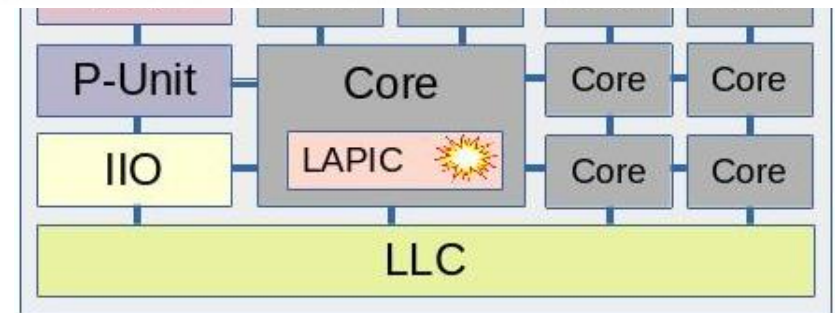
What is running on these microcontrollers?

Intel Corporation, Austin/Hillsboro/Bangalore

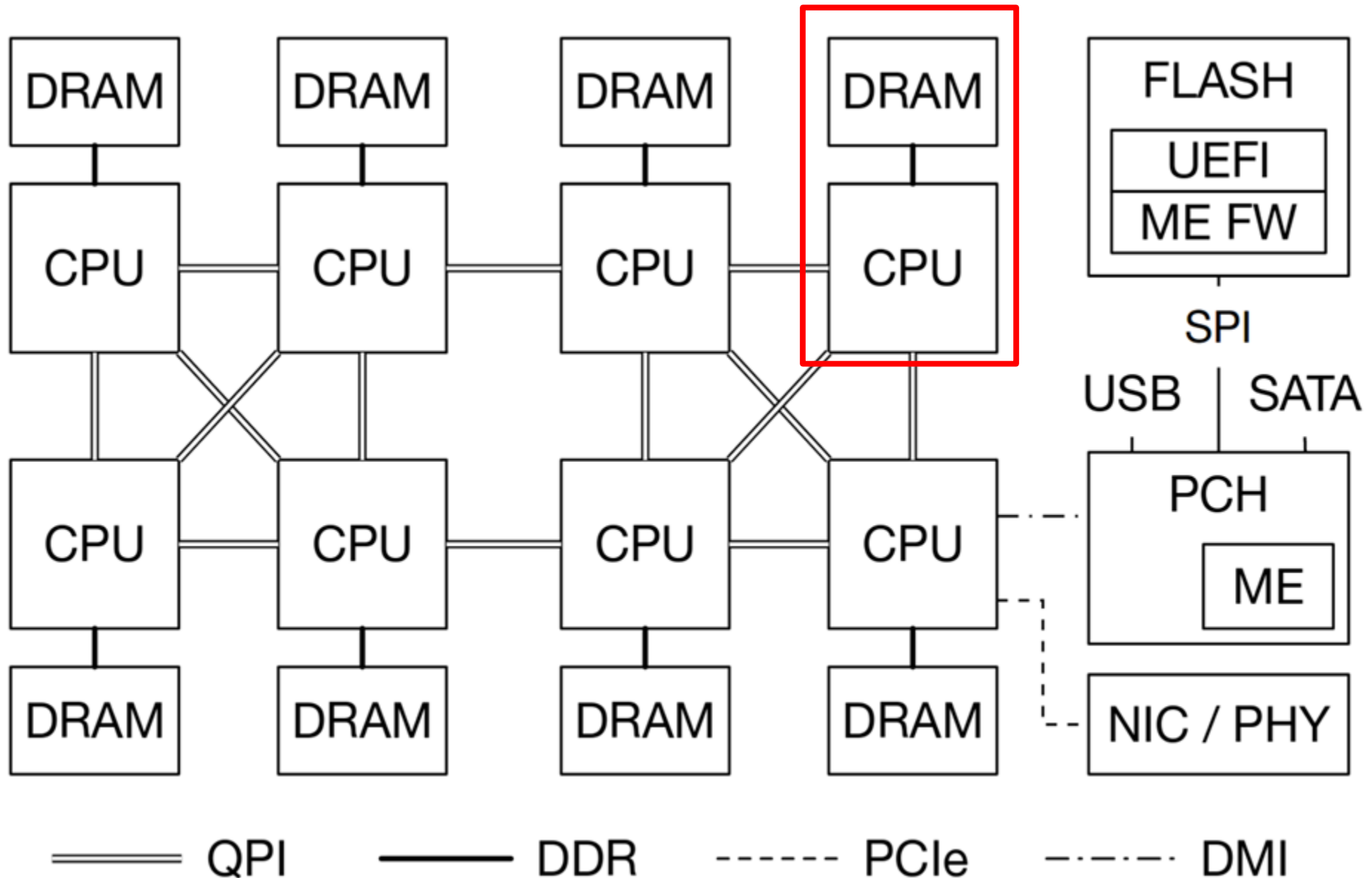
CPU POWER MANAGEMENT FIRMWARE ARCHITECT

Compute Die (CPU) power management firmware architect for devices & converged mobility Intel SoCs. Responsible for delivering pcode - power management firmware assembly code running on Foxton microcontroller, with the active/idle/thermal algorithms, cold/warm reset sequences, power delivery & sequencing of each IP. Also responsible to provide solutions/algorithms to enhance overall SoC Power & Performance.

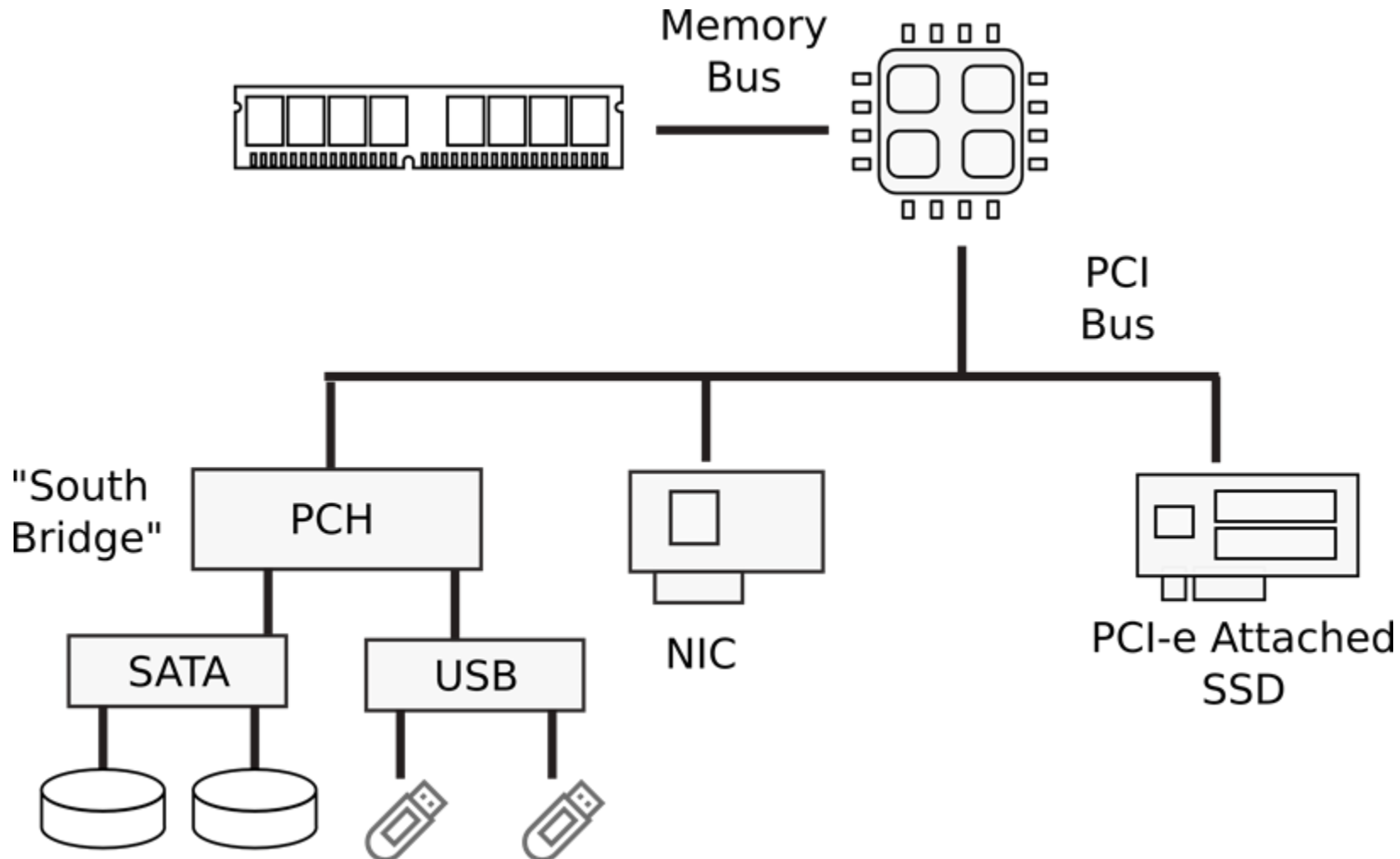
[March 2011 – Present]



PC motherboard components



I/O Devices



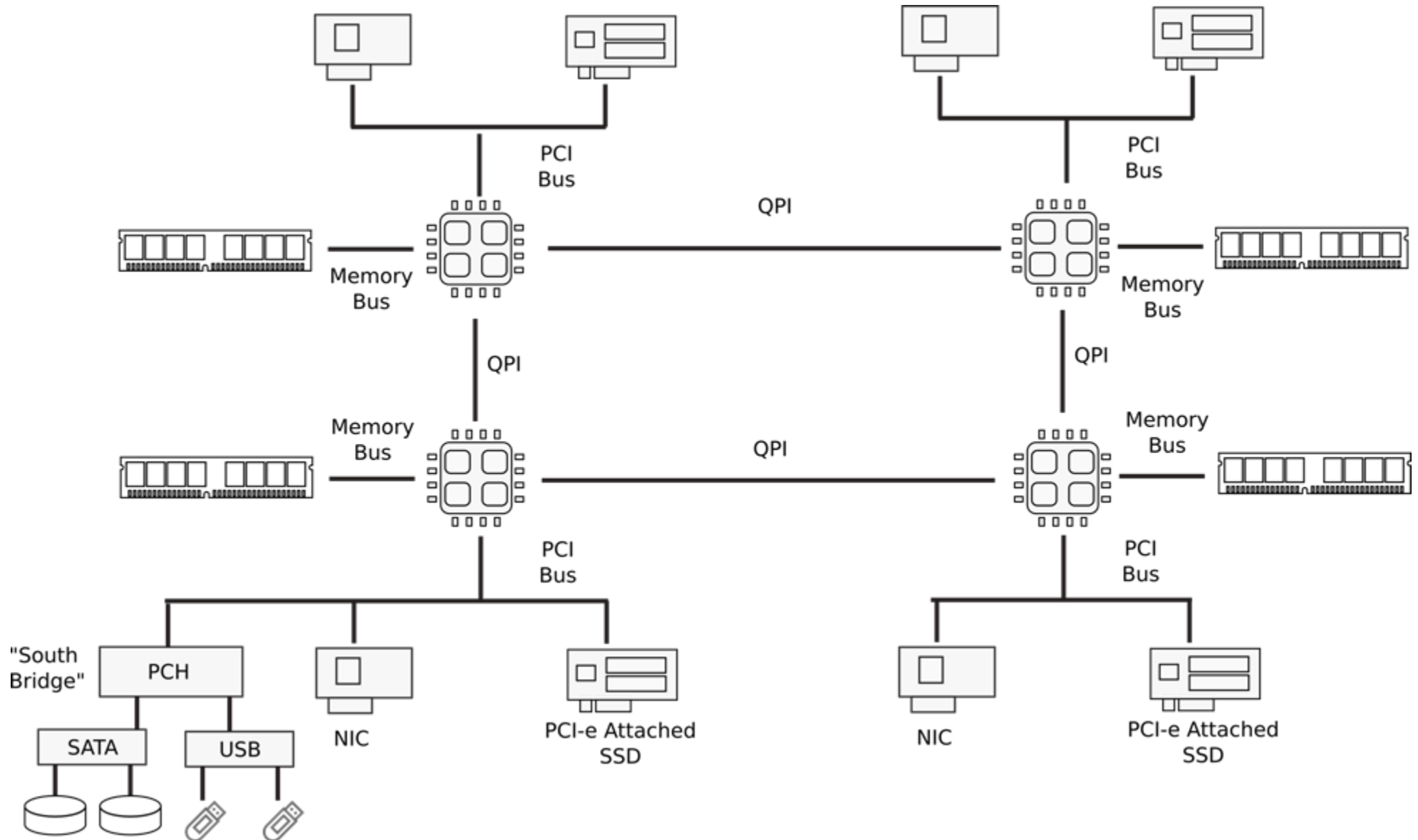
Dell R830 4-socket server



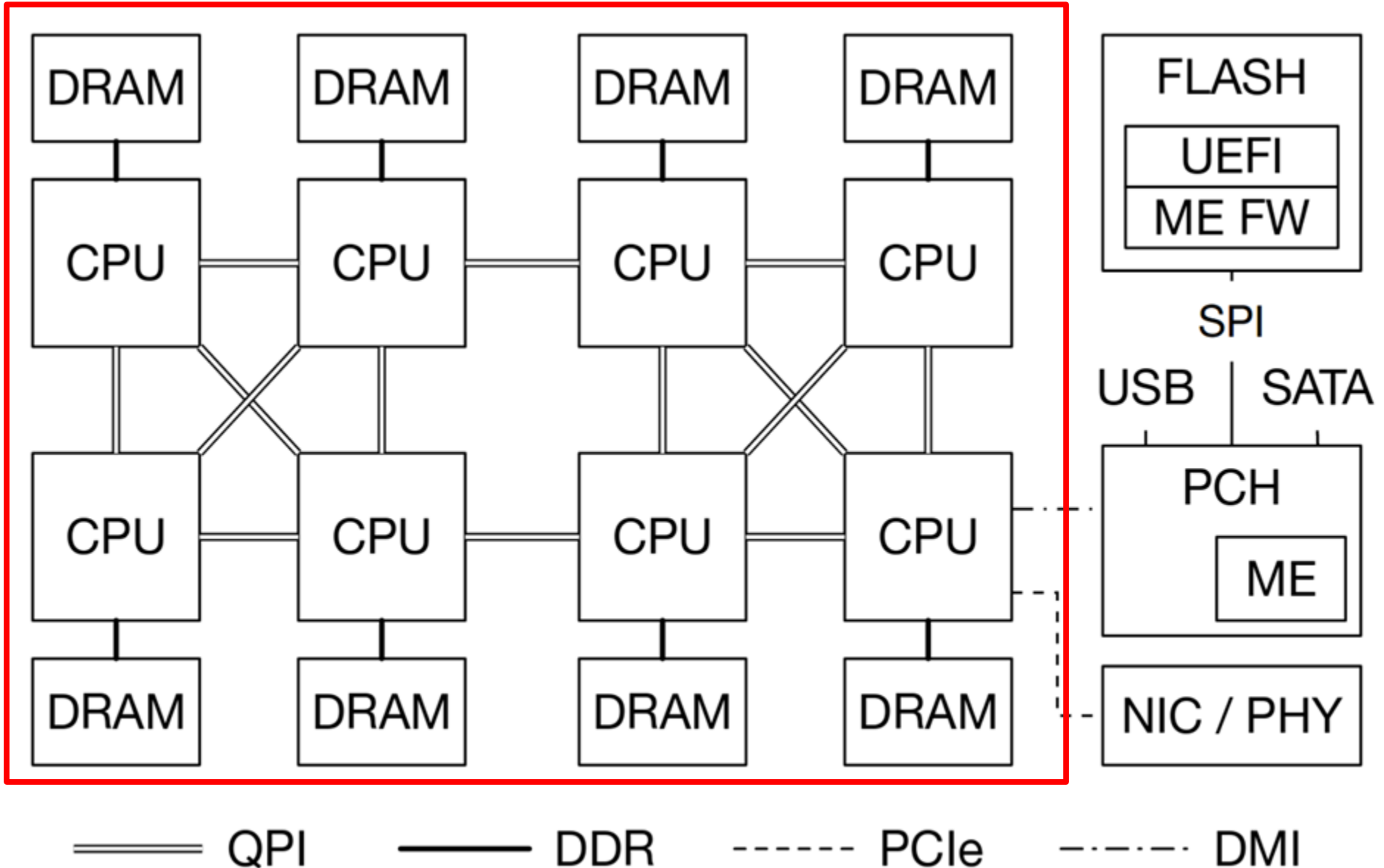
Dell Poweredge R830 System Server with 2 sockets on the main floor and 2 sockets on the expansion

http://www.dell.com/support/manuals/us/en/19/poweredge-r830/r830_om/supported-configurations-for-the-poweredge-r830-system?guid=guid-01303b2b-f884-4435-b4e2-57bec2ce225a&lang=en-us

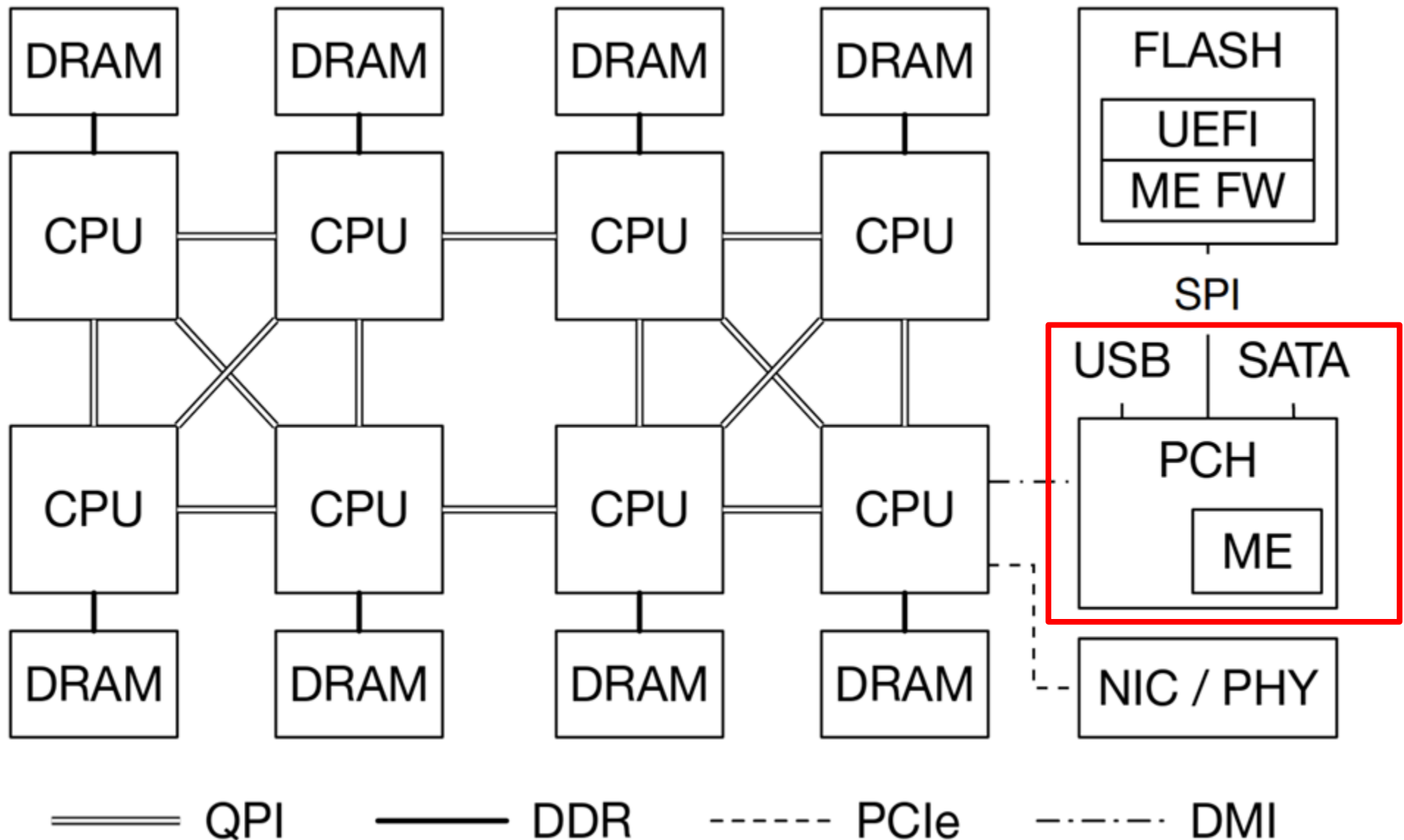
Multi-socket machines



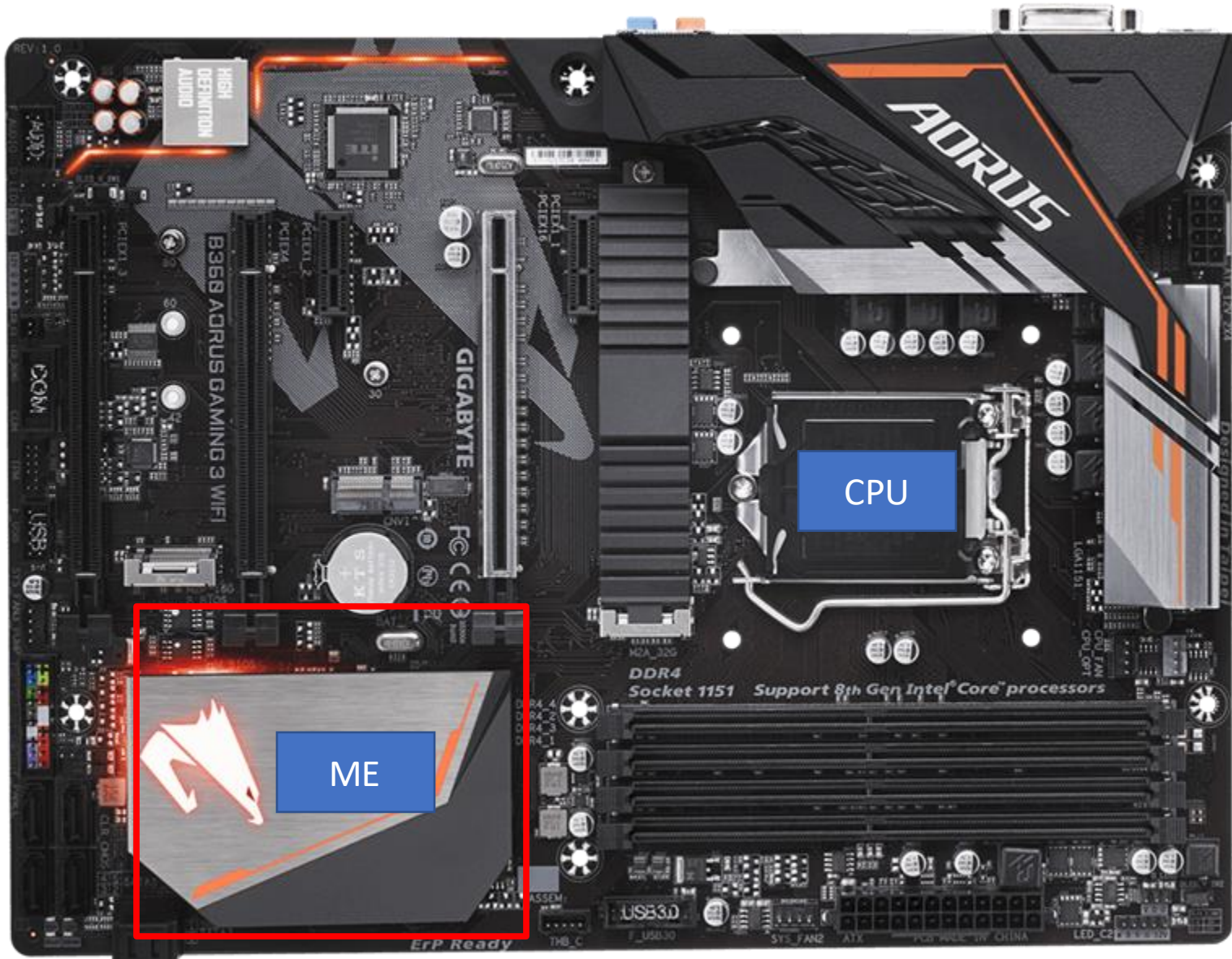
PC motherboard components



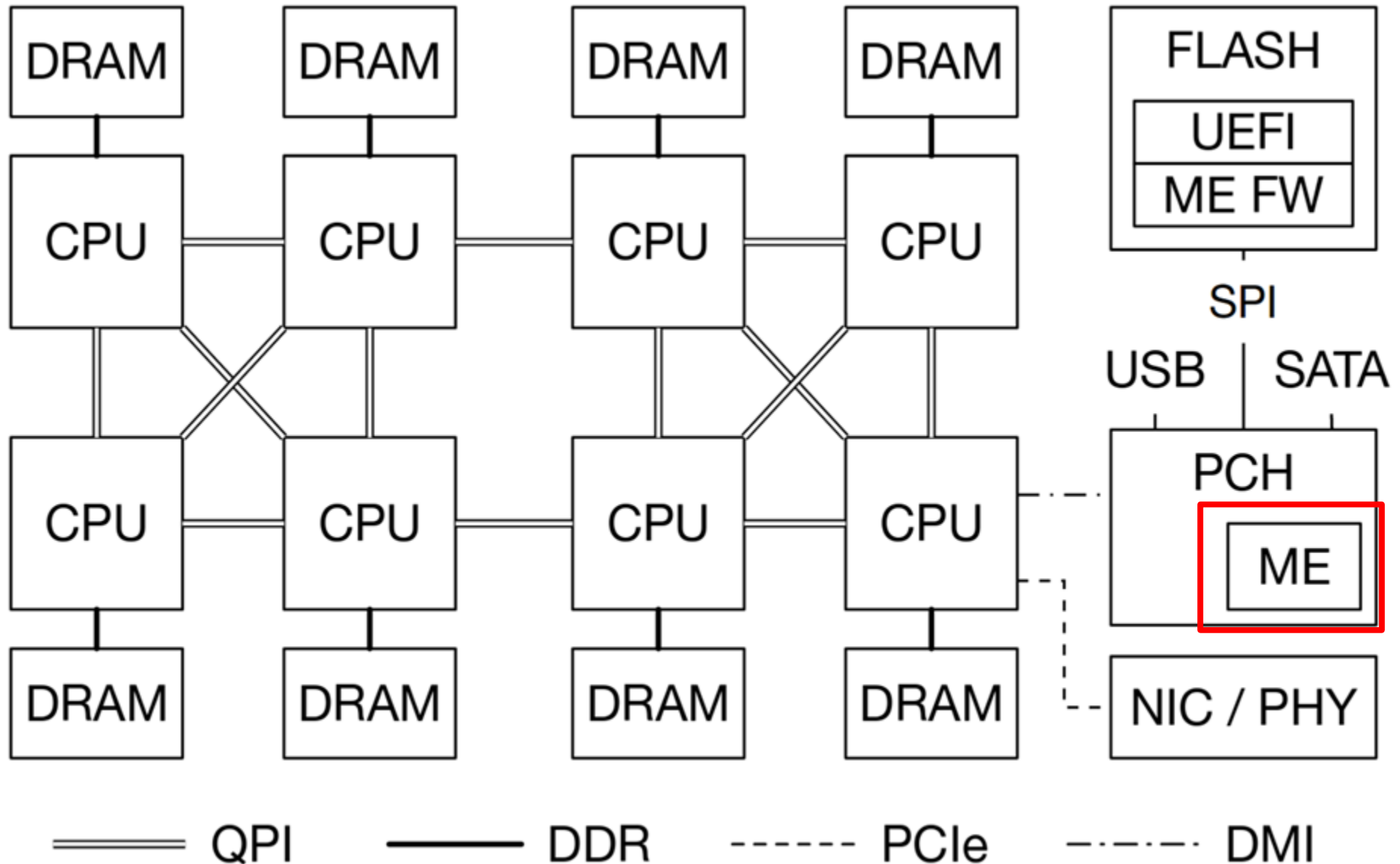
PCH – Platform Controller Hub



B360 AORUS Motherboard



ME gets power before CPUs



Intel Management Engine (ME)

- Full-featured computer
 - Intel Quark x86-based 32-bit CPU
 - Internal RAM (1.7MB)
- Can access all DRAM via DMA
- Can control boot chain
- Can access network interface (NIC) on the motherboard
 - Has it's own MAC and IP address
 - Via System Management Bus (SMBus)
 - Or an ATM compatible NIC
- Connected to the power supply
 - Stays on as long as power is provided to power supply

ME: Theft prevention use-case

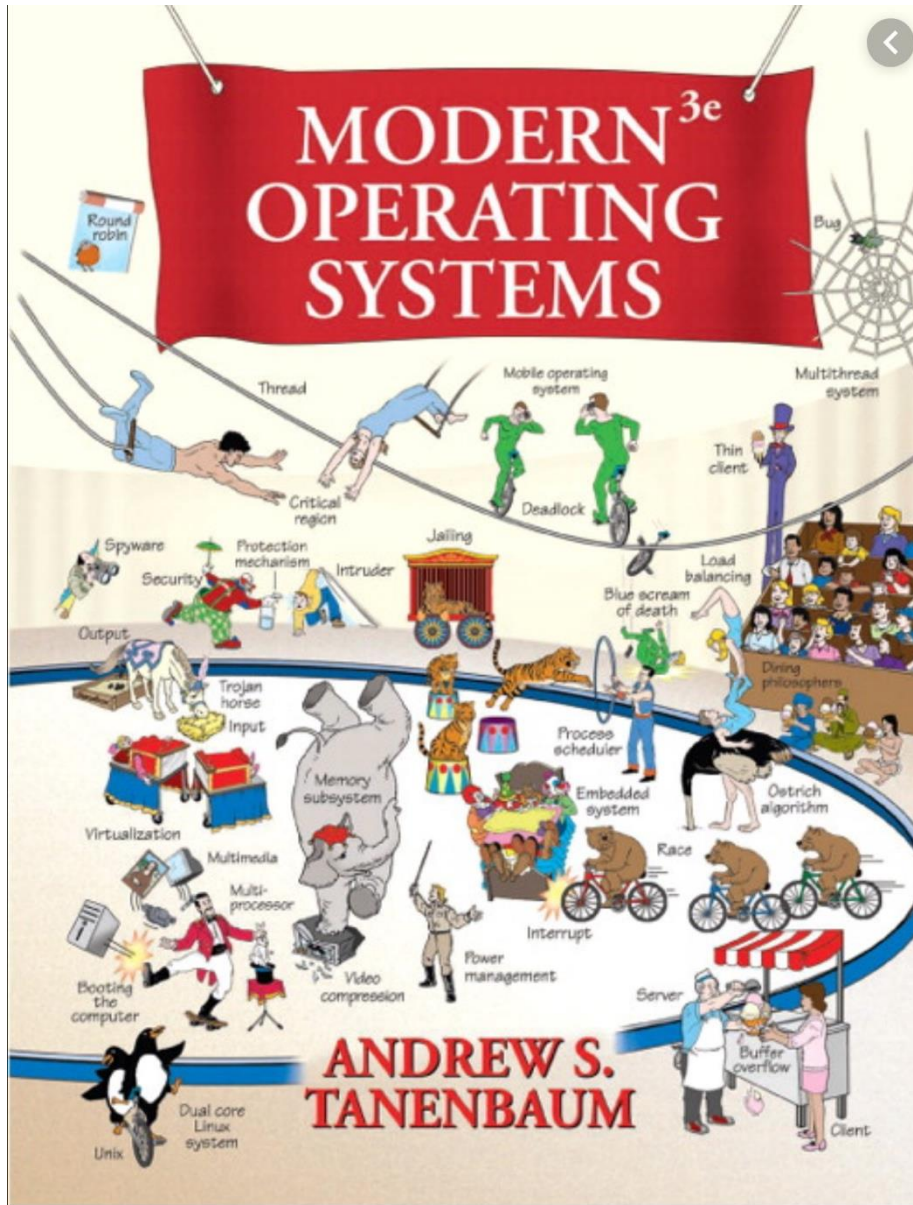
- In S5 (computer off) ME cannot access DRAM
 - DRAM is off
- But ME can use its internal memory
 - ME can disable a stolen laptop equipped with cellular modem remotely
- As long as power is connected
- And **cell** network has **signal**

Intel Management Engine (ME)

- All modern motherboard chips contain ME
- Part of Active Management Technology (AMT)
- Convenient way for administrators to fix your machine remotely
 - Obviously a huge opportunity for an attack

What's running there?

Have you read
“**Modern
Operating
Systems?**”



What's running there?

Do you ever read "Modern Operating Systems"?

POSITIVE TECHNOLOGIES

```
> strings vfs
...
..\..\src\os\servers\vfs\misc.c
FS: bogus child for forking
FS: forking on top of in-use child
...
```

MINIX3
by Andrew Tanenbaum

```
Directory of minix3-master\servers\vfs

14.03.2010  23:52    14'978  main.c
14.03.2010  23:52         741  Makefile
14.03.2010  23:52    17'653  misc.c
14.03.2010  23:52         677  mmap.c
14.03.2010  23:52    15'650  mount.c
...
```

"FS: bogus child for forking"

All

Images

Videos

News

Shopping

More

Settings

Tools

6 results (0.34 seconds)

[misc.c in minix-filesystem | source code search engine - Searchcode](https://searchcode.com/codesearch/view/55926734/)

<https://searchcode.com/codesearch/view/55926734/>

```
childno = _ENDPOINT_P(m_in.child_endpt); if(childno < 0 || childno >= NR_PROCS) panic(__FILE__, "FS:
bogus child for forking", m_in.child_endpt); ...
```

```
/* PM gives child endpoint, which implies process slot information.
 * Don't call isokendpt, because that will verify if the endpoint
 * number is correct in fproc, which it won't be.
 */
```

```
childno = _ENDPOINT_P(m_in.child_endpt);
if(childno < 0 || childno >= NR_PROCS)
    panic(__FILE__, "FS: bogus child for forking", m_in.child_endpt);
if(fproc[childno].fp_pid != PID_FREE)
    panic(__FILE__, "FS: forking on top of in-use child", childno);
```

Modern firmware is unreliable and insecure

Inherent complexity

- Functionality of a partial or sometimes complete operating system
- BMC, ME and IE
 - Full-featured operating systems, processes, network drivers, etc.

An Open Letter to Intel

Dear Mr. Krzanich,

Thanks for putting a version of MINIX inside the ME-11 management engine chip used on almost all recent desktop and laptop computers in the world. I guess that makes MINIX the most widely used computer operating system in the world, even more than Windows, Linux, or MacOS. And I didn't even know until I read a [press report](#) about it. Also [here](#) and [here](#) and [here](#) and [here](#) and [here](#) (in Dutch), and a bunch of other places.

I knew that Intel had some potential interest in MINIX several years ago when one of your engineering teams contacted me about some secret internal project and asked a large number of technical questions about MINIX, which I was happy to answer. I got another clue when your engineers began asking me to make a number of changes to MINIX, for example, making the memory footprint smaller and adding `#ifdefs` around pieces of code so they could be statically disabled by setting flags in the main configuration file. This made it possible to reduce the memory footprint even more by selectively disabling a number of features not always needed, such as floating point support. This made the system, which was already very modular since nearly all of the OS runs as a collection of separate processes (normally in user mode), all of which can be included or excluded in a build, as needed, even more modular.

Also a hint was the discussion about the license. I (implicitly) gathered that the fact that MINIX uses the Berkeley license was very important. I have run across this before, when companies have told me that they hate the GPL because they are not keen on spending a lot of time, energy, and money modifying some piece of code, only to be required to give it to their competitors for free. These discussions were why we put MINIX out under the Berkeley license in 2000 (after prying it loose from my publisher).

After that initial burst of activity, there was radio silence for a couple of years, until I read in the media (see above) that a modified version of MINIX was running on most x86 computers, deep inside one of the Intel chips. This was a complete surprise. I don't mind, of course, and was not expecting any kind of payment since that is not required. There isn't even any suggestion in the license that it would be appreciated.

The only thing that would have been nice is that after the project had been finished and the chip deployed, that someone from Intel would have told me, just as a courtesy, that MINIX was now probably the most widely used operating system in the world on x86 computers. That certainly wasn't required in any way, but I think it would have been polite to give me a heads up, that's all.

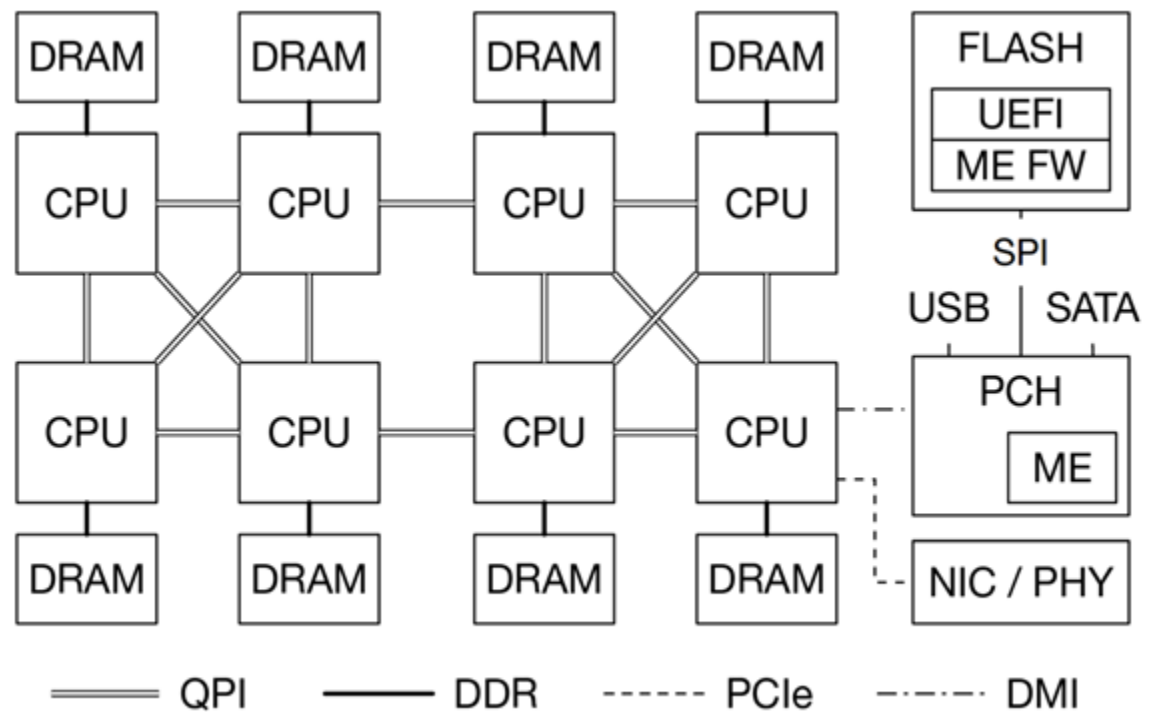
If nothing else, this bit of news reaffirms my view that the Berkeley license provides the maximum amount of freedom to potential users. If they want to publicize what they have done, fine. By all means, do so. If there are good reasons not to release the modified code, that's fine with me, too.

Yours truly,

Andrew S. Tanenbaum

ME starts first

- Reads its initialization code from the BIOS chip
- Via the SPI bus



Bootstrap processor (BSP)

- One of the logical processors is chosen as **bootstrap processor** (BSP)
 - Will start initialization
- Others become “**application processors**” (AP)
 - Waiting for a special interrupt from the BSP

BSP starts reading BIOS

- Executes instructions stored in the BIOS chip
 - Initially BIOS' ROM is mapped into memory address space of the CPU, so it can execute it
- An interesting detail is that BSP starts with DRAM disabled
 - Hence there is no stack to call functions
 - What can be done?

BSP starts without DRAM

- Custom-written assembly code that uses no stack
- Or a **ROMCC** compiler
 - Generates code from C that uses no stack
 - Used in the **coreboot** project

Cache-as-RAM

- Use CPU caches as temporary replacement for RAM
 - Initialize DRAM
 - Copy BIOS firmware into DRAM and continue

BIOS firmware

Initialize

- Interrupt controllers
- Devices, e.g., network interfaces
- If one of PCI devices contains “option ROM”
load and execute it
 - Network cards may contain iPXE ROM
 - Implement boot from the network host

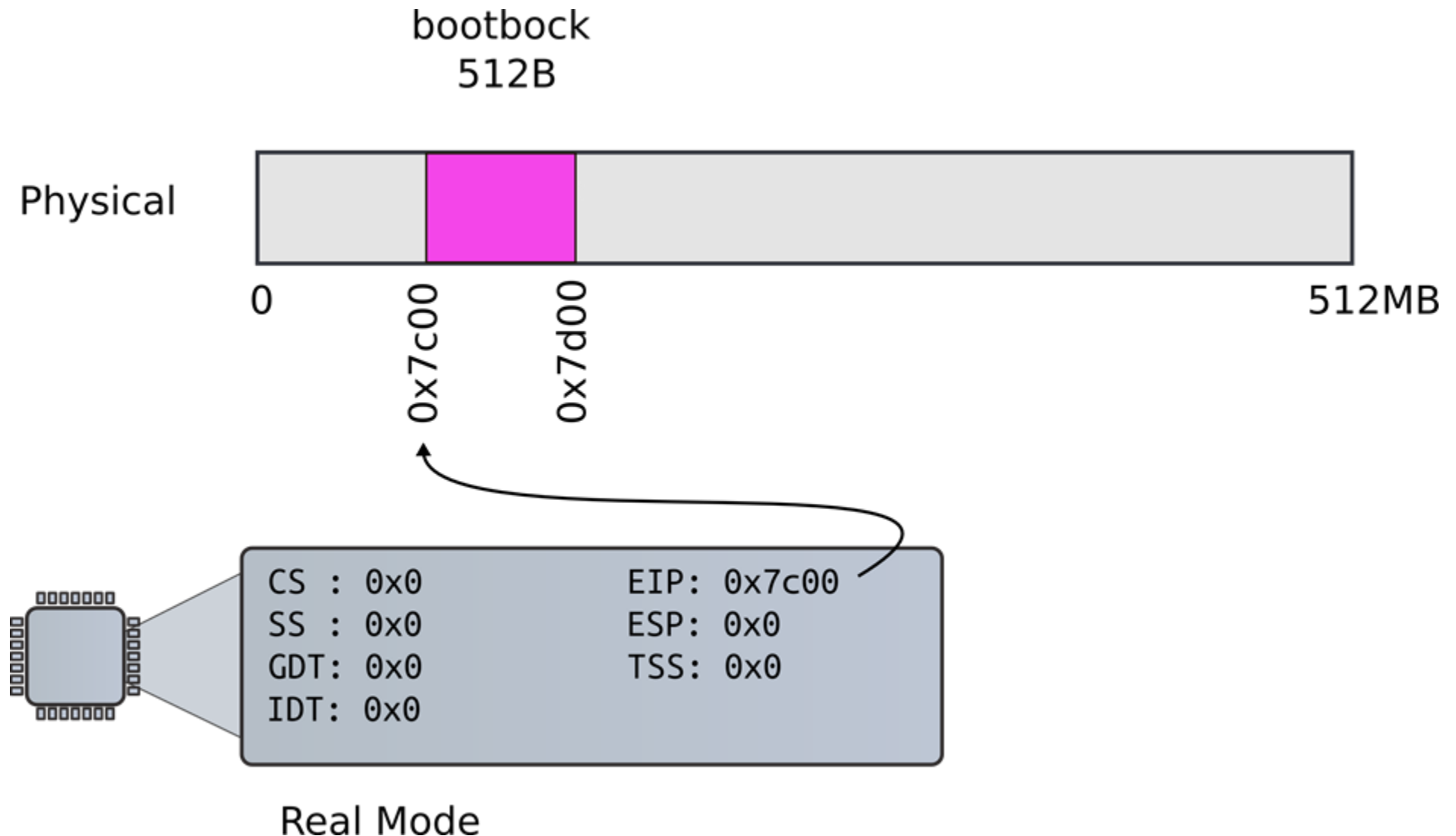
System Management Mode

- Another compartment that runs underneath your OS or a hypervisor
 - Initialized by BIOS
 - Protected with hardware memory mechanisms
 - OS cannot access this region of memory
 - Runs under your OS and the hypervisor
 - Receives interrupts periodically, can take over the entire system any time
- No way to disable

BIOS loads the boot loader

- BIOS ends by loading a **boot loader**
- Modern BIOSes can load the boot loader from a variety of sources (hard disks, USB drives, optical disks)
- Default way is to load the **first sector** (512 bytes) from disk into the memory location at **0x7c00**
- BIOS then starts executing instructions at the address 0x7c00
 - This is exactly what we see when we run xv6 under QEMU
 - QEMU emulates hardware: runs BIOS, follows the same protocol

BIOS loads bootloader



Outline of the boot sequence

Outline of the boot sequence

- Setup segments (data and code)
- Switch to protected mode
- Load GDT (segmentation is on)
- Setup stack (to call C functions)
- Load kernel from disk
- Setup first page table
 - 2 entries [0 : 4MB] and [2GB : (2GB + 4MB)]
- Setup high-address stack
- Jump to main()

Bootloader starts

9111 start:

9112 cli # BIOS enabled interrupts; disable

9113

9114 # Zero data segment registers DS,ES,and
SS.

9115 xorw %ax,%ax # Set %ax to zero

9116 movw %ax,%ds # -> Data Segment

9117 movw %ax,%es # -> Extra Segment

9118 movw %ax,%ss # -> Stack Segment

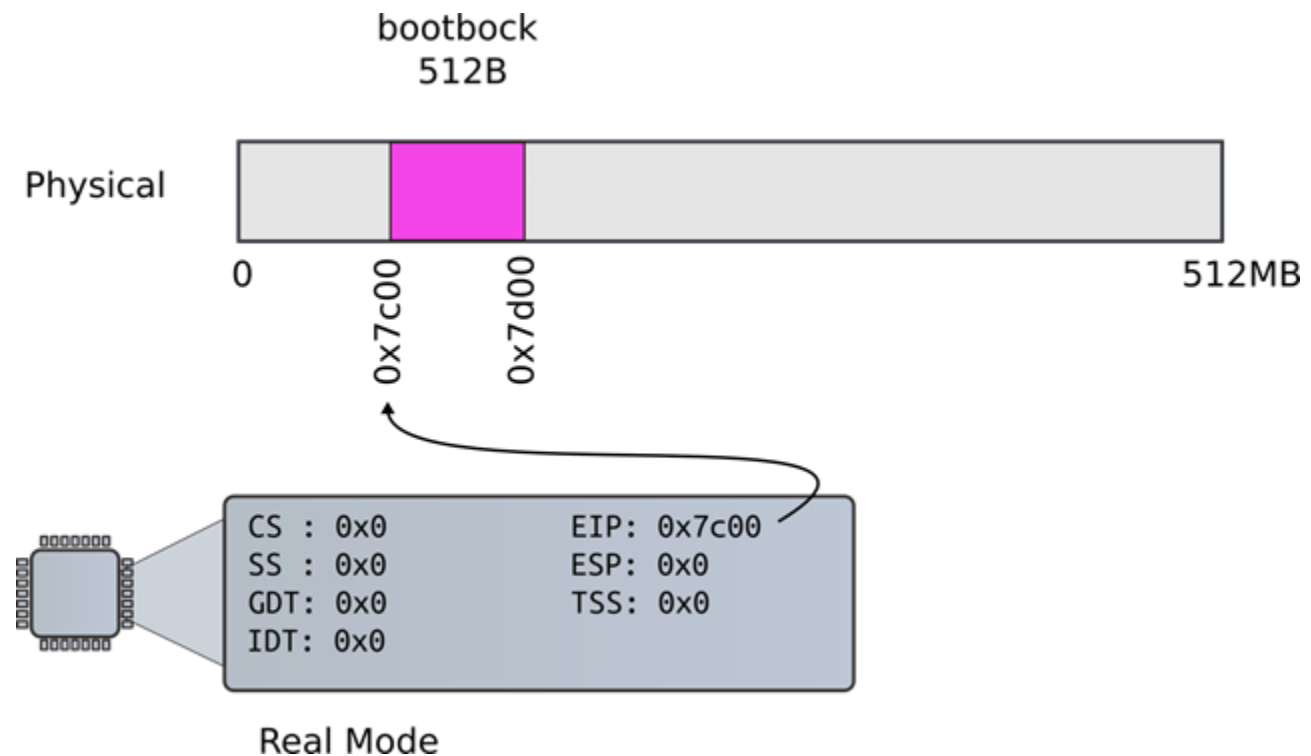
xv6/bootasm.S [bootloader]

Why start happens to be 0x7c00?

9111 start:

9112 cli # BIOS enabled interrupts; disable

9113



xv6/bootasm.S [bootloader]

Linker is instructed to link the boot block code in the Makefile

9111 start:

9112 cli # BIOS enabled interrupts; disable

9113

bootblock: bootasm.S bootmain.c

\$(CC) \$(CFLAGS) -fno-pic -O -nostdinc -I. -c bootmain.c

\$(CC) \$(CFLAGS) -fno-pic -nostdinc -I. -c bootasm.S

\$(LD) \$(LDFLAGS) -N -e start -Ttext 0x7C00 -o bootblock.o bootasm.o bootmain.o

\$(OBJDUMP) -S bootblock.o > bootblock.asm

\$(OBJCOPY) -S -O binary -j .text bootblock.o bootblock

./sign.pl bootblock

xv6/Makefile

Switch to protected mode

- Switch from real to protected mode
- Use a bootstrap GDT that makes virtual addresses map directly to physical addresses so that the effective memory map doesn't change during the transition.

```
9141 lgdt gtdesc
```

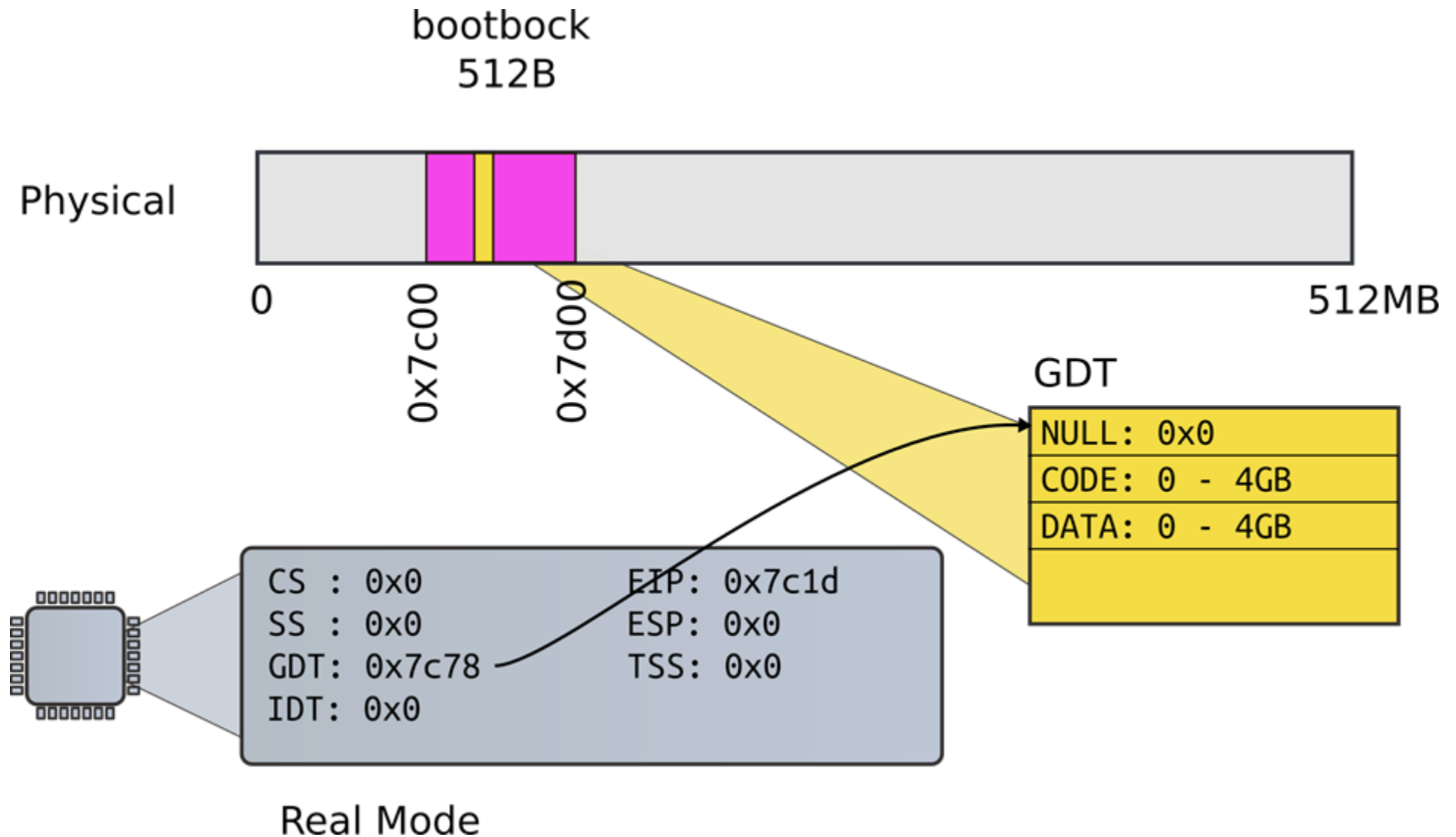
```
9142 movl %cr0, %eax
```

```
9143 orl $CR0_PE, %eax
```

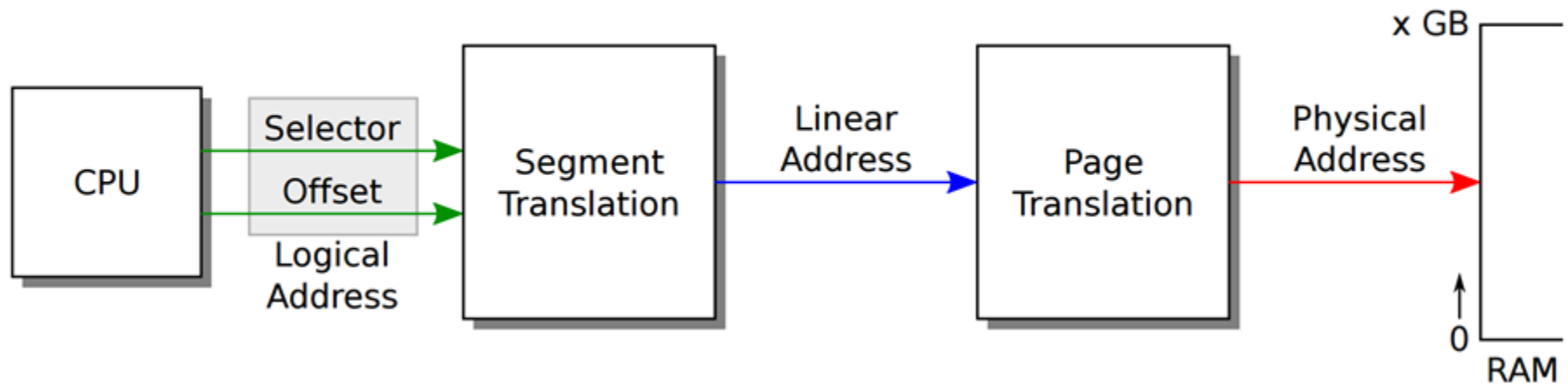
```
9144 movl %eax, %cr0
```

xv6/bootasm.S [bootloader]

Load GDT



Recap: complete address translation



How GDT is defined

9180 # Bootstrap GDT

9181 .p2align 2 # force 4 byte alignment

9182 gdt:

9183 SEG_NULLASM # null seg

9184 SEG_ASM(STA_X|STA_R, 0x0, 0xffffffff) # code seg

9185 SEG_ASM(STA_W, 0x0, 0xffffffff) # data seg

9186

9187 gdtdesc:

9188 .word (gdtdesc - gdt - 1) # sizeof(gdt) - 1

9189 .long gdt

xv6/bootasm.S [bootloader]

How GDT is defined

9180 # Bootstrap GDT

9181 .p2align 2 # force 4 byte alignment

9182 gdt:

9183 SEG_NULLASM # null seg

9184 SEG_ASM(STA_X|STA_R, 0x0, 0xffffffff) # code seg

9185 SEG_ASM(STA_W, 0x0, 0xffffffff) # data seg

9186

9187 gdtdesc:

9188 .word (gdtdesc - gdt - 1) # sizeof(gdt) - 1

9189 .long gdt

xv6/bootasm.S [bootloader]

Actual switch

- Use long jump to change code segment

9153 `ljmp $(SEG_KCODE<<3), $start32`

- Explicitly specify code segment, and address
- Segment is 0b1000 (0x8)

Why CS is 0x8, not 0x1?

- Segment selector:



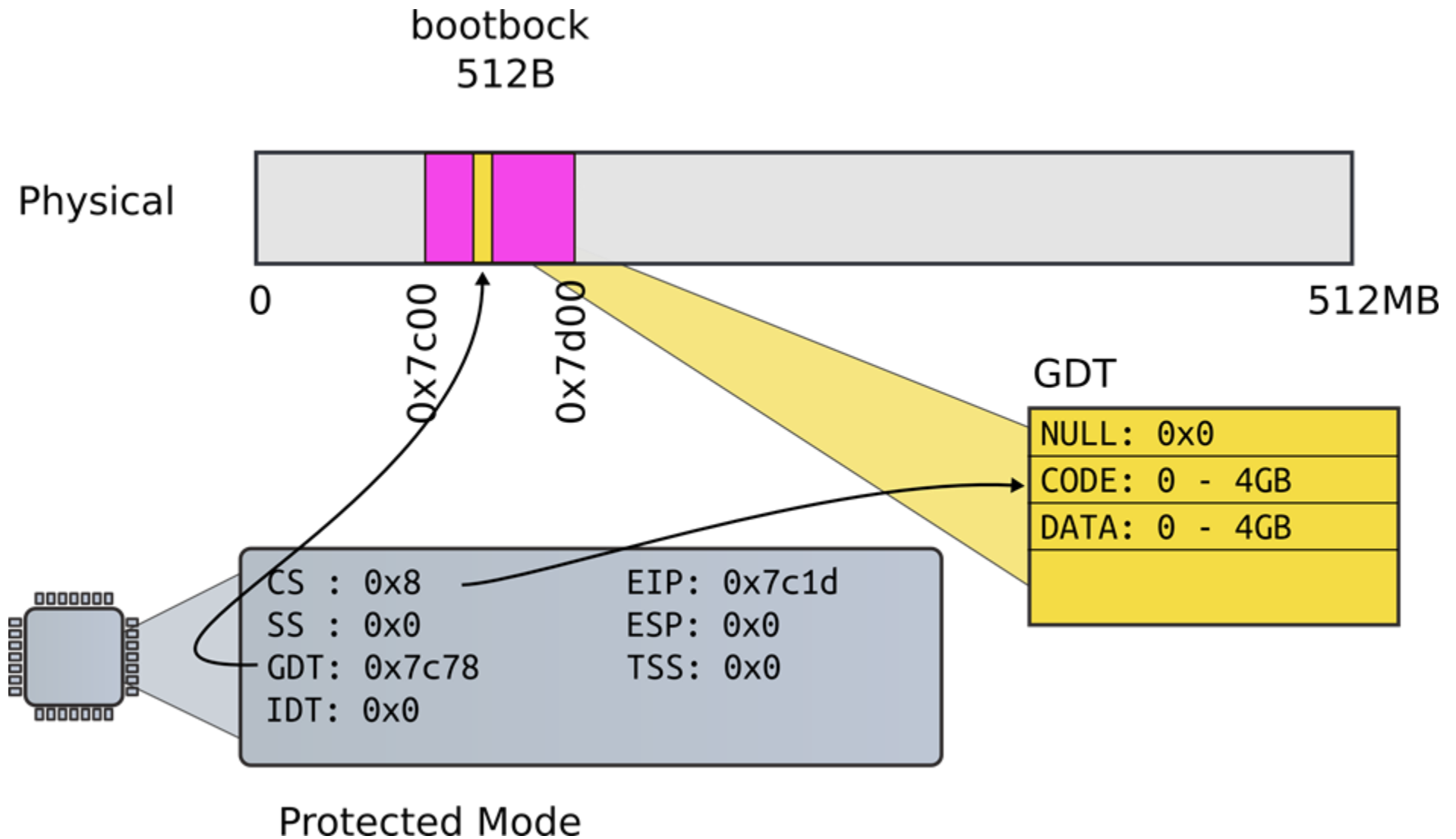
Table Indicator

0 = GDT

1 = LDT

Requested Privilege Level (RPL)

Long jump



Segments

9155 .code32 # Tell assembler to generate 32-bit code now.

9156 start32:

9157 # Set up the protected-mode data segment registers

9158 movw \$(SEG_KDATA<<3), %ax # Our data segment selector

9159 movw %ax, %ds # -> DS: Data Segment

9160 movw %ax, %es # -> ES: Extra Segment

9161 movw %ax, %ss # -> SS: Stack Segment

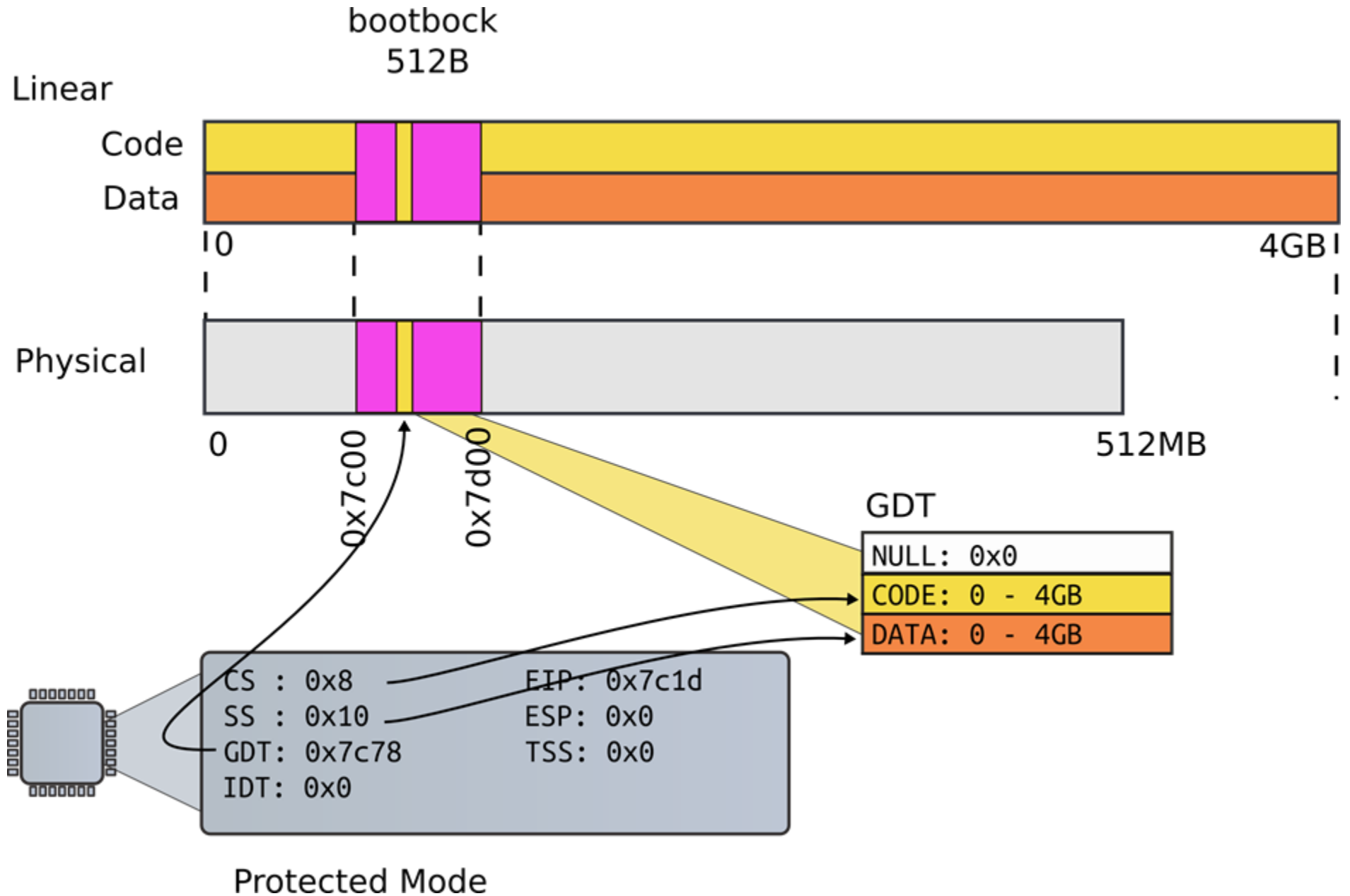
9162 movw \$0, %ax # Zero segments not ready for use

9163 movw %ax, %fs # -> FS

9164 movw %ax, %gs # -> GS

xv6/bootasm.S [bootloader]

Segments



Setup stack

- Why do we need a stack?

```
9166 movl $start, %esp
```

```
9167 call bootmain
```

```
xv6/bootasm.S [bootloader]
```


Setup stack

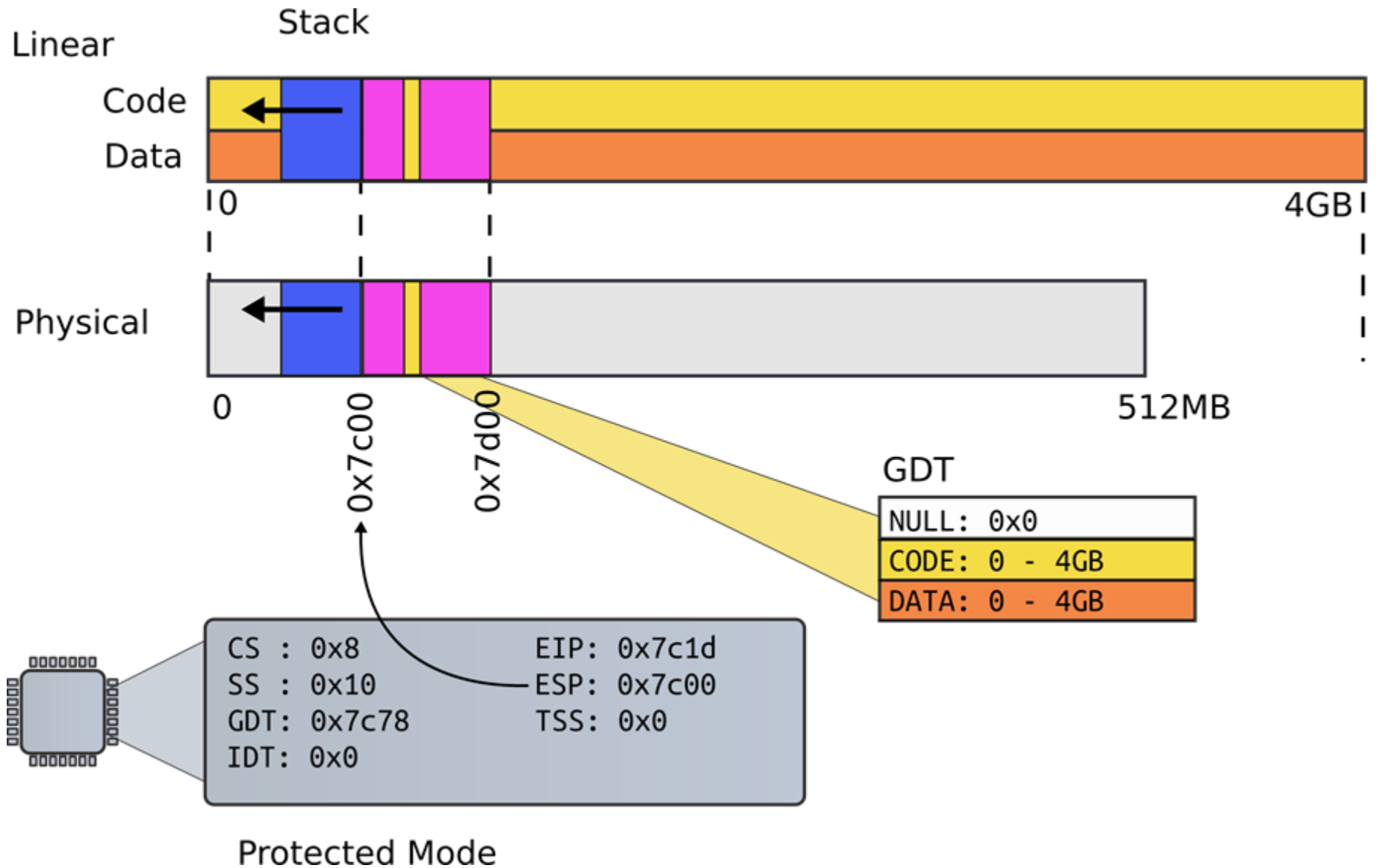
- Need stack to use C
- Function invocations
- Note, there were no stack instructions before that

9166 movl \$start, %esp

9167 call bootmain

xv6/bootasm.S [bootloader]

First stack



Invoke first C function

9166 movl \$start, %esp

9167 call bootmain

bootmain(): read kernel from disk

```
9216 void
9217 bootmain(void)
9218 {
9219     struct elfhdr *elf;
9220     struct proghdr *ph, *eph;
9221     void (*entry)(void);
9222     uchar* pa;
9223
9224     elf = (struct elfhdr*)0x10000; // scratch space
9225
9226     // Read 1st page off disk
9227     readseg((uchar*)elf, 4096, 0);
9228
9229     // Is this an ELF executable?
9230     if(elf->magic != ELF_MAGIC)
9231         return; // let bootasm.S handle error
9232
```

xv6/bootmain.c [bootloader]

```
9232
9233 // Load each program segment (ignores ph flags).
9234 ph = (struct proghdr*)((uchar*)elf + elf->phoff);
9235 eph = ph + elf->phnum;
9236 for(; ph < eph; ph++){
9237     pa = (uchar*)ph->paddr;
9238     readseg(pa, ph->filesz, ph->off);
9239     if(ph->memsz > ph->filesz)
9240         stosb(pa + ph->filesz, 0, ph->memsz - ph->filesz);
9241 }
9242
9243 // Call the entry point from the ELF header.
9244 // Does not return!
9245 entry = (void (*)(void))(elf->entry);
9246 entry();
9247 }
```

bootmain(): read kernel

xv6/bootmain.c [bootloader] from disk

How do we read disk?

```
9257
9258 // Read a single sector at offset into dst.
9259 void
9260 readsect(void *dst, uint offset)
9261 {
9262     // Issue command.
9263     waitdisk();
9264     outb(0x1F2, 1); // count = 1
9265     outb(0x1F3, offset);
9266     outb(0x1F4, offset >> 8);
9267     outb(0x1F5, offset >> 16);
9268     outb(0x1F6, (offset >> 24) | 0xE0);
9269     outb(0x1F7, 0x20); // cmd 0x20 – read sectors
9270
9271     // Read data.
9272     waitdisk();
9273     insl(0x1F0, dst, SECTSIZE/4);
9274 }
```

xv6/bootmain.c [bootloader]

How do we read disk (cont)?

```
9250 void
```

```
9251 waitdisk(void)
```

```
9252 {
```

```
9253     // Wait for disk ready.
```

```
9254     while((inb(0x1F7) & 0xC0) != 0x40)
```

```
9255     ;
```

```
9256 }
```

```
9257
```

xv6/bootmain.c [bootloader]

How do we read disk?

```
9257
9258 // Read a single sector at offset into dst.
9259 void
9260 readsect(void *dst, uint offset)
9261 {
9262     // Issue command.
9263     waitdisk();
9264     outb(0x1F2, 1); // count = 1
9265     outb(0x1F3, offset);
9266     outb(0x1F4, offset >> 8);
9267     outb(0x1F5, offset >> 16);
9268     outb(0x1F6, (offset >> 24) | 0xE0);
9269     outb(0x1F7, 0x20); // cmd 0x20 – read sectors
9270
9271     // Read data.
9272     waitdisk();
9273     insl(0x1F0, dst, SECTSIZE/4);
9274 }
```

xv6/bootmain.c [bootloader]

```
9232
9233 // Load each program segment (ignores ph flags).
9234 ph = (struct proghdr*)((uchar*)elf + elf->phoff);
9235 eph = ph + elf->phnum;
9236 for(; ph < eph; ph++){
9237     pa = (uchar*)ph->paddr;
9238     readseg(pa, ph->filesz, ph->off);
9239     if(ph->memsz > ph->filesz)
9240         stosb(pa + ph->filesz, 0, ph->memsz - ph->filesz);
9241 }
9242
9243 // Call the entry point from the ELF header.
9244 // Does not return!
9245 entry = (void (*)(void))(elf->entry);
9246 entry();
9247 }
```

Call kernel entry

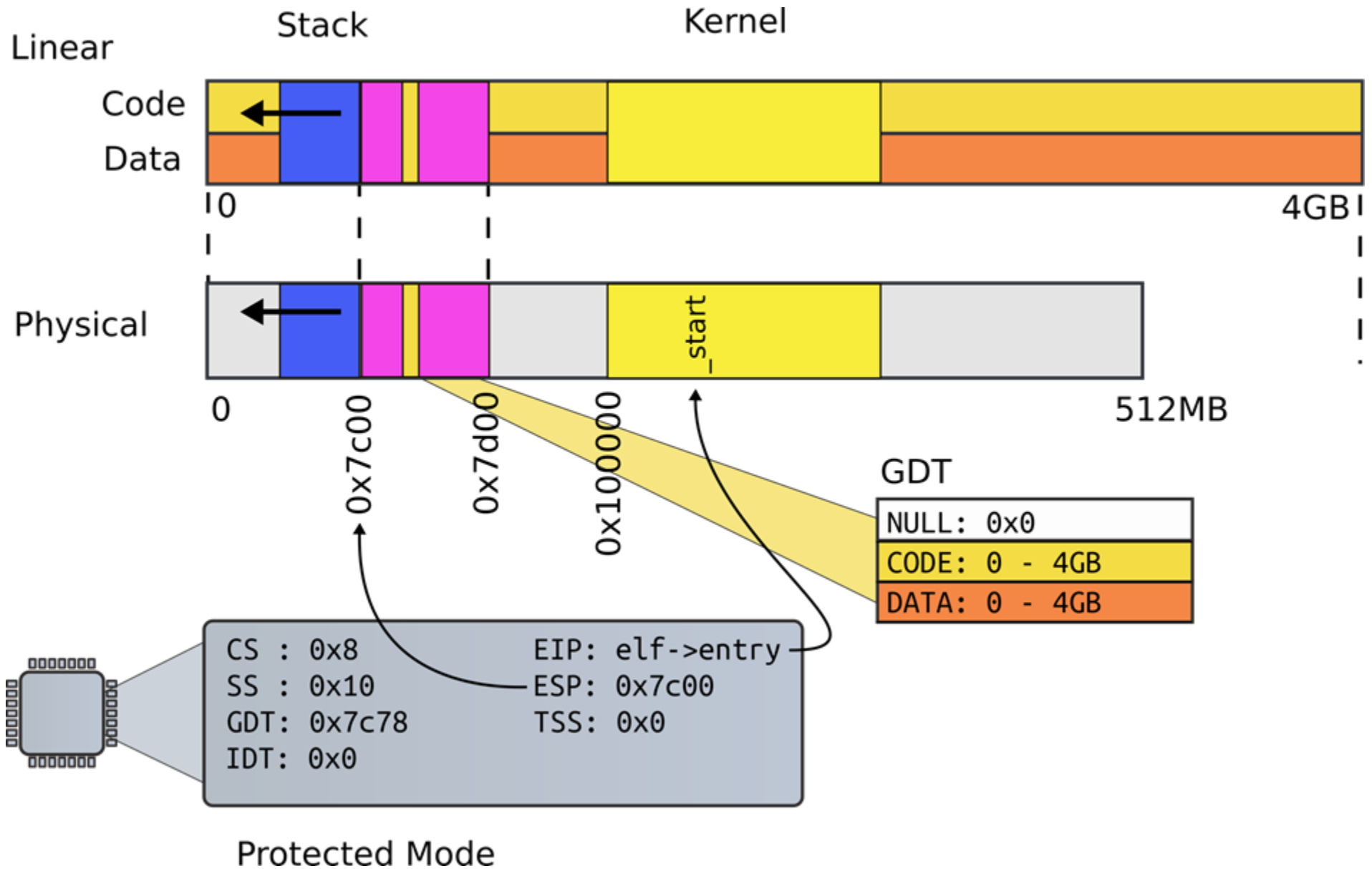
xv6/bootmain.c [bootloader]

```
1039 .globl entry
1136 # By convention, the _start symbol specifies the ELF entry point.
1137 # Since we haven't set up virtual memory yet, our entry point is
1138 # the physical address of 'entry'.
1139 .globl _start
1140 _start = V2P_WO(entry)
1141
1142 # Entering xv6 on boot processor, with paging off.
1143 .globl entry
1144 entry:
1145 # Turn on page size extension for 4Mbyte pages
1146     movl %cr4, %eax
1147     orl $(CR4_PSE), %eax
1148     movl %eax, %cr4
```

entry(): kernel ELF entry

xv6/entry.S [kernel]

Kernel



entry(): kernel ELF entry

1039 .globl entry

1136 # By convention, the _start symbol specifies the ELF entry point.

1137 # Since we haven't set up virtual memory yet, our entry point is

1138 # the physical address of 'entry'.

1139 .globl _start

1140 _start = V2P_WO(entry)

1141

1142 # Entering xv6 on boot processor, with paging off.

1143 .globl entry

1144 entry:

1145 # Turn on page size extension for 4Mbyte pages

1146 movl %cr4, %eax

1147 orl \$(CR4_PSE), %eax

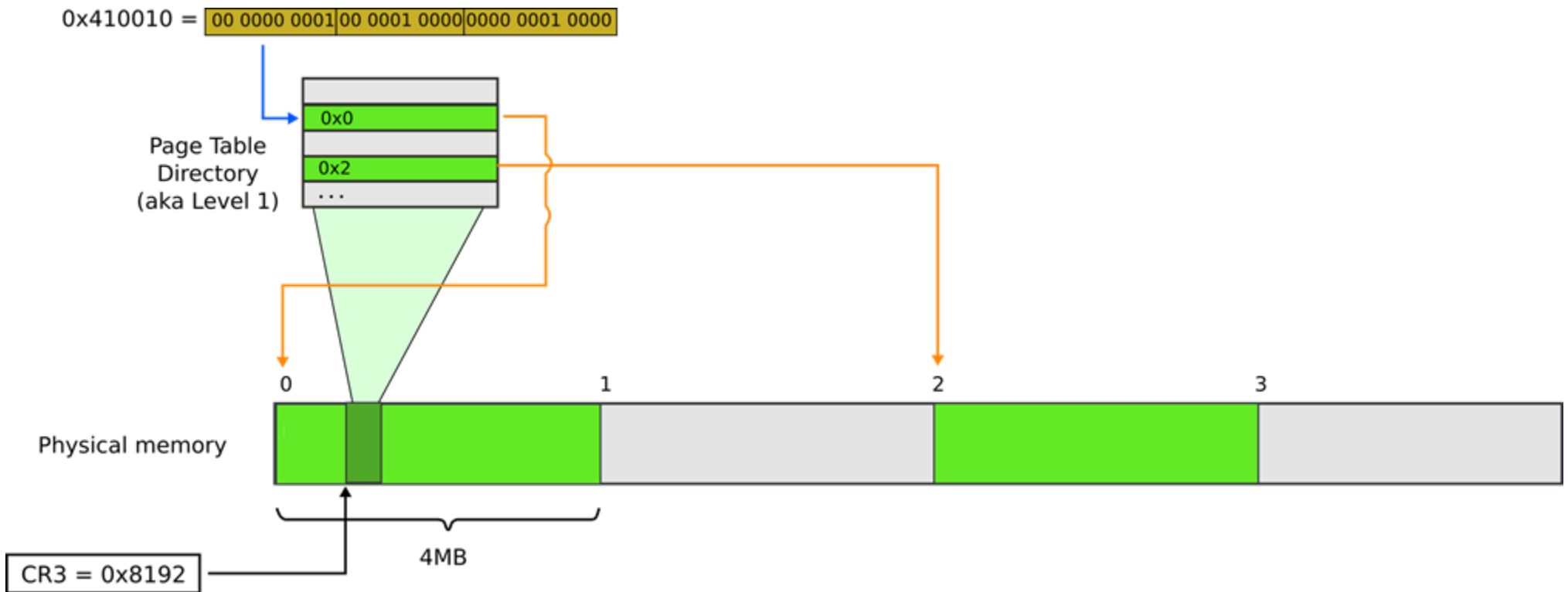
1148 movl %eax, %cr4

xv6/entry.S [kernel]

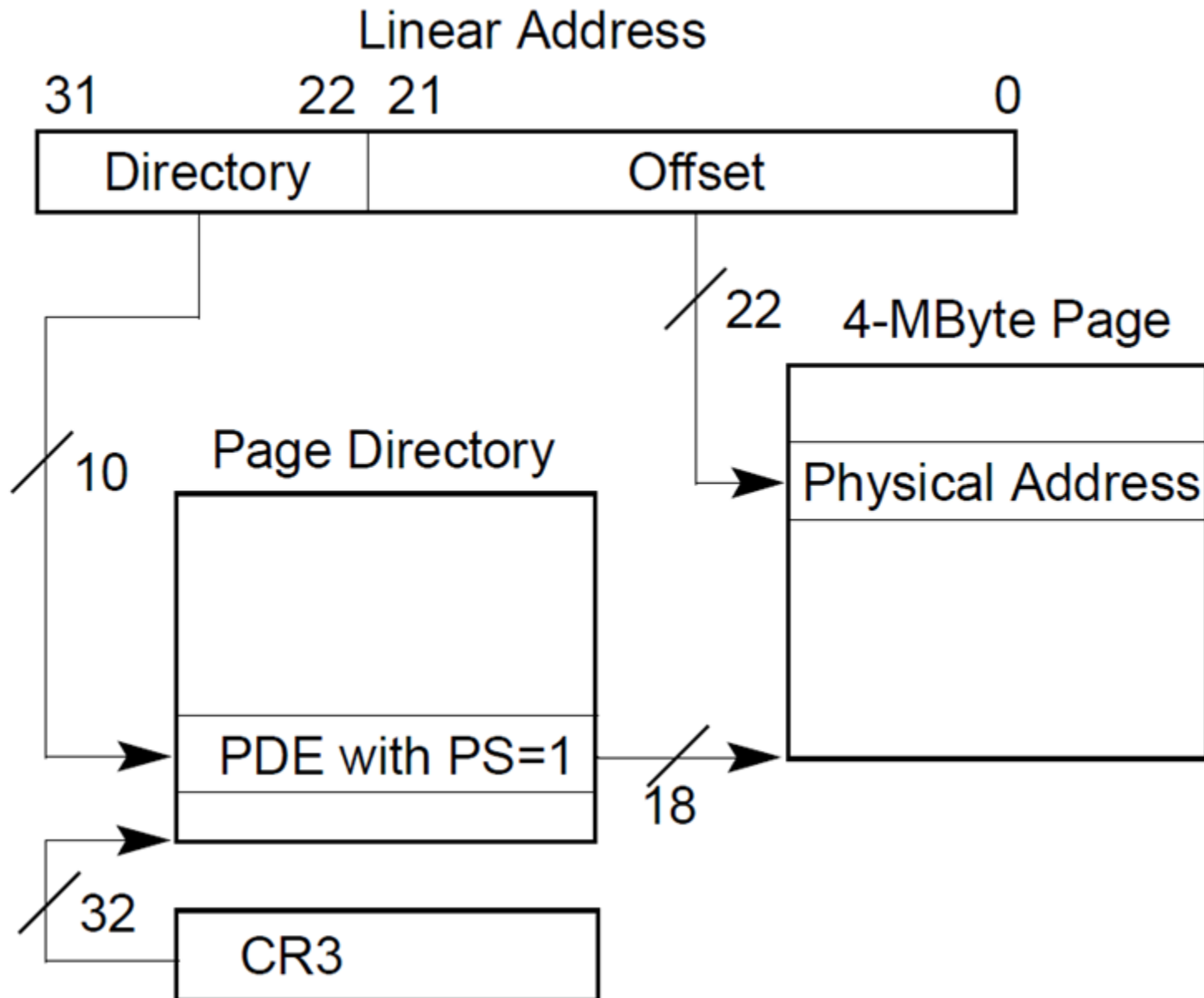
32bit x86 supports two page sizes

- 4KB pages
- 4MB pages

Page translation for 4MB pages



Page translation for 4MB pages



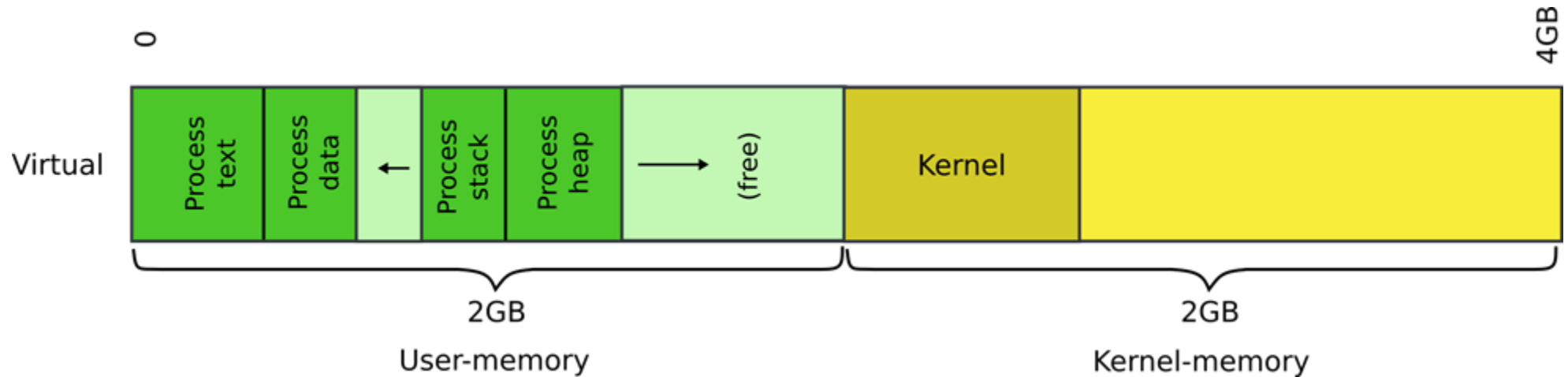
Set up page directory

1149 # Set page directory

1150 movl \$(V2P_WO(entrypgdir)), %eax

1151 movl %eax, %cr3

Our goal: 2GB/2GB address space



First page table

- Two 4MB entries (large pages)
- Entry #0
 - 0x0 – 4MB → 0x0:0x400000
- Entry #512
 - 0x0 – 4MB → 0x80000000:0x80400000

1406 // The boot page table used in entry.S and entryother.S.

1407 // Page directories (and page tables) must start on page boundaries,

1408 // hence the __aligned__ attribute.

1409 // PTE_PS in a page directory entry enables 4Mbyte pages.

1410

1411 __attribute__((__aligned__(PGSIZE)))

1412 pde_t entrypgdir[NPDENTRIES] = {

1413 // Map VA's [0, 4MB) to PA's [0, 4MB)

1414 [0] = (0) | PTE_P | PTE_W | PTE_PS,

1415 // Map VA's [KERNBASE, KERNBASE+4MB) to PA's [0, 4MB)

1416 [KERNBASE>>PDXSHIFT] = (0) | PTE_P | PTE_W | PTE_PS,

1417 };

First page table

```
1406 // The boot page table used in entry.S and entryother.S.

1407 // Page directories (and page tables) must start on page boundaries,

1408 // hence the __aligned__ attribute.

1409 // PTE_PS in a page directory entry enables 4Mbyte pages.

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1413 // Map VA's [0, 4MB) to PA's [0, 4MB)

1414 [0] = (0) | PTE_P | PTE_W | PTE_PS,

1415 // Map VA's [KERNBASE, KERNBASE+4MB) to PA's [0, 4MB)

1416 [KERNBASE>>PDXSHIFT] = (0) | PTE_P | PTE_W | PTE_PS,

1417 };
```

First page table

First page table (cont)

0870 // Page directory and page table constants.

0871 #define NPDENTRIES 1024


```
1406 // The boot page table used in entry.S and entryother.S.

1407 // Page directories (and page tables) must start on page boundaries,

1408 // hence the __aligned__ attribute.

1409 // PTE_PS in a page directory entry enables 4Mbyte pages.

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1412 pde_t entrypgdir[NPDENTRIES] = {

1413 // Map VA's [0, 4MB) to PA's [0, 4MB)

1414 [0] = (0) | PTE_P | PTE_W | PTE_PS,

1415 // Map VA's [KERNBASE, KERNBASE+4MB) to PA's [0, 4MB)

1416 [KERNBASE>>PDXSHIFT] = (0) | PTE_P | PTE_W | PTE_PS,

1417 };
```

First page table

```
1406 // The boot page table used in entry.S and entryother.S.

1407 // Page directories (and page tables) must start on page boundaries,

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1414 [0] = (0) | PTE_P | PTE_W | PTE_PS,

1415 // Map VA's [KERNBASE, KERNBASE+4MB) to PA's [0, 4MB)

1416 [KERNBASE >> PDXSHIFT] = (0) | PTE_P | PTE_W | PTE_PS,

1417 };
```

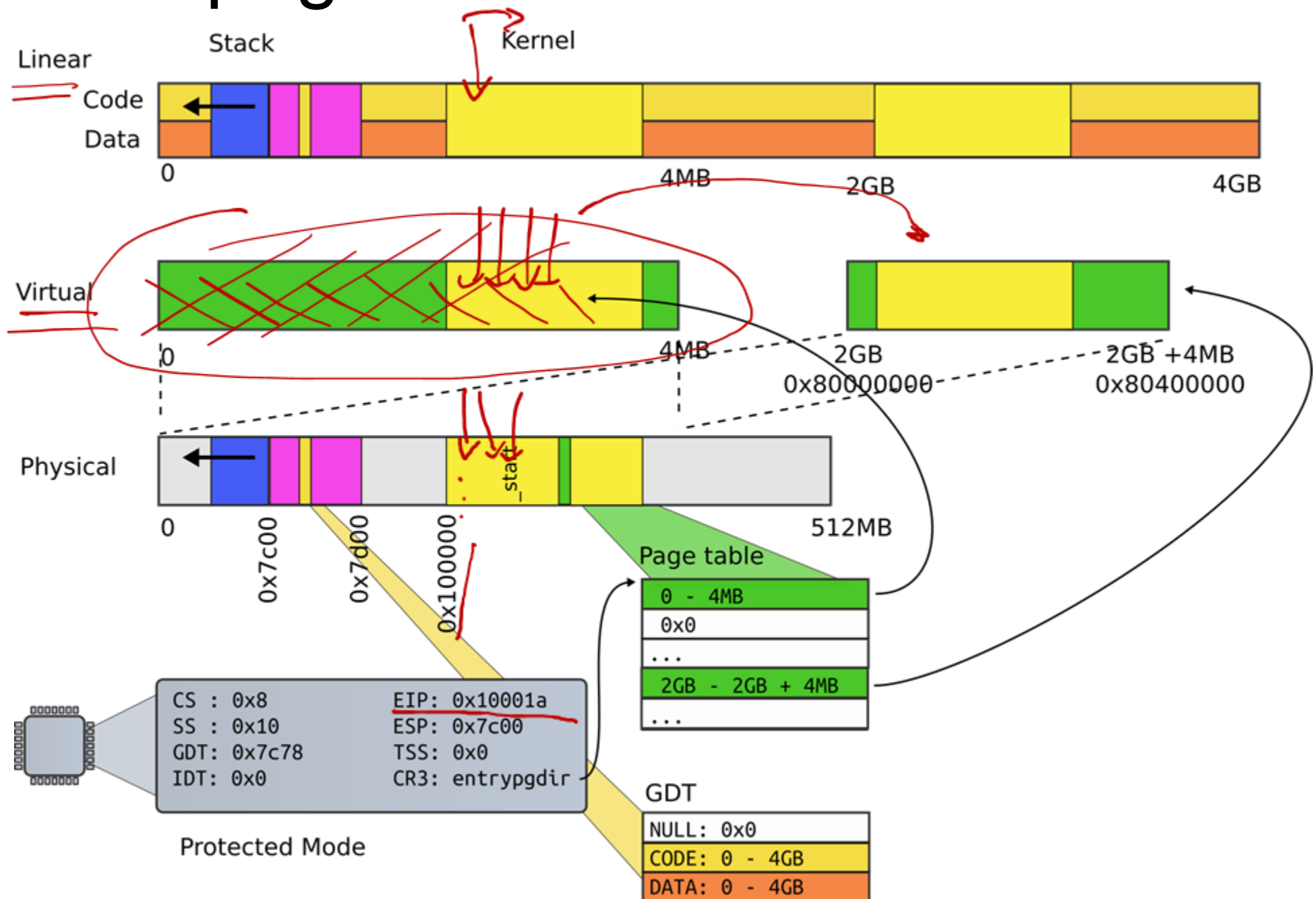
First page table

```
1406 // The boot page table used in entry.S and entryother.S.
1407 // Page directories (and page tables) must start on page boundaries,
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1410
1411 __attribute__((__aligned__(PGSIZE)))
1412 pde_t entrypgdir[NPDENTRIES] = {
1413     // Map VA's [0, 4MB) to PA's [0, 4MB)
1414     [0] = (0) | PTE_P | PTE_W | PTE_PS,
1415     // Map VA's [KERNBASE, KERNBASE+4MB) to PA's [0, 4MB)
1416     [KERNBASE>>PDXSHIFT] = (0) | PTE_P | PTE_W | PTE_PS,
1417 };
```

First page table

First page table

EIP ~ 1MB + 0x1a



Turn on paging

1152 # Turn on paging.

1153 movl %cr0, %eax

1154 orl \$(CR0_PG|CR0_WP), %eax

1155 movl %eax, %cr0

xv6/entry.S [kernel]

High address stack (4K)

1157 # Set up the stack pointer.

1158 movl \$(stack + KSTACKSIZE), %esp

1159

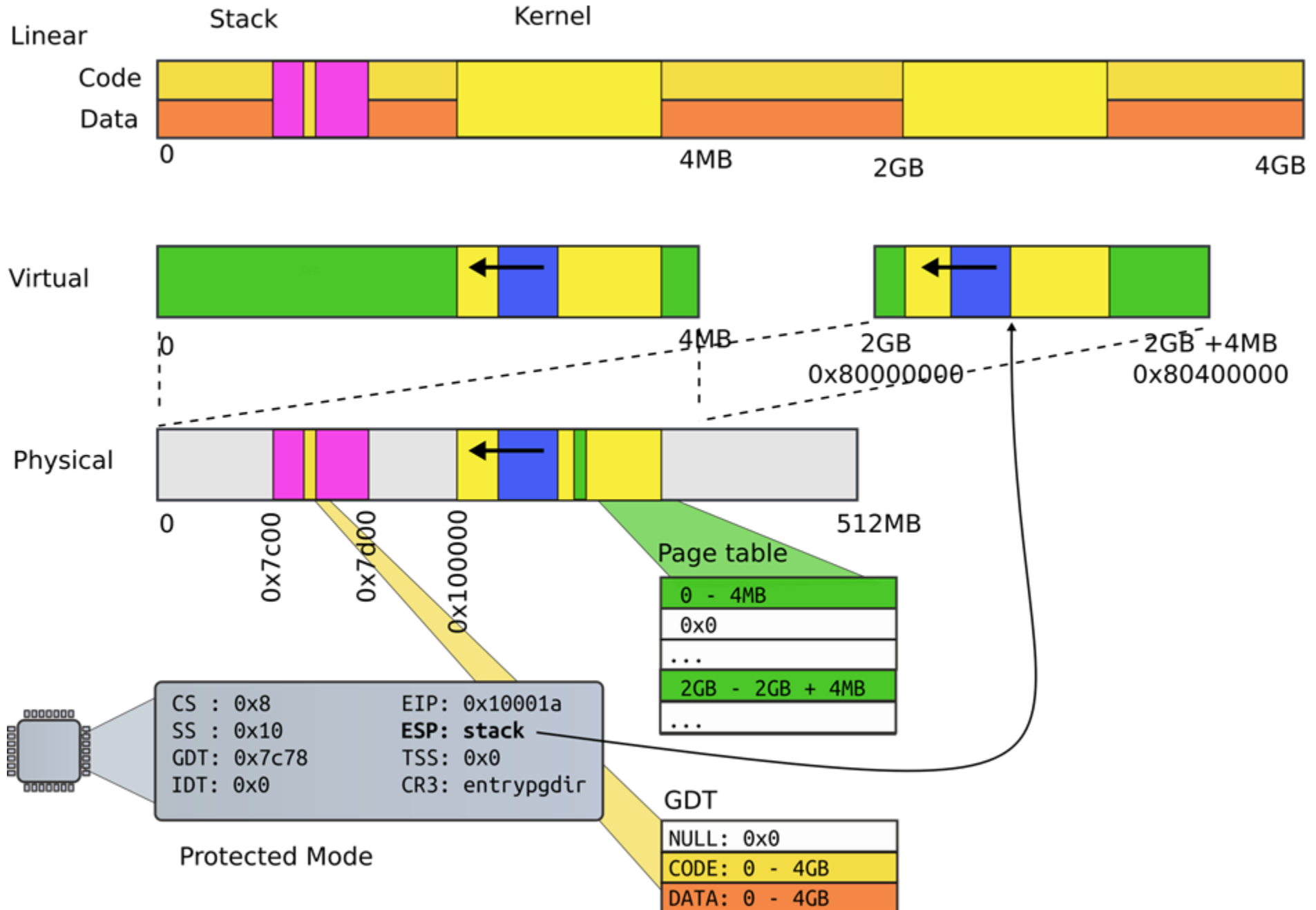
...

1167 .comm stack, KSTACKSIZE

0151 #define KSTACKSIZE 4096 // size of
per-process kernel stack

xv6/entry.S [kernel]

High address stack (4K)



Jump to main()

1160 # Jump to main(), and switch to executing at

1161 # high addresses. The indirect call is

needed because

1162 # the assembler produces a PC-relative

instruction

1163 # for a direct jump.

1164 mov \$main, %eax

1165 jmp *%eax

1166

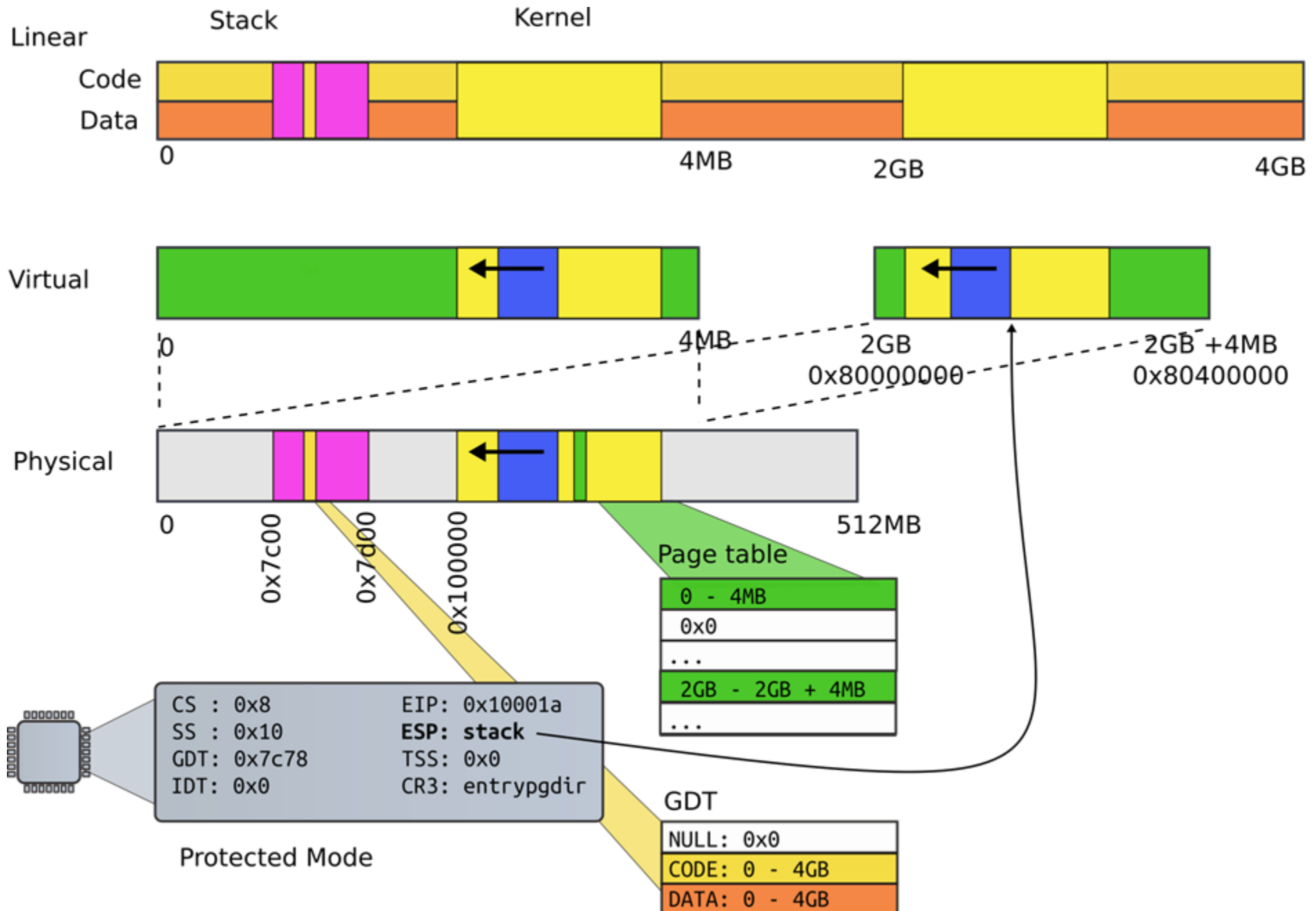
xv6/entry.S [kernel]

Running in main()

```
1313 // Bootstrap processor starts running C code here.
1314 // Allocate a real stack and switch to it, first
1315 // doing some setup required for memory allocator to work.
1316 int
1317 main(void)
1318 {
1319     kinit1(end, P2V(4*1024*1024)); // phys page allocator
1320     kvmalloc(); // kernel page table
1321     mpinit(); // detect other processors
1322     lapicinit(); // interrupt controller
1323     seginit(); // segment descriptors
1324     cprintf("\ncpu%d: starting xv6\n\n", cpunum());
    ...
1340 }
```

xv6/main.c [kernel]

Poll: PollEv.com/antonburtsev



Recap of the boot sequence

- Setup segments (data and code)
- Switched to protected mode
- Loaded GDT (segmentation is on)
- Setup stack (to call C functions)
- Loaded kernel from disk
- Setup first page table
 - 2 entries [0 : 4MB] and [2GB : (2GB + 4MB)]
- Setup high-address stack
- Jumped to main()

Conclusion

- We've booted
- We're running in main()

Thank you!

References

- [1] Costan, Victor, and Srinivas Devadas. "Intel SGX Explained." IACR Cryptology ePrint Archive 2016 (2016): 86.
<https://eprint.iacr.org/2016/086.pdf>

```
1. #include <stdio.h>

2. void func_a(void){
3.     printf("func_a\n");
4.     return;
5. }

6. void func_b(void) {
7.     printf("func_b\n");
8.     return;
9. }

10. int main(int ac, char **av)
11. {
12.     void (*fp)(void);

13.     fp = func_b;
14.     fp();
15.     return;
16. }
```

Function pointers

08048432 <func_b>:

```
8048432: 55          push  %ebp
8048433: 89 e5       mov   %esp,%ebp
8048435: 83 ec 18    sub   $0x18,%esp
8048438: c7 04 24 07 85 04 08 movl  $0x8048507,(%esp)
804843f: e8 ac fe ff ff call  80482f0 <puts@plt>
8048444: 90          nop
8048445: c9          leave
8048446: c3          ret
```

08048447 <main>:

```
8048447: 55          push  %ebp
8048448: 89 e5       mov   %esp,%ebp
804844a: 83 e4 f0    and   $0xffffffff0,%esp
804844d: 83 ec 10    sub   $0x10,%esp
                # Load pointer to func_p on the stack
8048450: c7 44 24 0c 32 84 04 movl  $0x8048432,0xc(%esp)
8048457: 08
8048458: 8b 44 24 0c    mov  0xc(%esp),%eax
804845c: ff d0       call  *%eax
804845e: 90          nop
804845f: c9          leave
8048460: c3          ret
```

Function pointers

08048432 <func_b>:

```
8048432: 55          push  %ebp
8048433: 89 e5       mov   %esp,%ebp
8048435: 83 ec 18    sub   $0x18,%esp
8048438: c7 04 24 07 85 04 08  movl  $0x8048507,(%esp)
804843f: e8 ac fe ff  call  80482f0 <puts@plt>
8048444: 90          nop
8048445: c9          leave
8048446: c3          ret
```

08048447 <main>:

```
8048447: 55          push  %ebp
8048448: 89 e5       mov   %esp,%ebp
804844a: 83 e4 f0    and   $0xffffffff0,%esp
804844d: 83 ec 10    sub   $0x10,%esp
                # Load pointer to func_p on the stack
8048450: c7 44 24 0c 32 84 04  movl  $0x8048432,0xc(%esp)
8048457: 08
                # Move func_b into %eax
8048458: 8b 44 24 0c  mov   0xc(%esp),%eax
804845c: ff d0       call  *%eax # Call %eax
804845e: 90          nop
804845f: c9          leave
8048460: c3          ret
```

Function pointers