

cs5460/6460: Operating Systems

Lecture: Interrupts and Exceptions

Anton Burtsev
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```
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());
1325     picinit(); // another interrupt controller
1326     ioapicinit(); // another interrupt controller
1327     consoleinit(); // console hardware
1328     uartinit(); // serial port
1329     pinit(); // process table
1330     tvinit(); // trap vectors
1331     binit(); // buffer cache
1332     fileinit(); // file table
1333     ideinit(); // disk
1334     if(!ismp)
1335         timerinit(); // uniprocessor timer
1336     startothers(); // start other processors
1337     kinit2(P2V(4*1024*1024), P2V(PHYSTOP)); // must come after startothers()
1338     userinit(); // first user process
1339     mpmain(); // finish this processor's setup
1340 }
```

main()

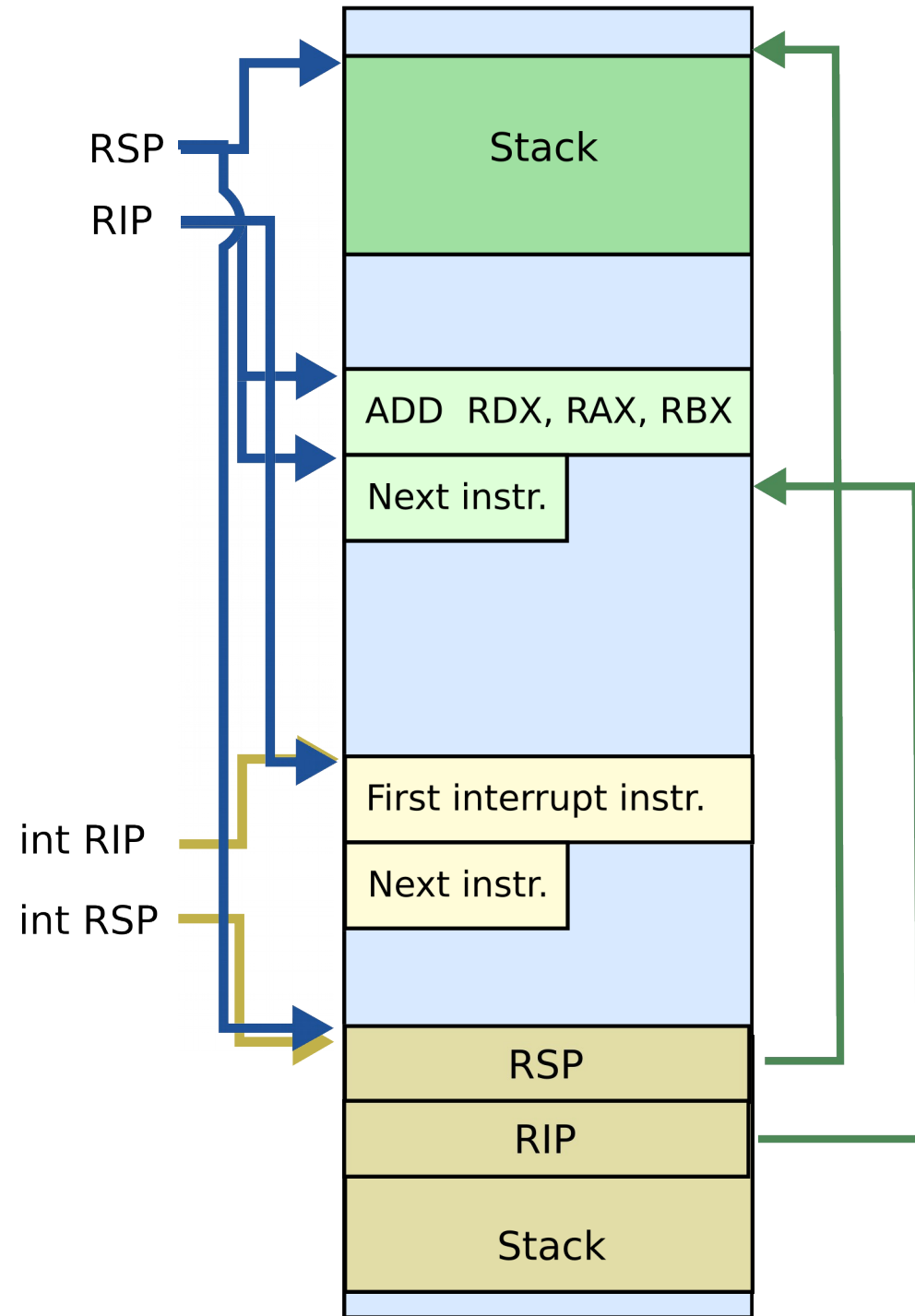
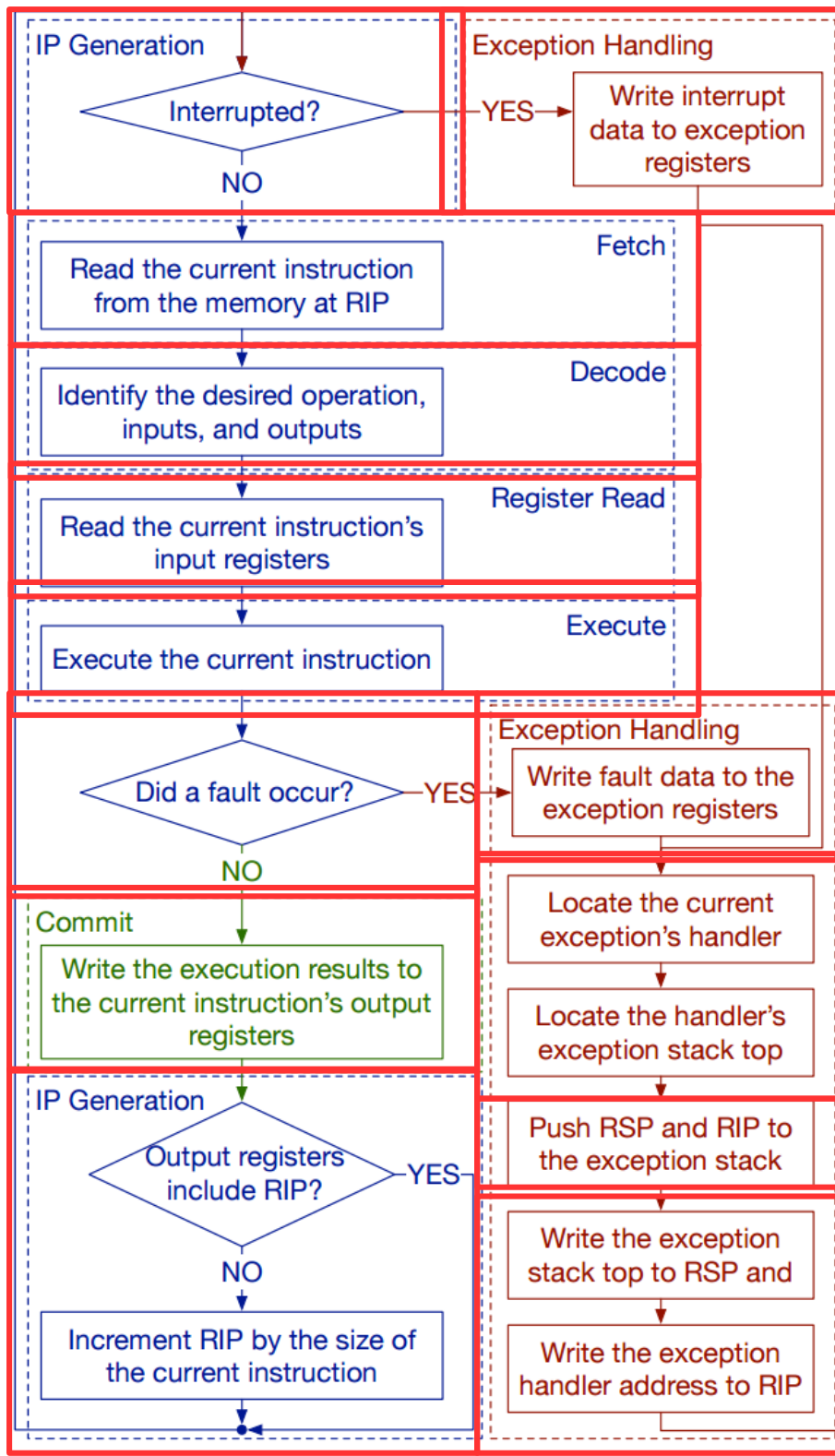
Why do we need interrupts?

Remember:
hardware interface is designed to help OS

Why do we need interrupts?

- Two main use cases:
 - [Synchronous] Something bad happened and OS needs to fix it
 - Program tries to access an unmapped page (OS maps the page if its on disk)
 - [Asynchronous] Notifications from external devices
 - Network packet arrived (OS will copy the packet from temporary buffer in memory (to avoid overflowing) and may switch to a process waiting on that packet)
 - Timer interrupt (OS may switch to another process)
- A third, special, use-case
 - [It's also synchronous] For many years an interrupt, e.g., int 0x80 instruction, was used as a mechanism to transfer control flow from user-level to kernel in a secure manner
 - In other words, to implement system calls
 - Now, a faster mechanism is available (sysenter)

How do we handle an interrupt?



Handling interrupts and exceptions

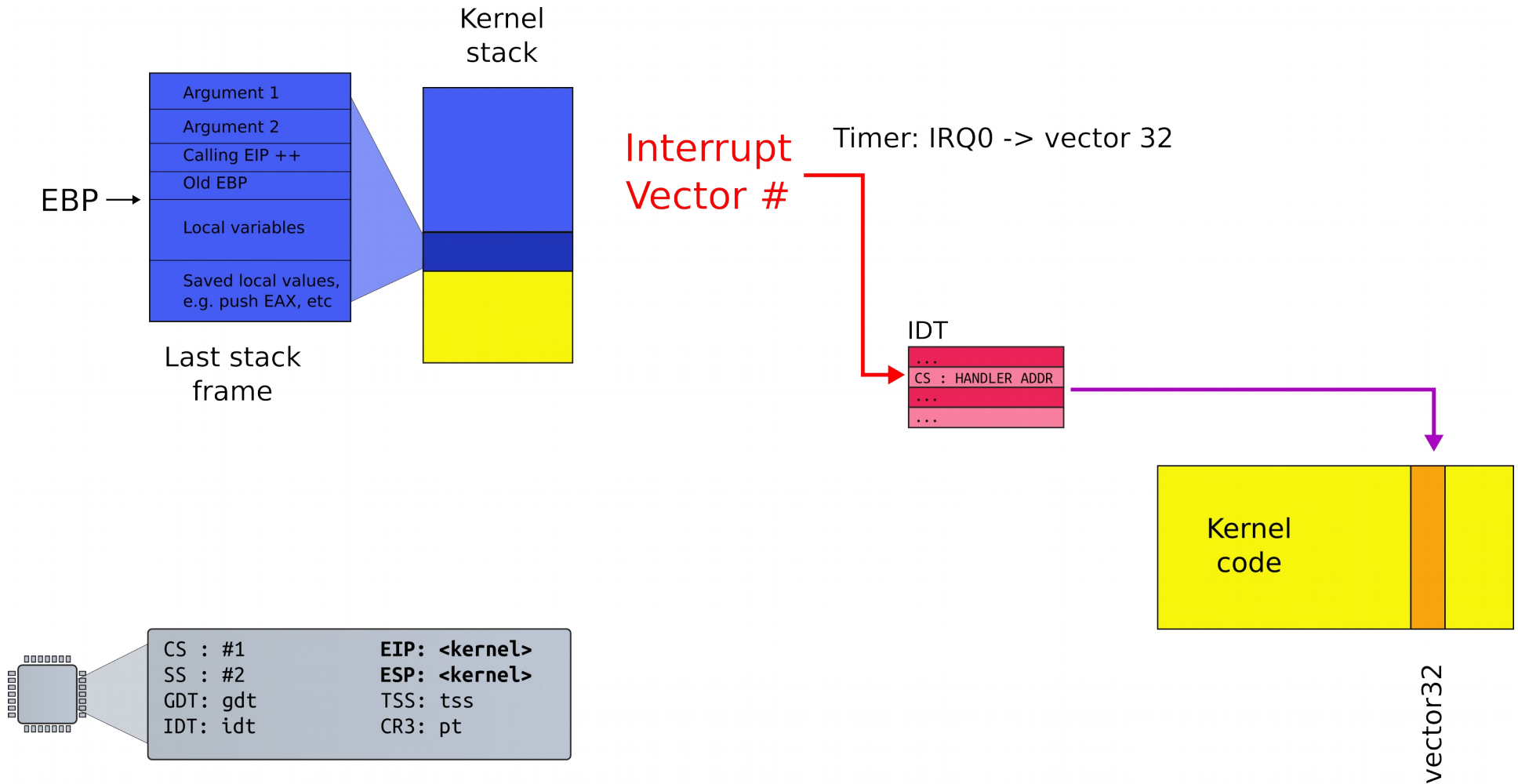
- In both synchronous and asynchronous cases the CPU follows the **same procedure**
 - Stop execution of the current program
 - Start execution of a handler
 - Processor accesses the handler through an entry in the Interrupt Descriptor Table (IDT)
- Each interrupt is defined by a number
 - E.g., 14 is pagefault, 3 debug
 - This number is an index into the interrupt table (IDT)

There might be two cases

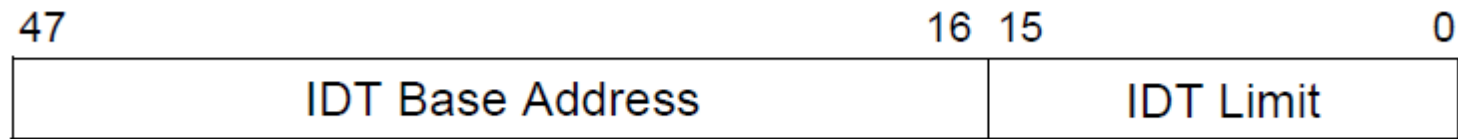
- Interrupt requires **no change** of privilege level
 - i.e., the CPU runs kernel code (privilege level 0) when
 - a timer interrupt arrives, or
 - kernel tries to access an unmapped page
- Interrupt **changes** privilege level
 - i.e., the CPU runs **user** code (privilege level 3) when
 - a timer interrupt arrives, or
 - User code tries to access an unmapped page

Case #1: Interrupt path no change in privilege level

- e.g., we're already running in the kernel

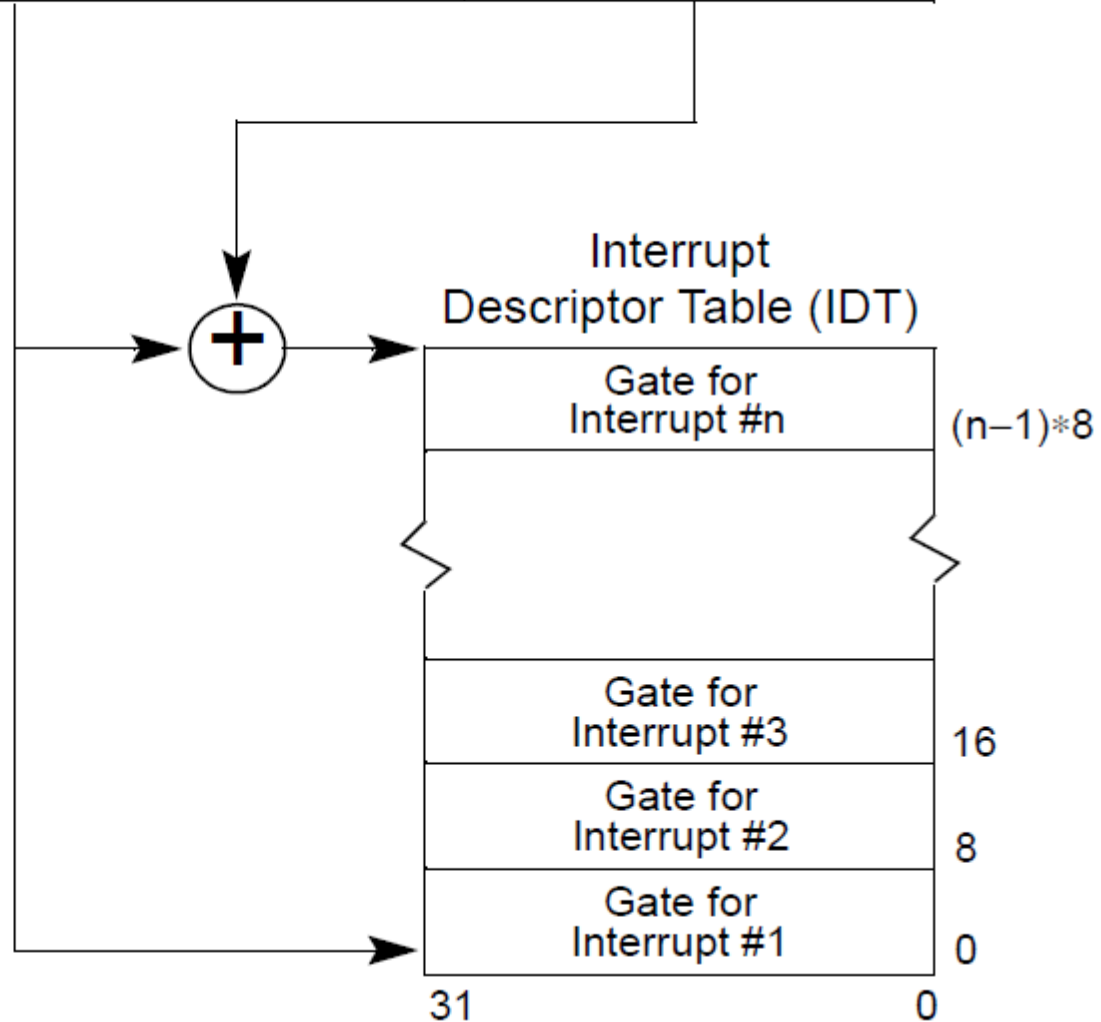


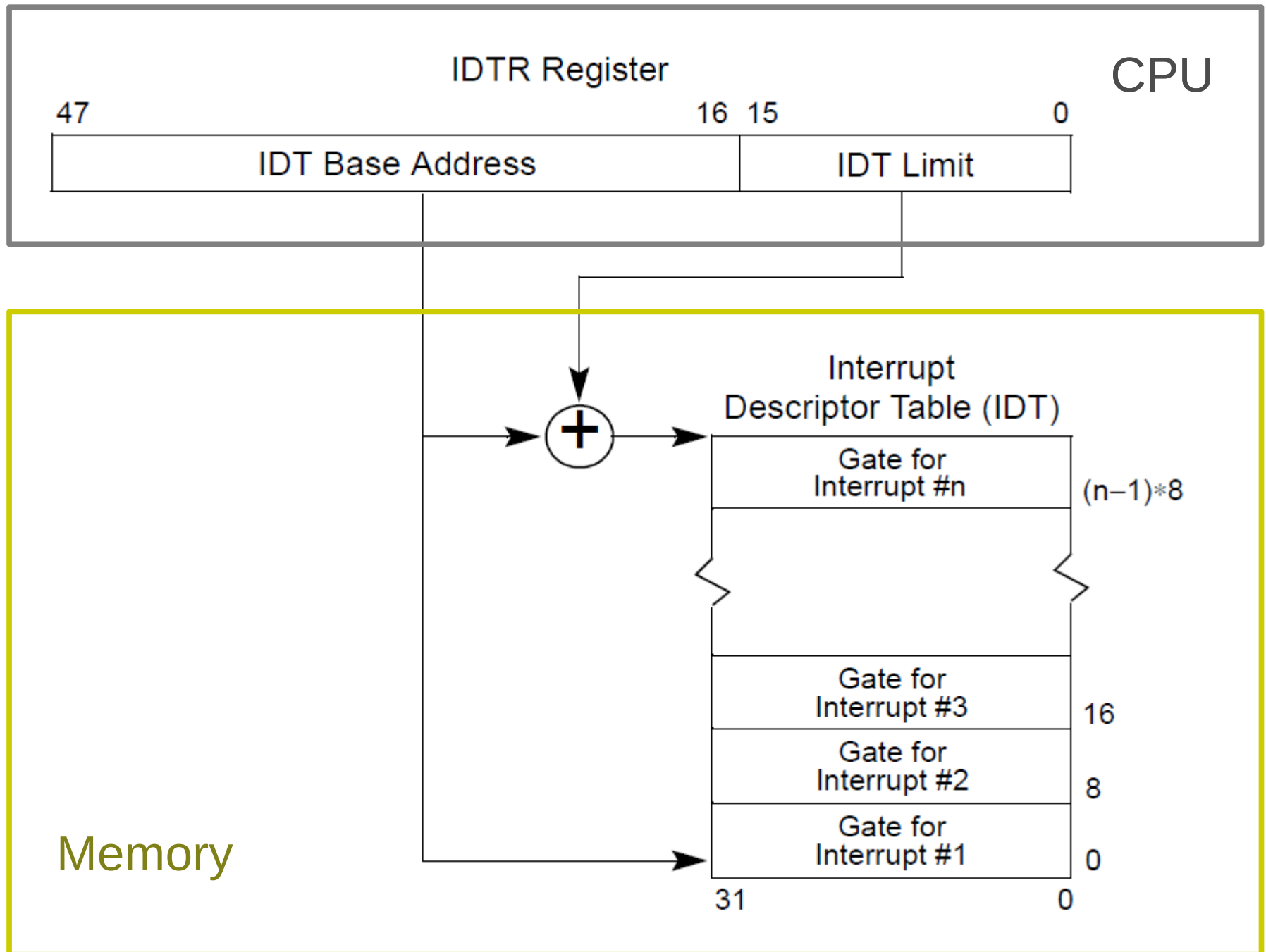
IDTR Register



Interrupt descriptor table (IDT)

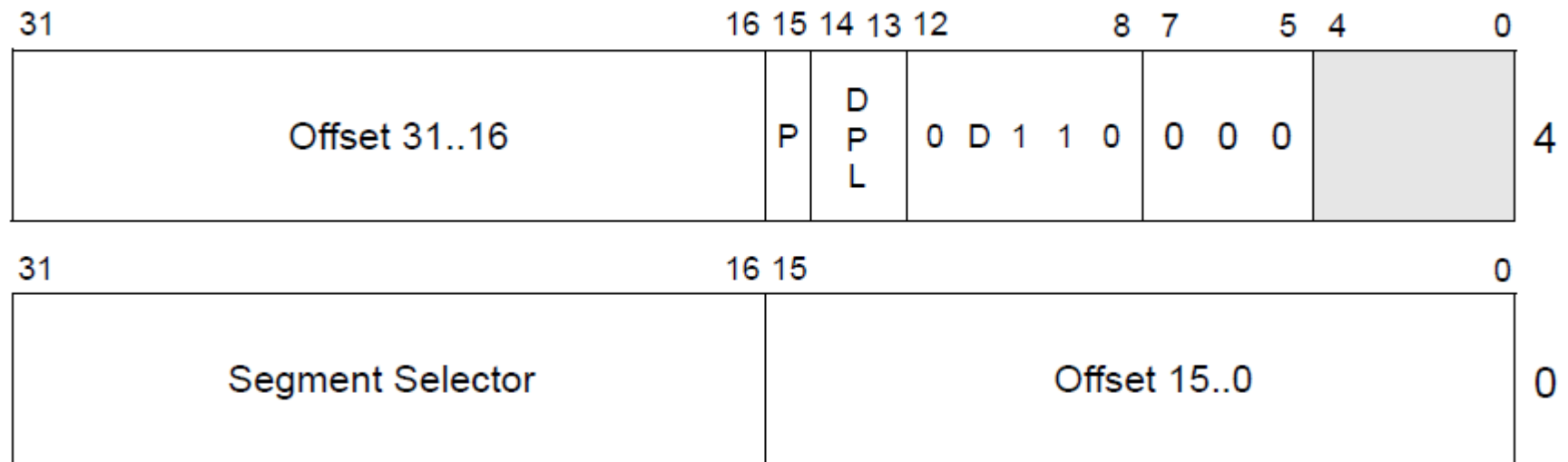
- Is pointed by the IDTR register
 - Virtual address
- OS configures the value and loads it into the register (normally during boot)



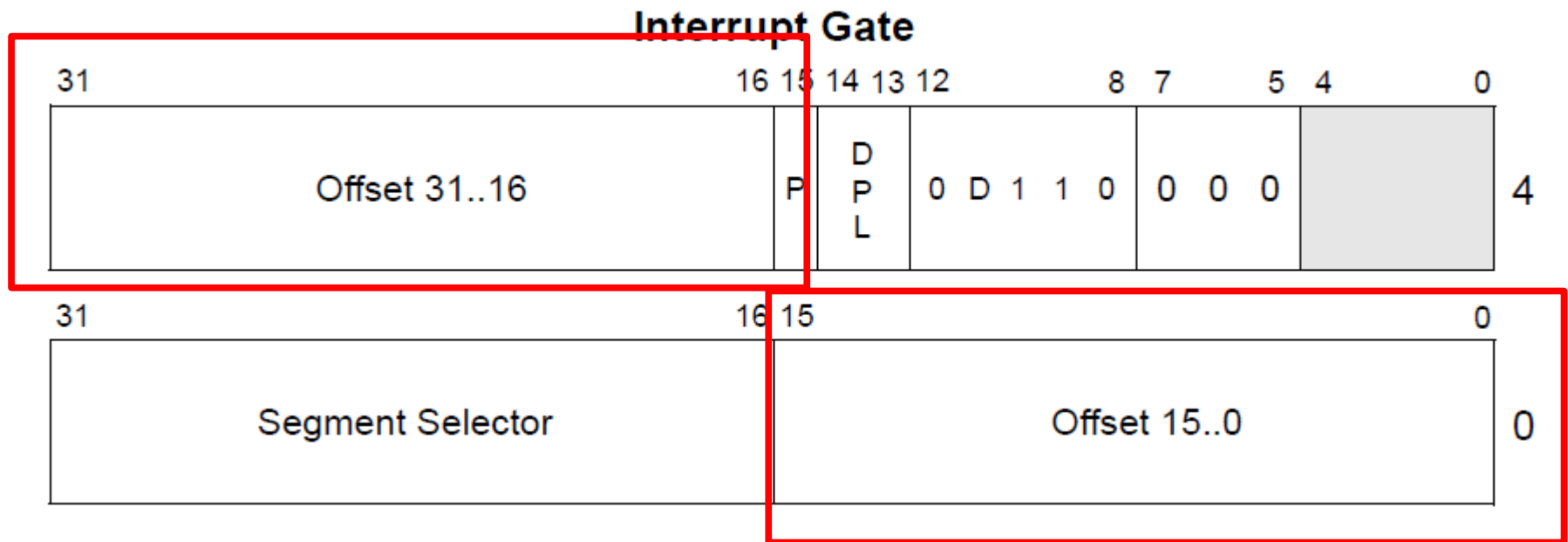


Interrupt descriptor

Interrupt Gate



Interrupt descriptor

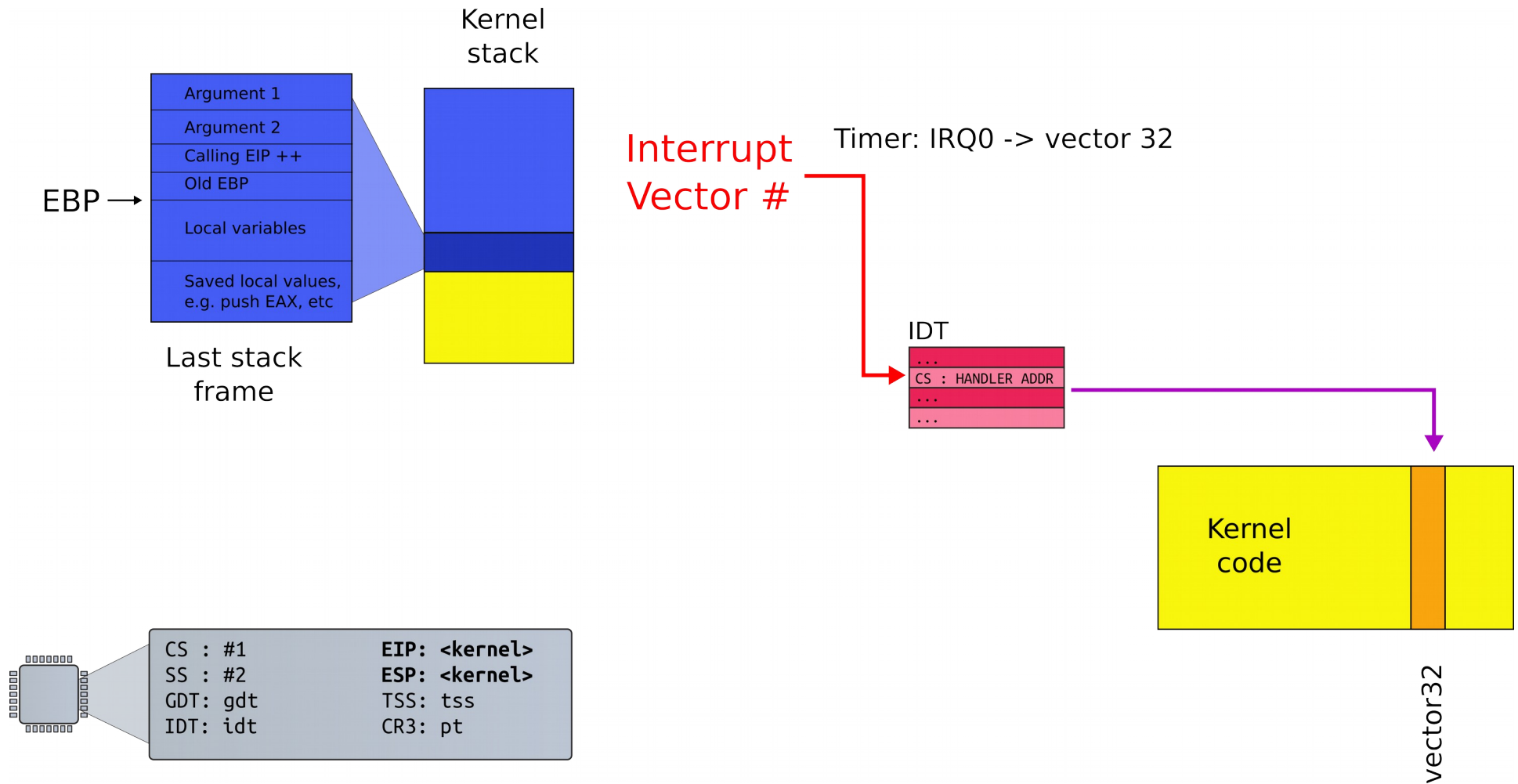


- We will walk through these fields gradually
 - For now we care about vector offset
 - Pointer to the interrupt handler

Interrupt handlers

- Just plain old code in the kernel
- The IDT stores a pointer to the right handler routine

Interrupt path

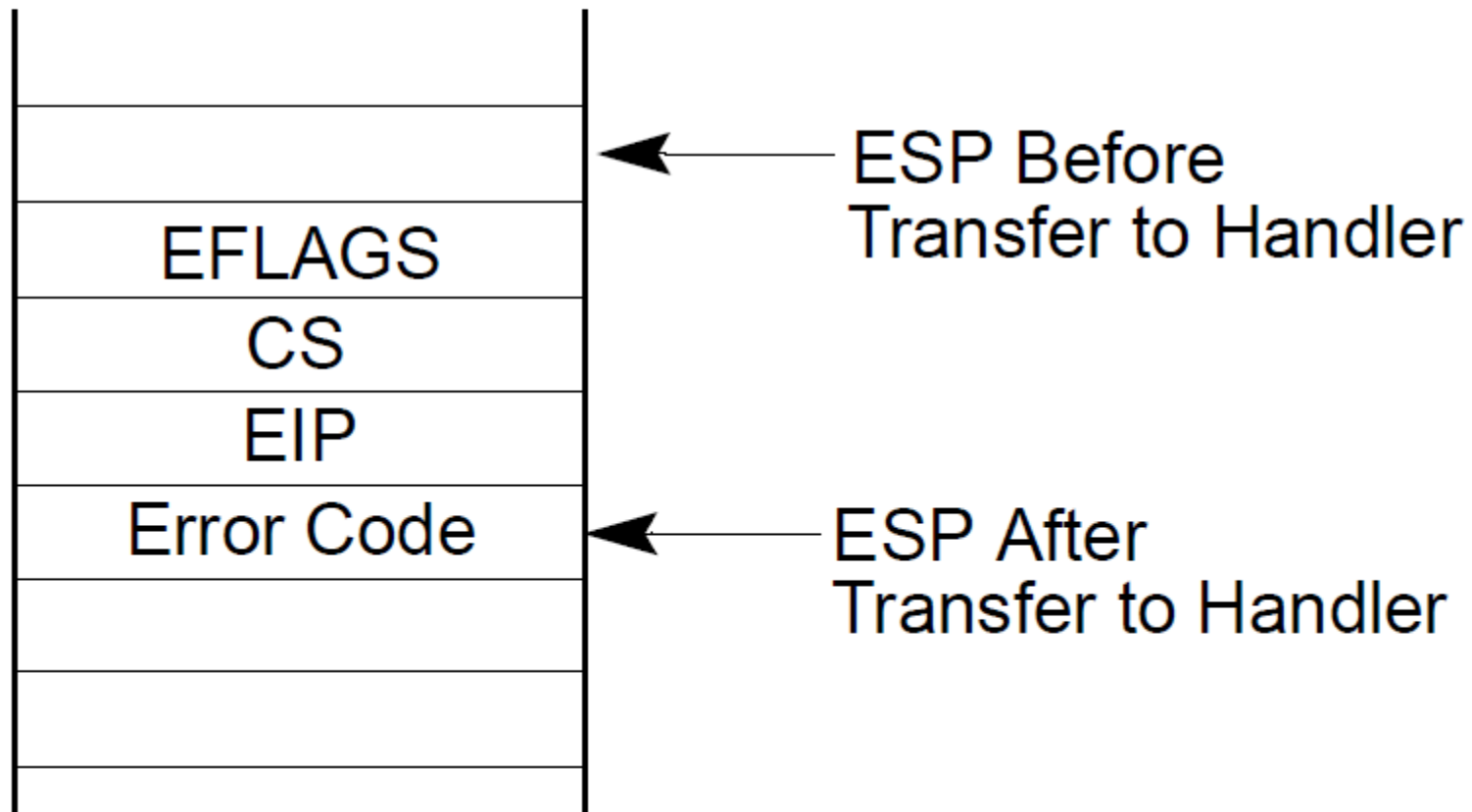


Processing of interrupt (same PL)

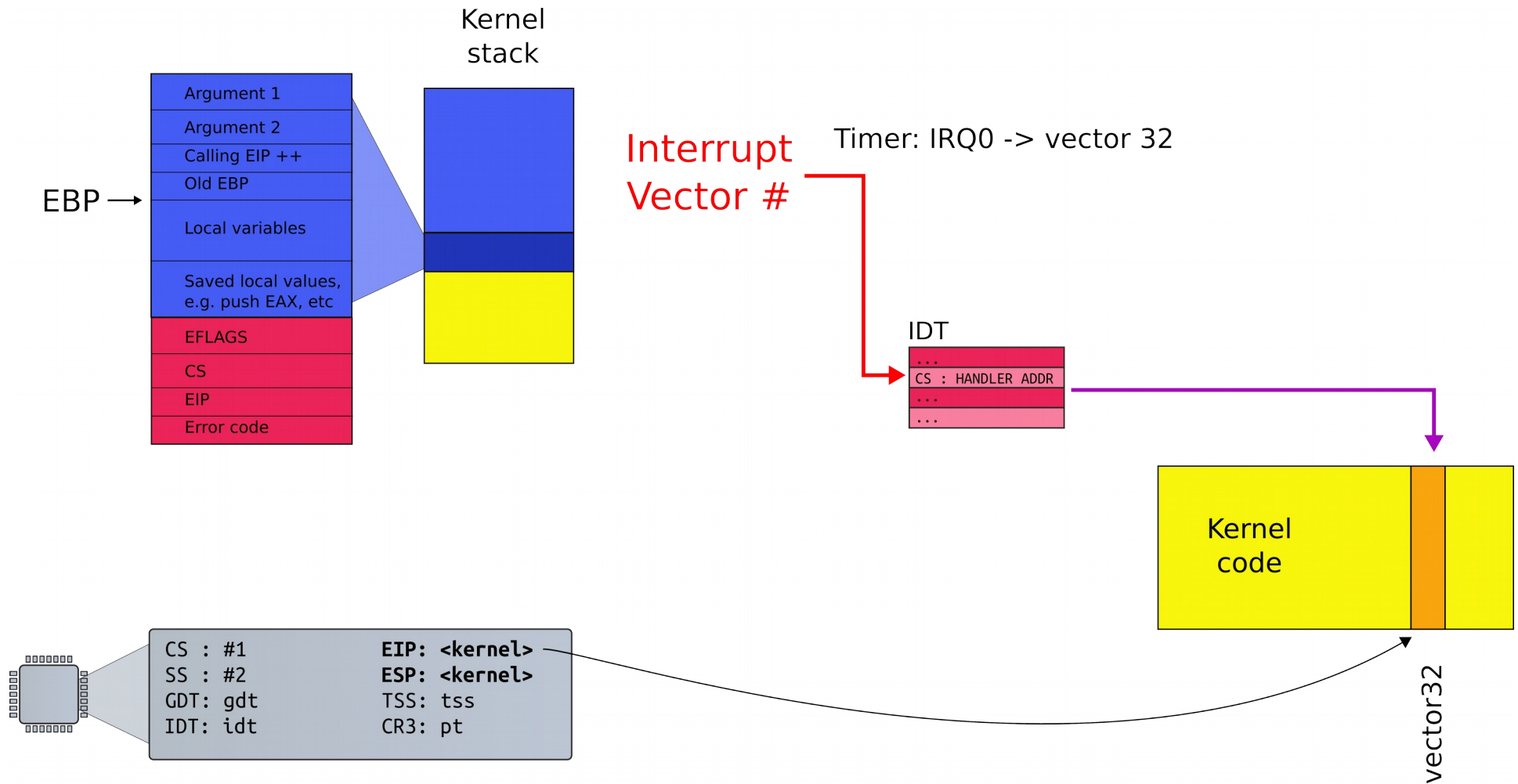
1. Push the current contents of the EFLAGS, CS, and EIP registers (in that order) on the stack
2. Push an error code (if appropriate) on the stack
3. Load the segment selector for the new code segment and the new instruction pointer (from the interrupt gate or trap gate) into the CS and EIP registers
4. If the call is through **an interrupt gate**, clear the IF flag in the EFLAGS register (**disable further interrupts**)
5. Begin execution of the handler

Stack Usage with No Privilege-Level Change

Interrupted Procedure's
and Handler's Stack



Interrupt path



Return from an interrupt

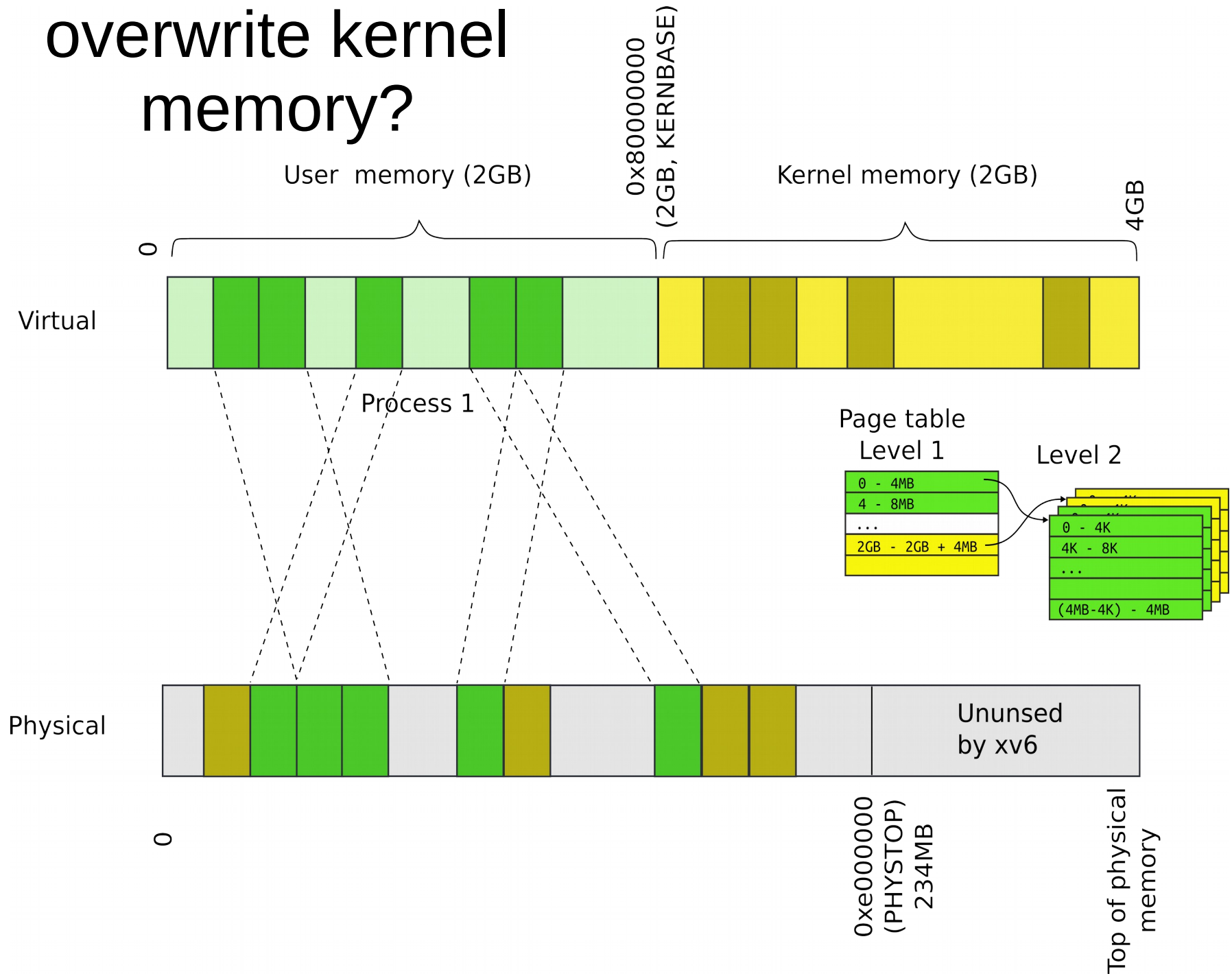
- Starts with IRET
 1. Restore the CS and EIP registers to their values prior to the interrupt or exception
 2. Restore EFLAGS
 3. Restore SS and ESP to their values prior to interrupt
 - This results in a stack switch
 4. Resume execution of interrupted procedure

Processing of interrupt (cross PL)

- Need to change privilege level...

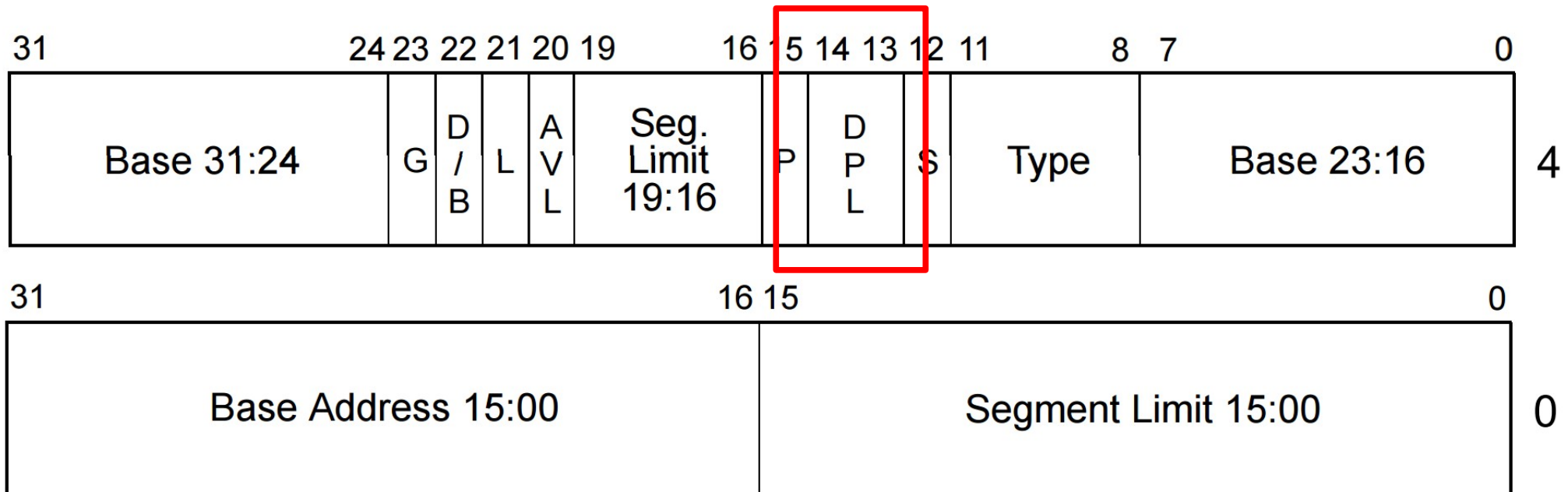
Detour:
What are those privilege levels?

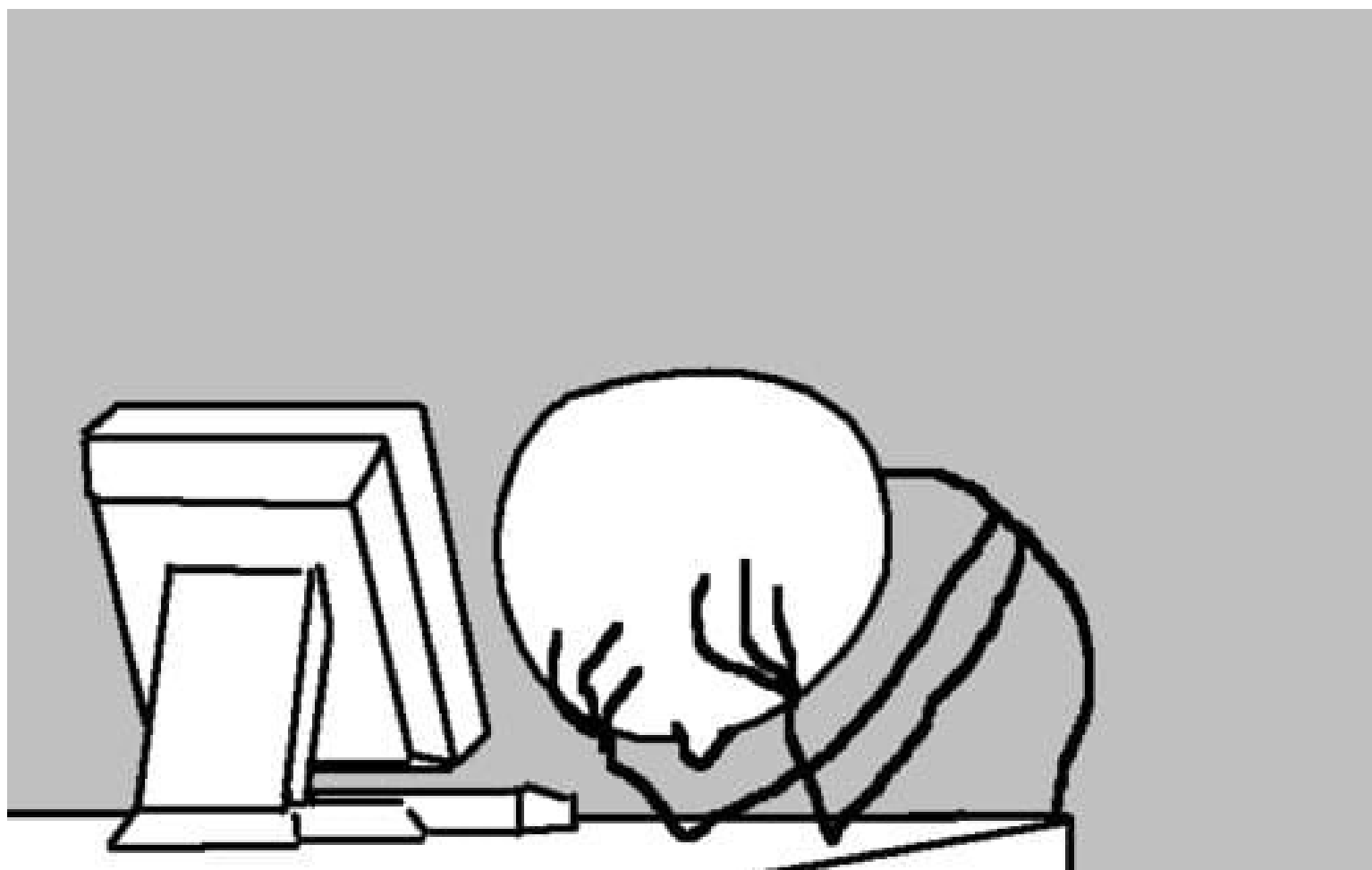
Recap: Can a process overwrite kernel memory?

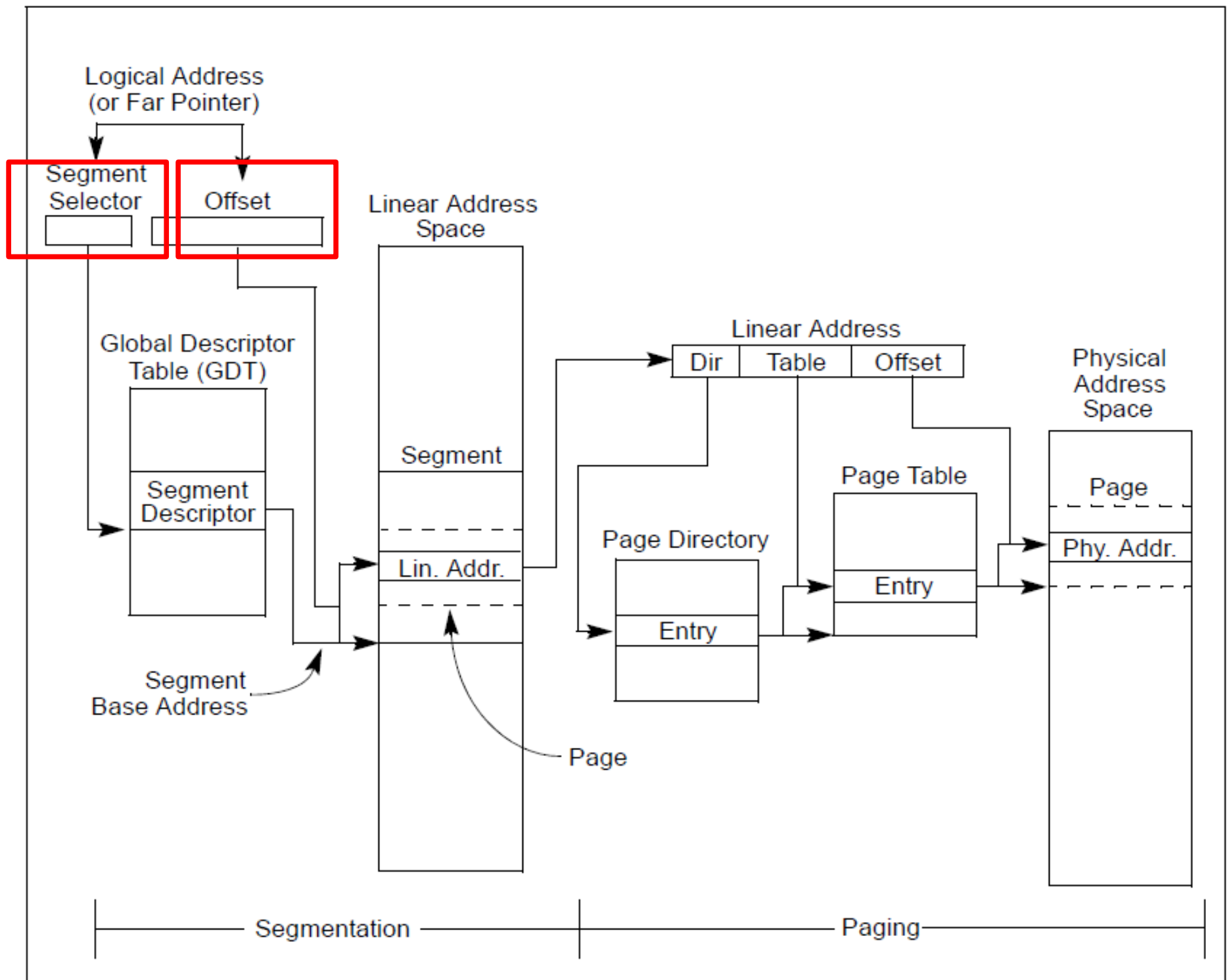


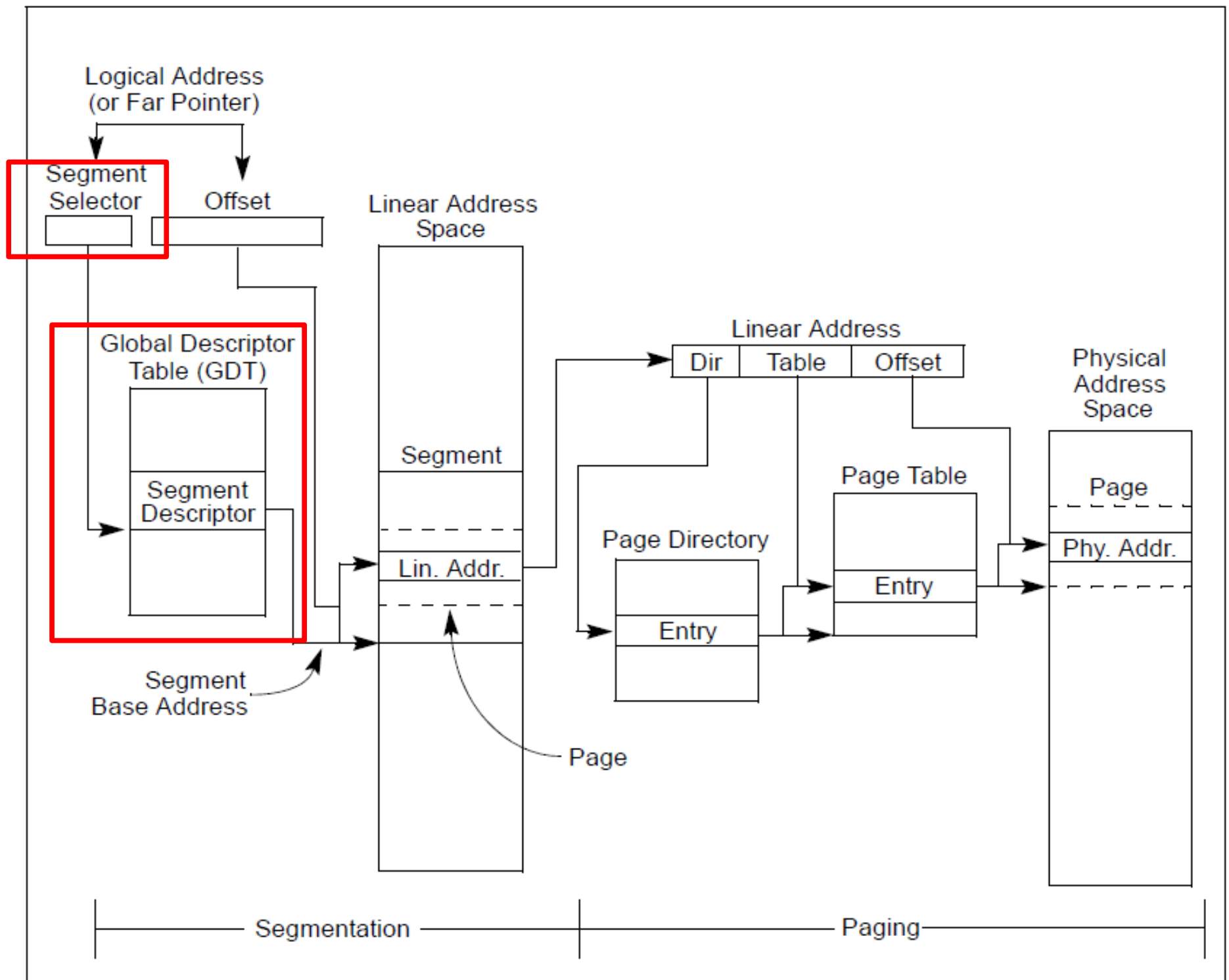
Privilege levels

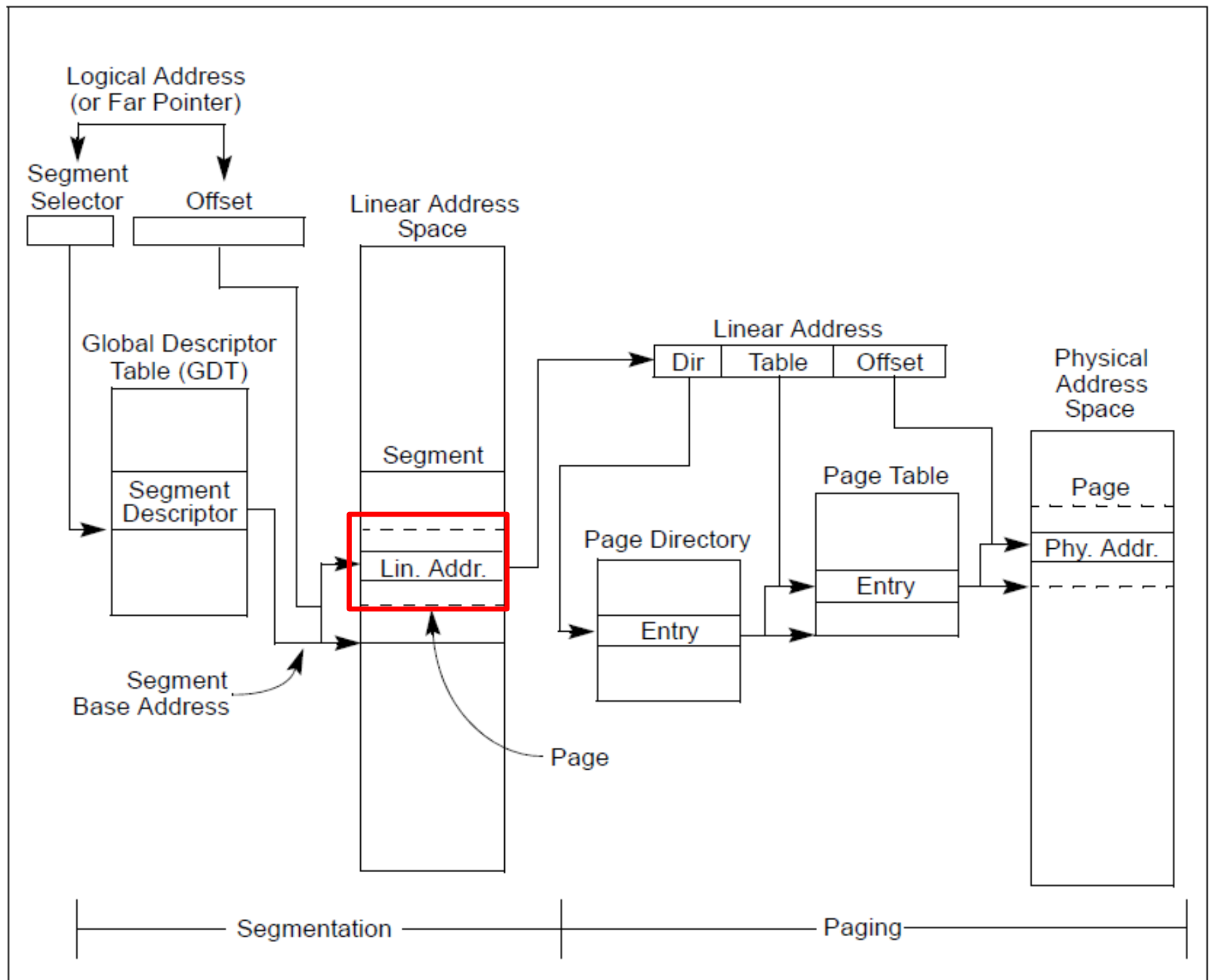
- Each segment has a privilege level
 - DPL (descriptor privilege level)
 - 4 privilege levels ranging 0-3





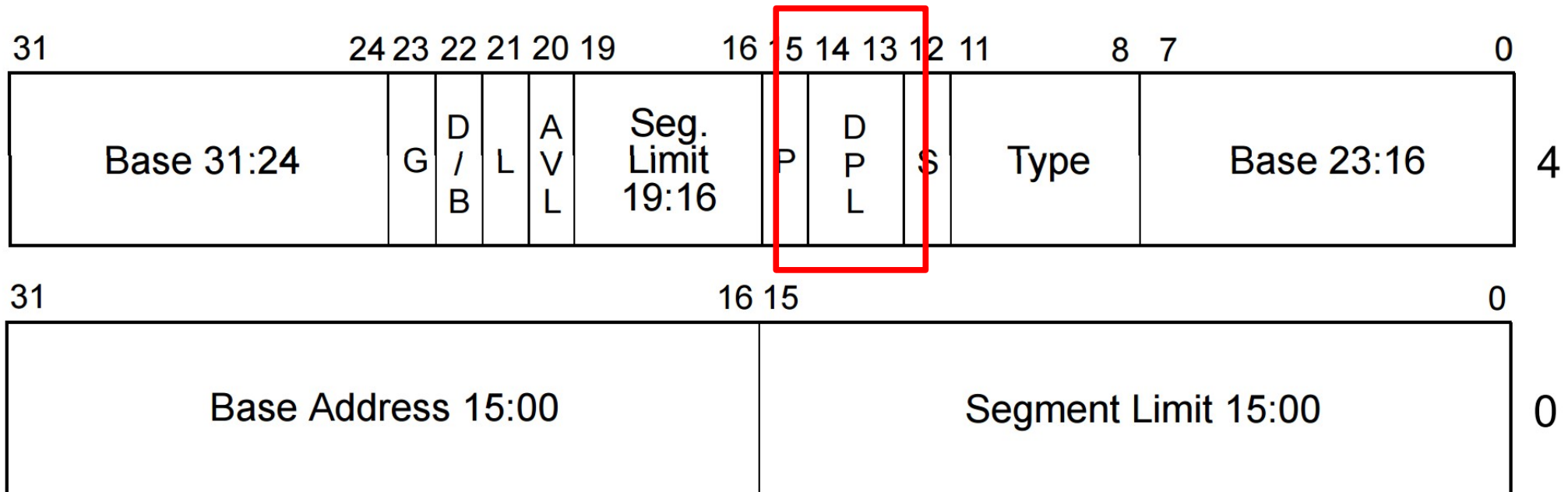






Privilege levels

- Each segment has a privilege level
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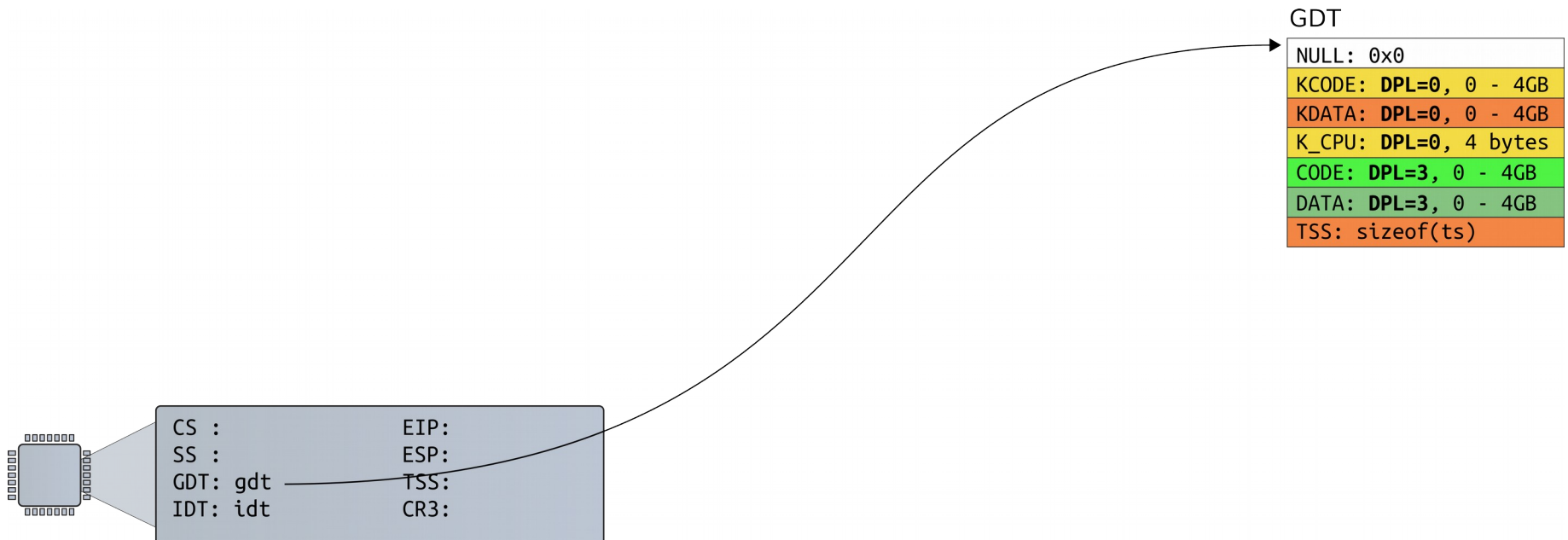
Privilege levels

- Currently running code also has a privilege level
 - “Current privilege level” (CPL): 0-3
 - It is saved in the %cs register
 - It was loaded there when the descriptor for the currently running code was loaded into %cs

Privilege level transitions

- CPL can access only less privileged segments
 - E.g., 0 can access 0, 1, 2, 3
 - 1 can access 1, 2, 3
 - 3 can access 3
- Some instructions are “privileged”
 - Can only be invoked at CPL = 0
 - Examples:
 - Load GDT
 - MOV <control register>
 - E.g. reload a page table by changing CR3

Xv6 example: started boot (no CPL yet)



Xv6 example: prepare to load GDT entry #1

`ljmp 1, $start32`

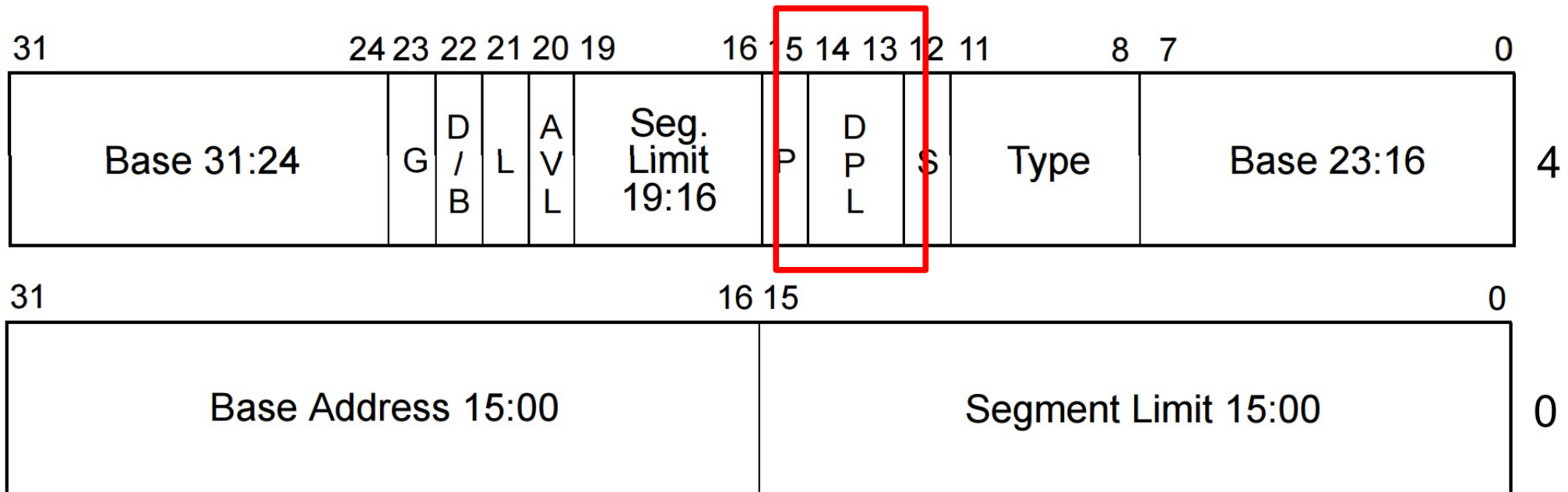


GDT

NULL: 0x0
KCODE: DPL=0, 0 - 4GB
KDATA: DPL=0, 0 - 4GB
K_CPU: DPL=0, 4 bytes
CODE: DPL=3, 0 - 4GB
DATA: DPL=3, 0 - 4GB
TSS: sizeof(ts)

Privilege levels

- Each segment has a privilege level
 - DPL (descriptor privilege level)
 - 4 privilege levels ranging 0-3



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
```

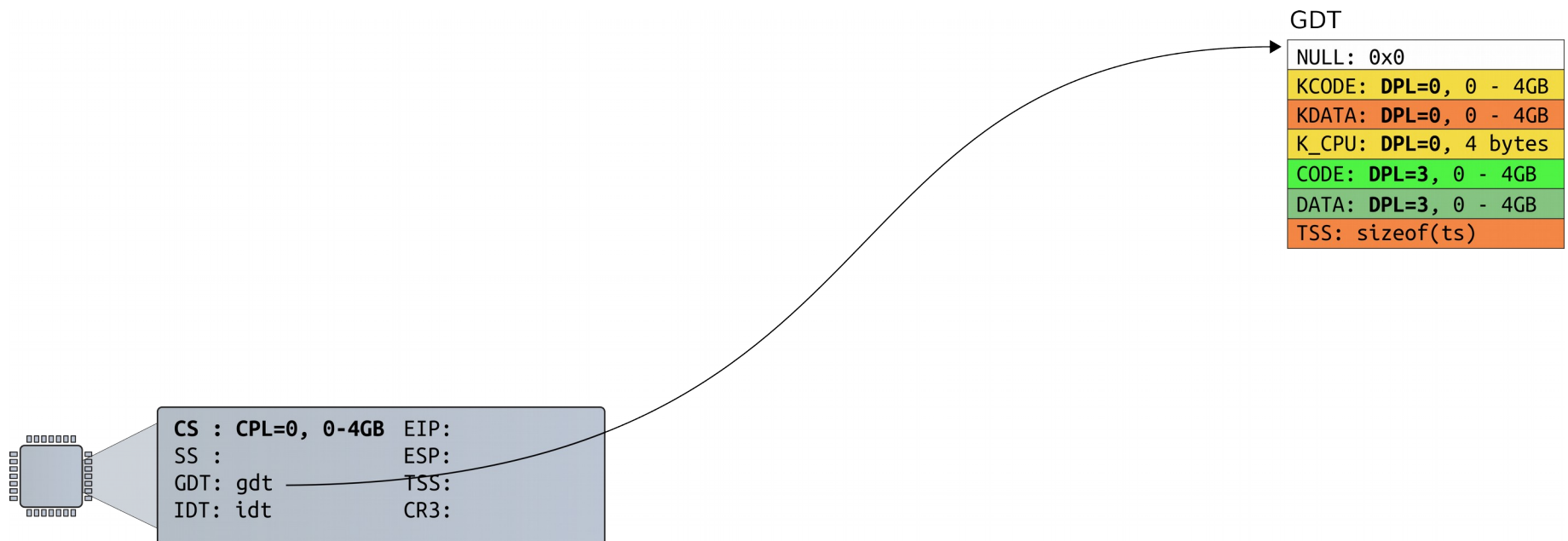
```
9186
```

```
9187 gdtdesc:
```

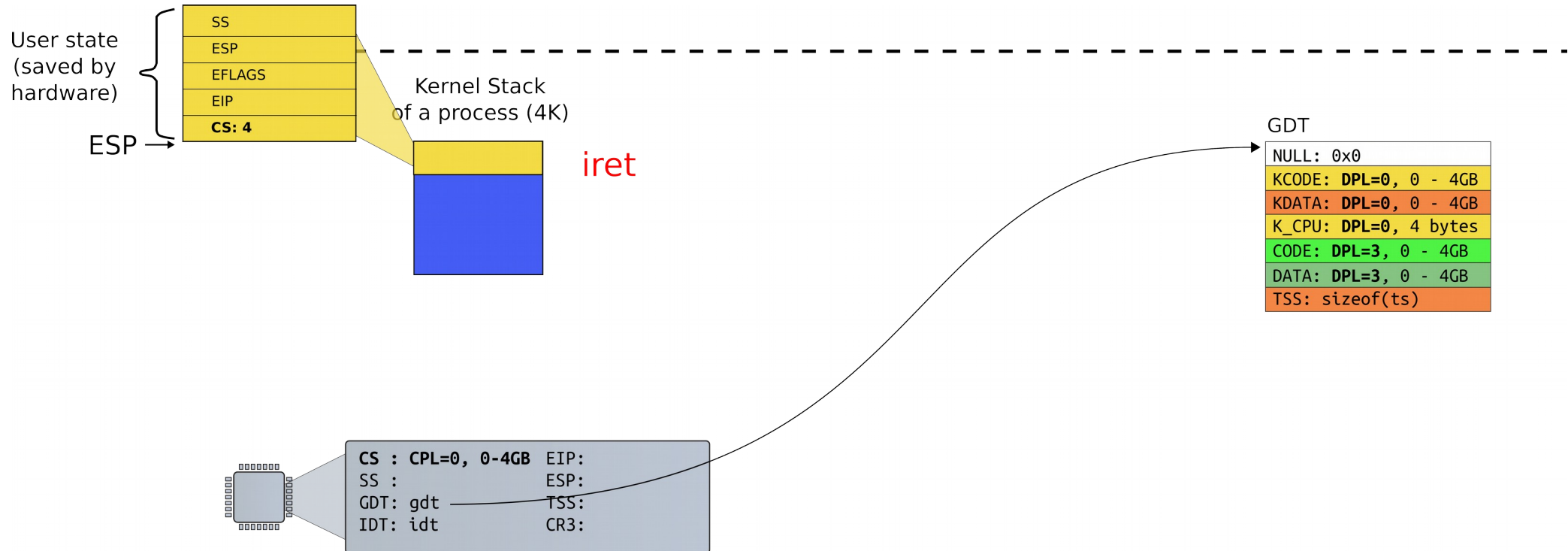
```
9188     .word (gdtdesc - gdt - 1) # sizeof(gdt) - 1
```

```
9189     .long gdt
```

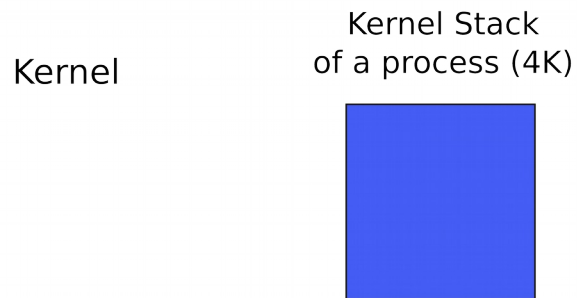
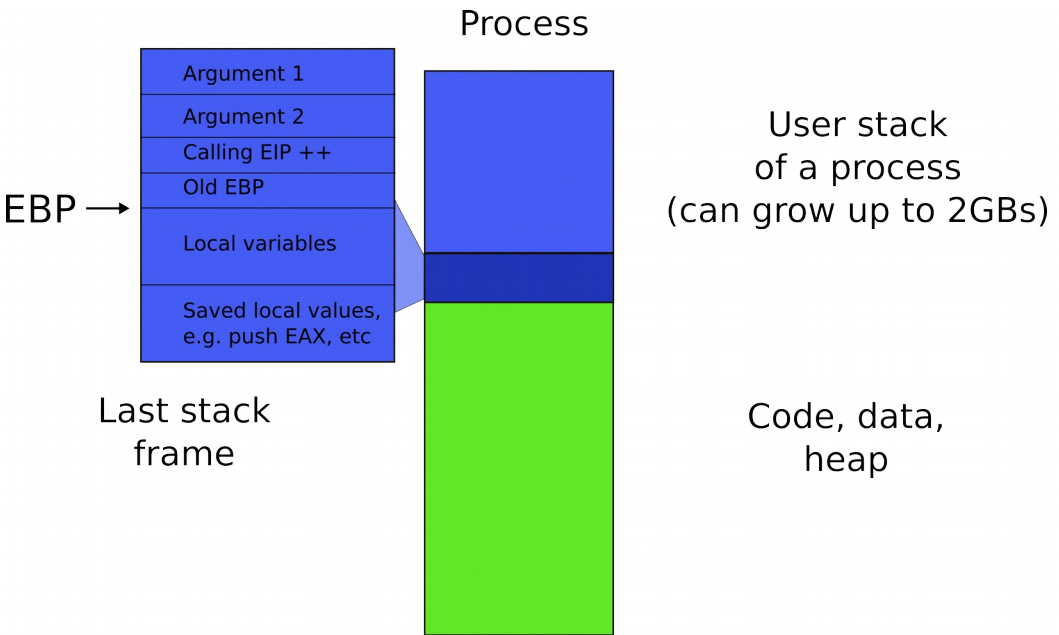
Now CPL=0. We run in the kernel



iret: return to user, load GDT #4

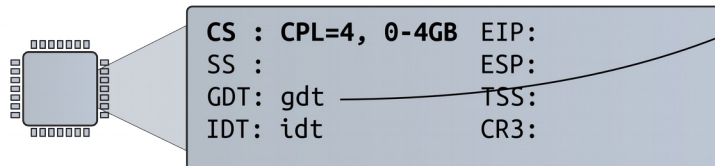


Run in user, CPL=3



GDT

NULL:	0x0
KCODE:	DPL=0, 0 - 4GB
KDATA:	DPL=0, 0 - 4GB
K_CPU:	DPL=0, 4 bytes
CODE:	DPL=3, 0 - 4GB
DATA:	DPL=3, 0 - 4GB
TSS:	sizeof(ts)



Real world

- Only two privilege levels are used in modern OSes:
 - OS kernel runs at 0
 - User code runs at 3
- This is called “flat” segment model
 - Segments for both 0 and 3 cover entire address space

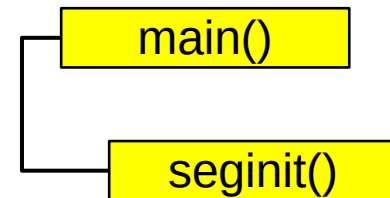
How GDT is initialized in xv6?

```
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());
1325     picinit(); // another interrupt controller
1326     ioapicinit(); // another interrupt controller
1327     consoleinit(); // console hardware
1328     uartinit(); // serial port
1329     pinit(); // process table
1330     tvinit(); // trap vectors
1331     binit(); // buffer cache
1332     fileinit(); // file table
1333     ideinit(); // disk
1334     if(!ismp)
1335         timerinit(); // uniprocessor timer
1336     startothers(); // start other processors
1337     kinit2(P2V(4*1024*1024), P2V(PHYSTOP)); // must come after startothers()
1338     userinit(); // first user process
1339     mpmain(); // finish this processor's setup
1340 }
```

main()

Initialize GDT

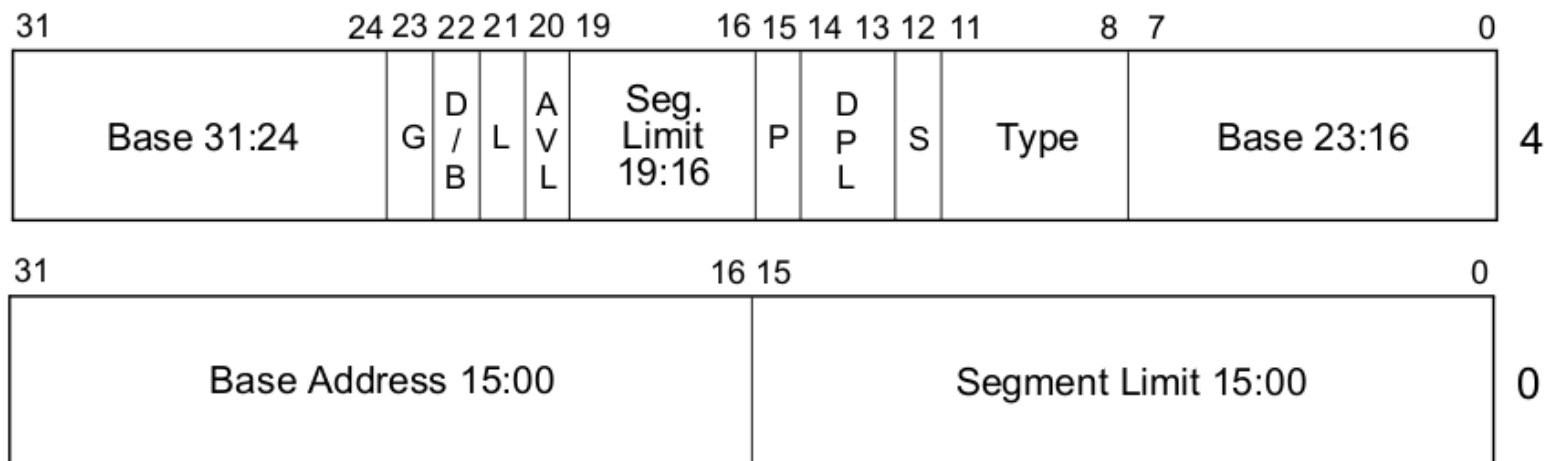
```
1712 // Set up CPU's kernel segment descriptors.
1713 // Run once on entry on each CPU.
1714 void
1715 seginit(void)
1716 {
1717     struct cpu *c;
1718
1719     // Map "logical" addresses to virtual addresses using identity map.
1720     // Cannot share a CODE descriptor for both kernel and user
1721     // because it would have to have DPL_USR, but the CPU forbids
1722     // an interrupt from CPL=0 to DPL=3.
1723     c = &cpus[cpuid()];
1724     c->gdt[SEG_KCODE] = SEG(STA_X|STA_R, 0, 0xffffffff, 0);
1725     c->gdt[SEG_KDATA] = SEG(STA_W, 0, 0xffffffff, 0);
1726     c->gdt[SEG_UCODE] = SEG(STA_X|STA_R, 0, 0xffffffff, DPL_USER);
1727     c->gdt[SEG_UDATA] = SEG(STA_W, 0, 0xffffffff, DPL_USER);
1728     lgdt(c->gdt, sizeof(c->gdt));
1729 }
```



Struct CPU

```
2300 // Per-CPU state
2301 struct cpu {
2302     uchar apicid;                // Local APIC ID
2303     struct context *scheduler;   // swtch() here to enter scheduler
2304     struct taskstate ts;         // Used by x86 to find stack for interrupt
2305     struct segdesc gdt[NSEGS];   // x86 global descriptor table
2306     volatile uint started;       // Has the CPU started?
2307     int ncli;                    // Depth of pushcli nesting.
2308     int intena;                  // Were interrupts enabled before pushcli?
2309     struct proc *proc;           // The process running on this cpu or null
2310 };
2311
2312 extern struct cpu cpus[NCPU];
```

Segment descriptor



- L — 64-bit code segment (IA-32e mode only)
- AVL — Available for use by system software
- BASE — Segment base address
- D/B — Default operation size (0 = 16-bit segment; 1 = 32-bit segment)
- DPL — Descriptor privilege level
- G — Granularity
- LIMIT — Segment Limit
- P — Segment present
- S — Descriptor type (0 = system; 1 = code or data)
- TYPE — Segment type

Segment Descriptor

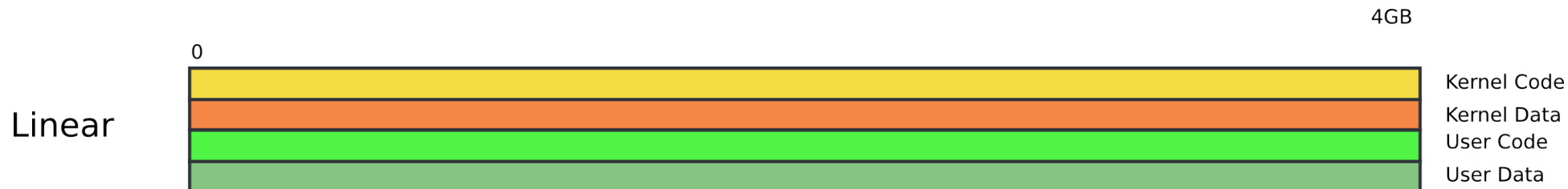
```
0724 // Segment Descriptor
0725 struct segdesc {
0726     uint lim_15_0 : 16; // Low bits of segment limit
0727     uint base_15_0 : 16; // Low bits of segment base address
0728     uint base_23_16 : 8; // Middle bits of segment base address
0729     uint type : 4;      // Segment type (see STS_ constants)
0730     uint s : 1;        // 0 = system, 1 = application
0731     uint dpl : 2;      // Descriptor Privilege Level
0732     uint p : 1;        // Present
0733     uint lim_19_16 : 4; // High bits of segment limit
0734     uint avl : 1;      // Unused (available for software use)
0735     uint rsv1 : 1;     // Reserved
0736     uint db : 1;       // 0 = 16-bit segment, 1 = 32-bit segment
0737     uint g : 1;        // Granularity: limit scaled by 4K when set
0738     uint base_31_24 : 8; // High bits of segment base address
0739 };
```

Real world

- Only two privilege levels are used in modern OSes:
 - OS kernel runs at 0
 - User code runs at 3
- This is called “flat” segment model
 - Segments for both 0 and 3 cover entire address space
- **But then... how the kernel is protected?**

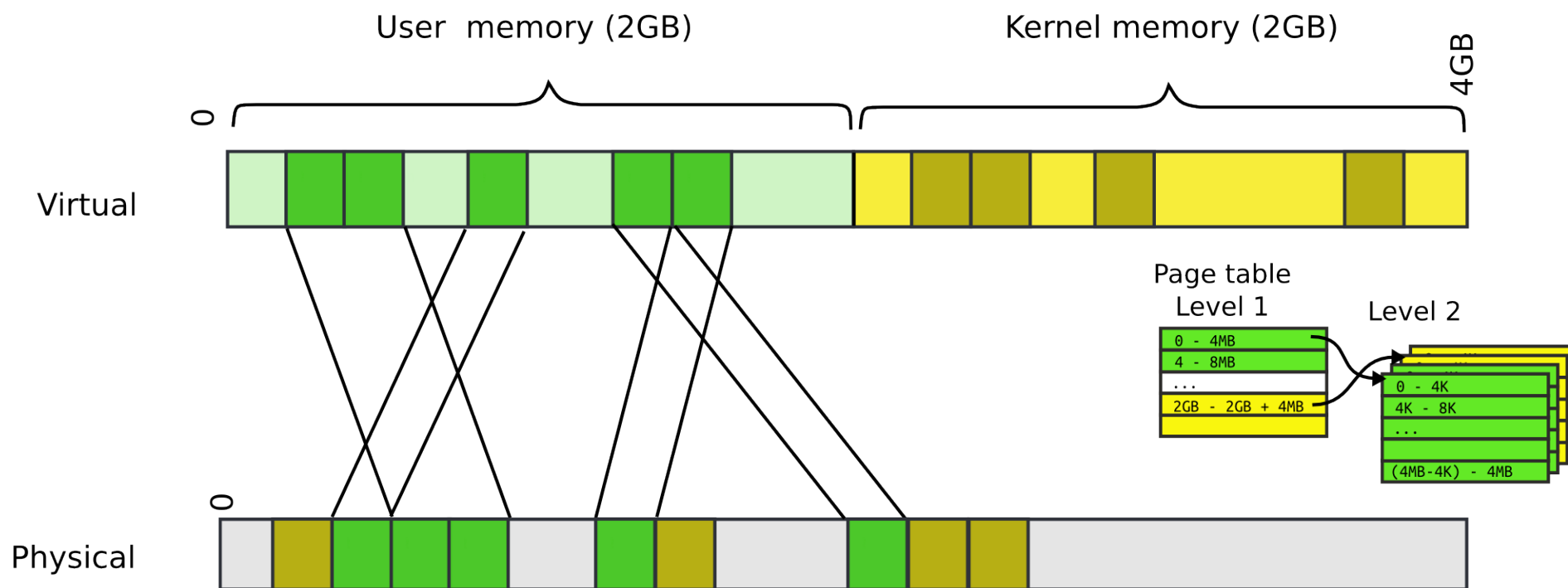
Real world

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- But then... how the kernel is protected?
 - **Page tables**



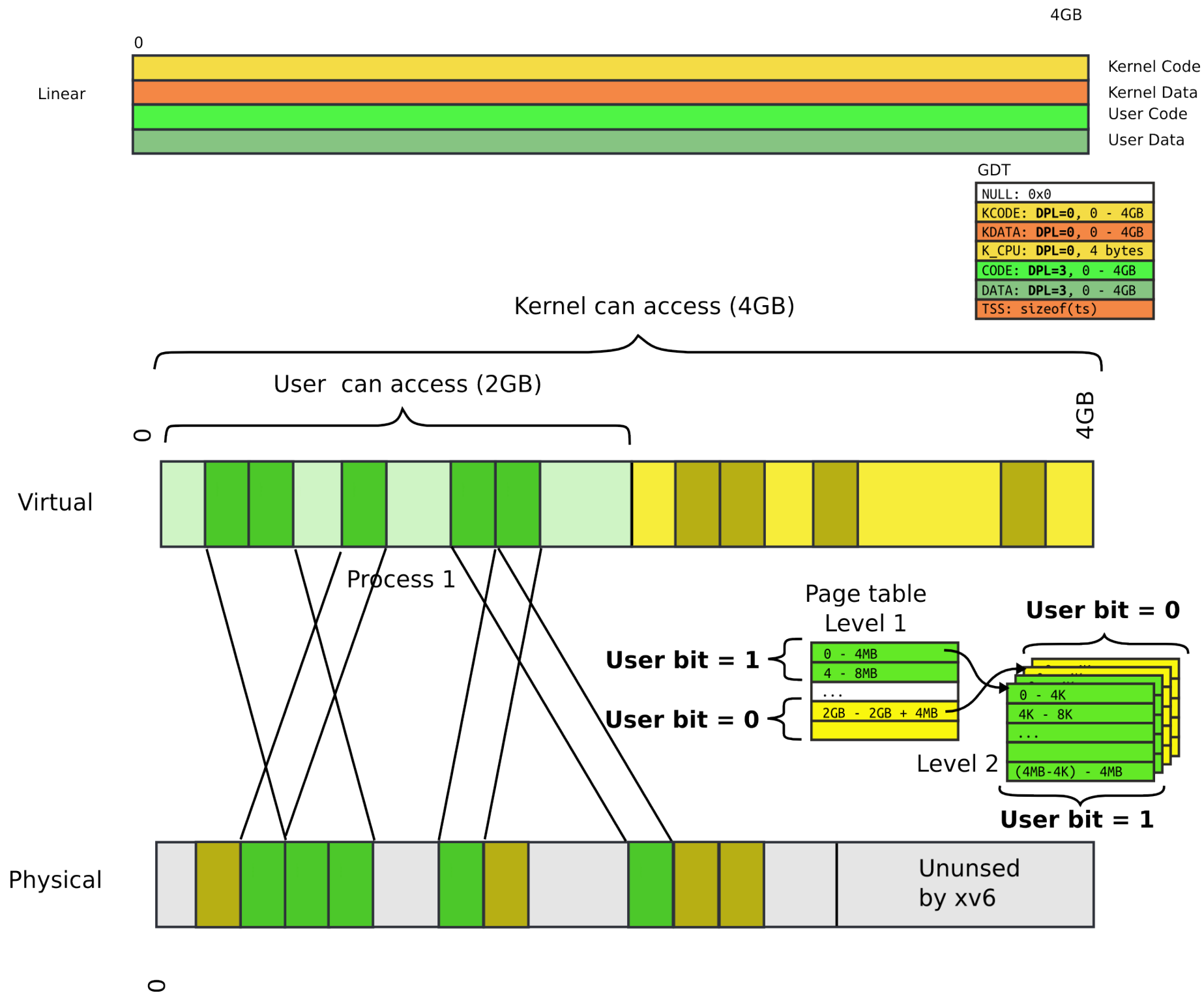
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K_CPU:	DPL=0, 4 bytes
CODE:	DPL=3, 0 - 4GB
DATA:	DPL=3, 0 - 4GB
TSS:	sizeof(ts)



Page table: user bit

- Each entry (both Level 1 and Level 2) has a bit
 - If set, code at privilege level 3 can access
 - If not, only levels 0-2 can access
- Note, only 2 levels, not 4 like with segments
- All kernel code is mapped with the user bit clear
 - This protects user-level code from accessing the kernel



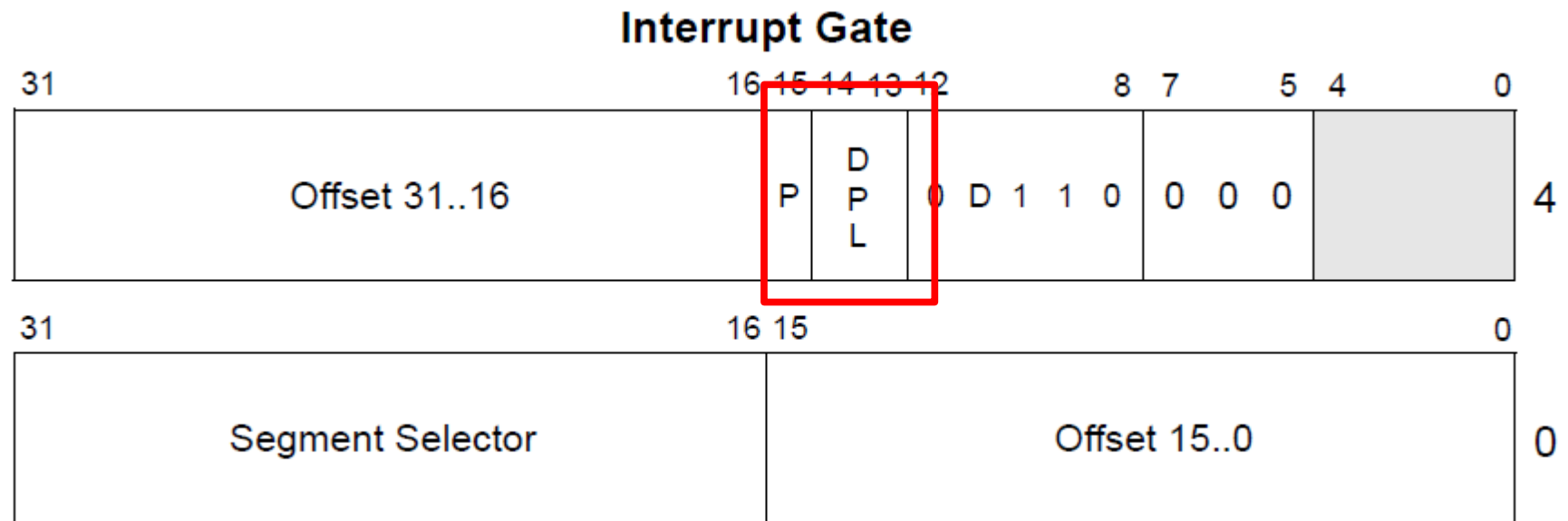
End of detour:
Back to handling interrupts

Processing of an interrupt when change of a
privilege level is required

Processing of interrupt (cross PL)

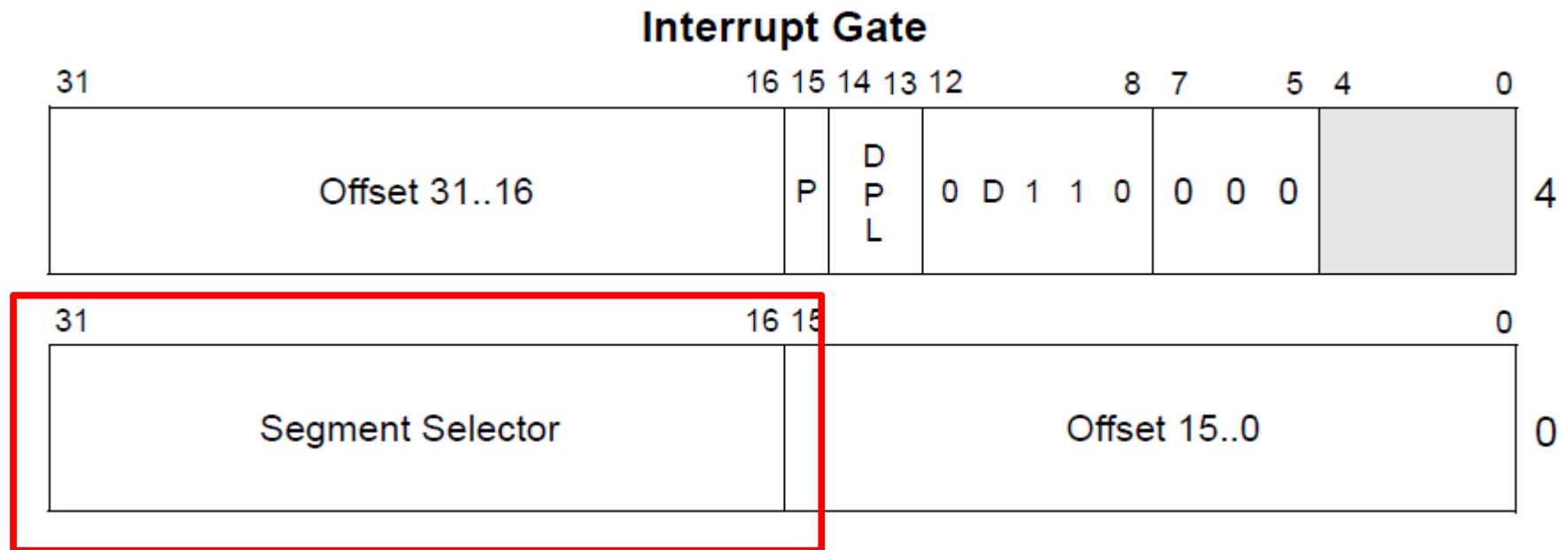
- Assume we're at CPL =3 (user)

Interrupt descriptor (an entry in the IDT)



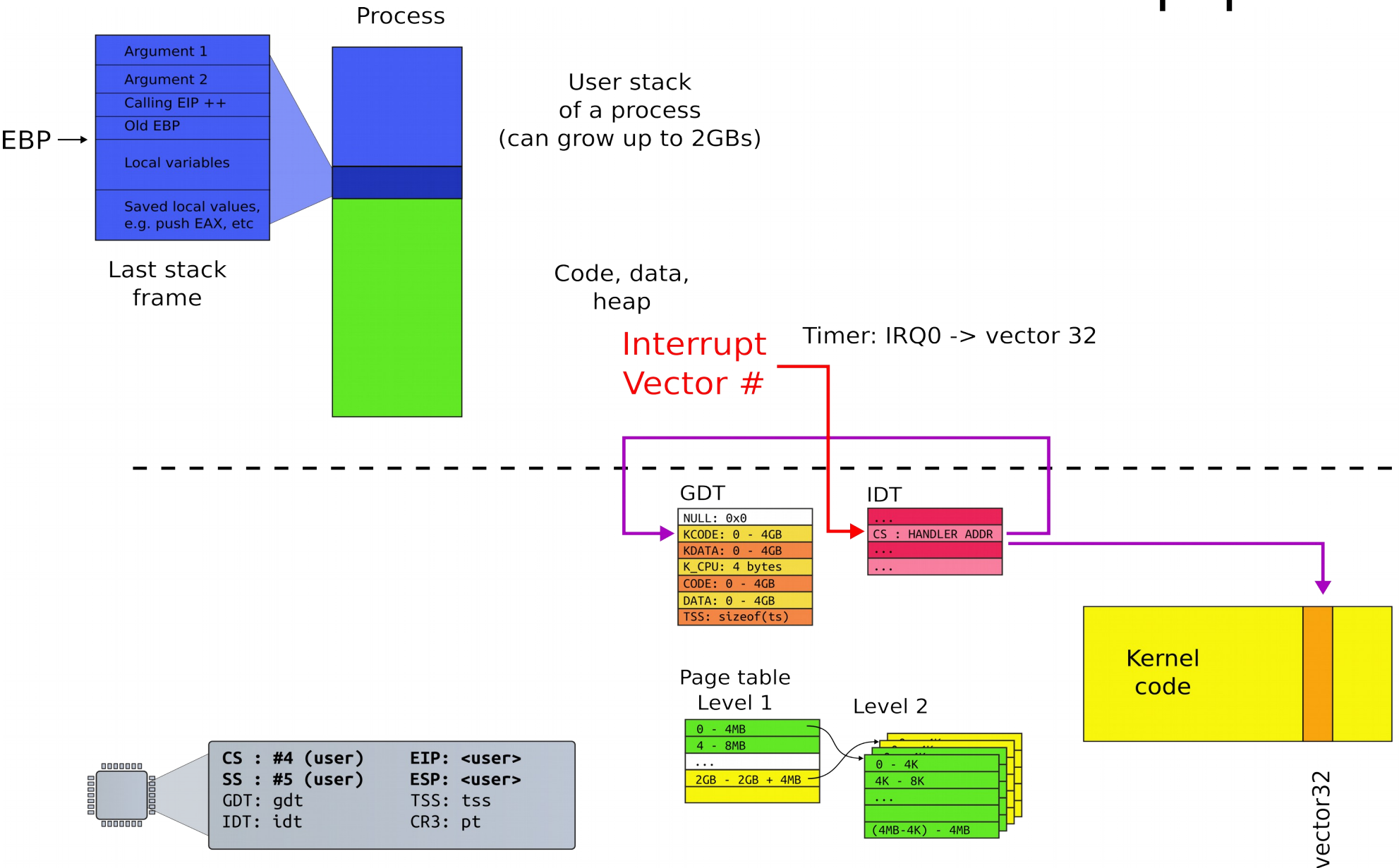
- Interrupt is allowed if...
 - current privilege level (CPL) is less or equal to descriptor privilege level (DPL)
- The kernel protects device interrupts from user

Interrupt descriptor (an entry in the IDT)



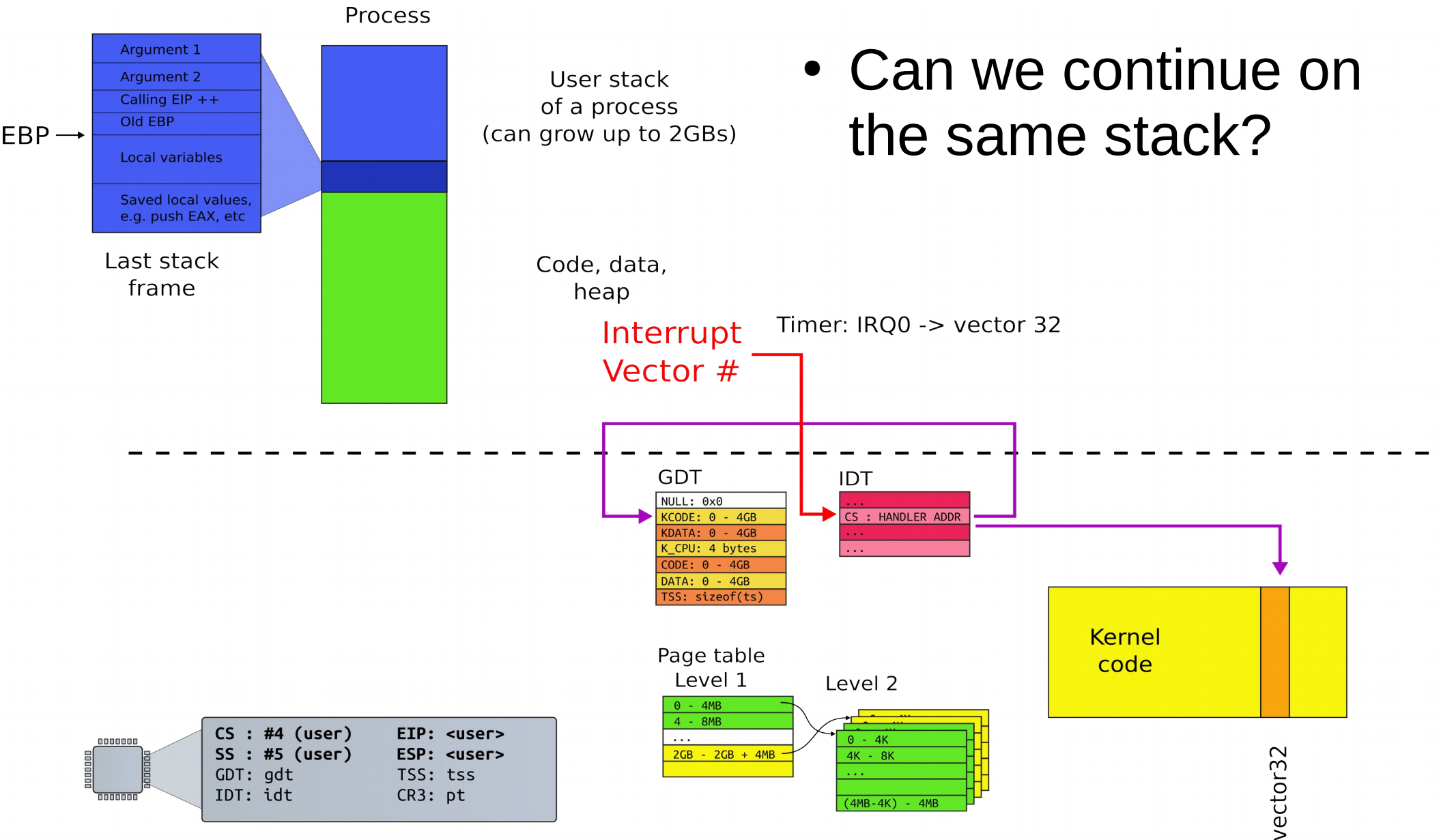
- Note that this new segment can be more privileged
 - E.g., CPL = 3, DPL = 3, new segment can be PL = 0
 - This is how user-code (PL=3) transitions into kernel (PL=0)

Interrupt path



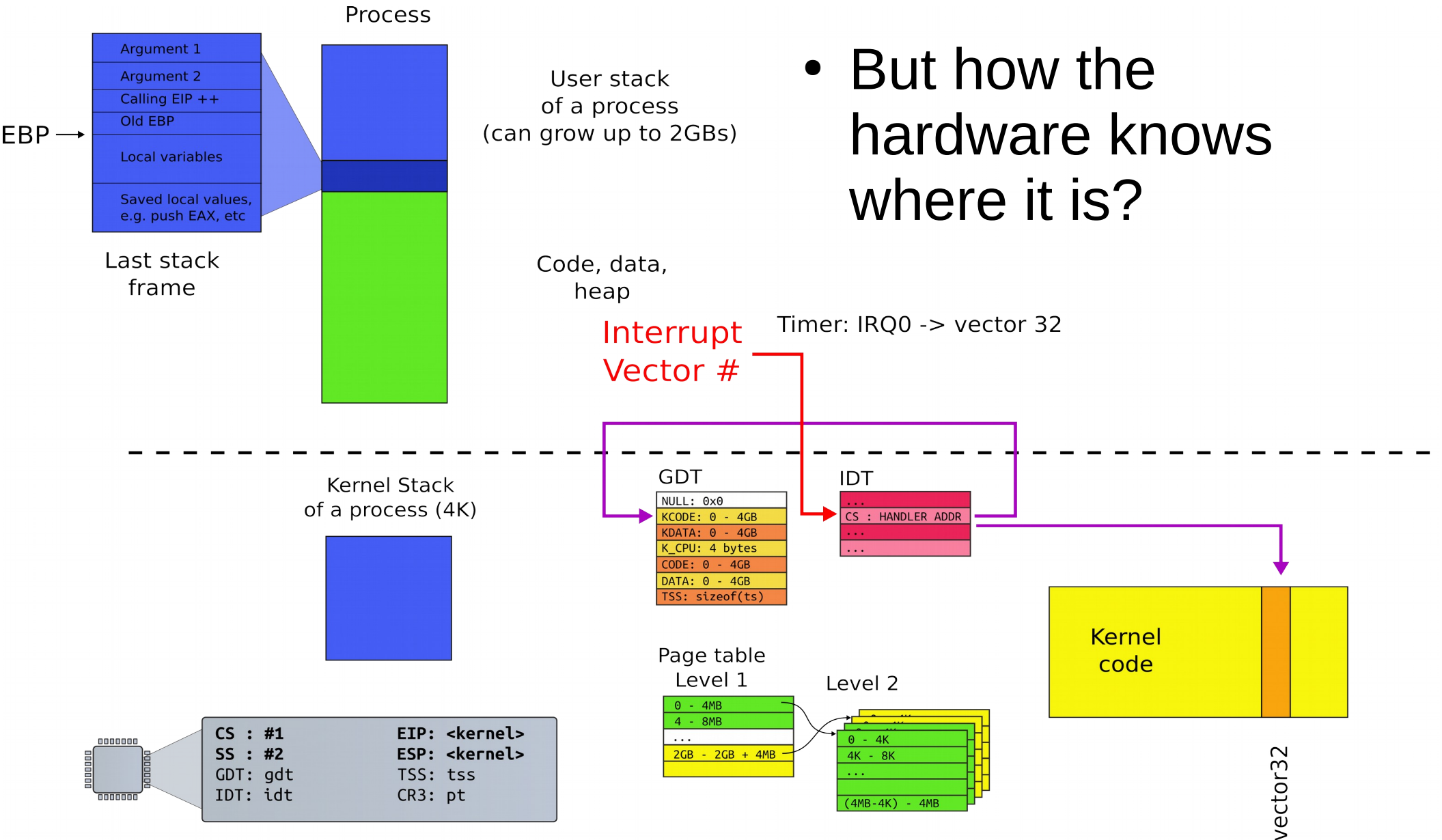
Stack

- Can we continue on the same stack?

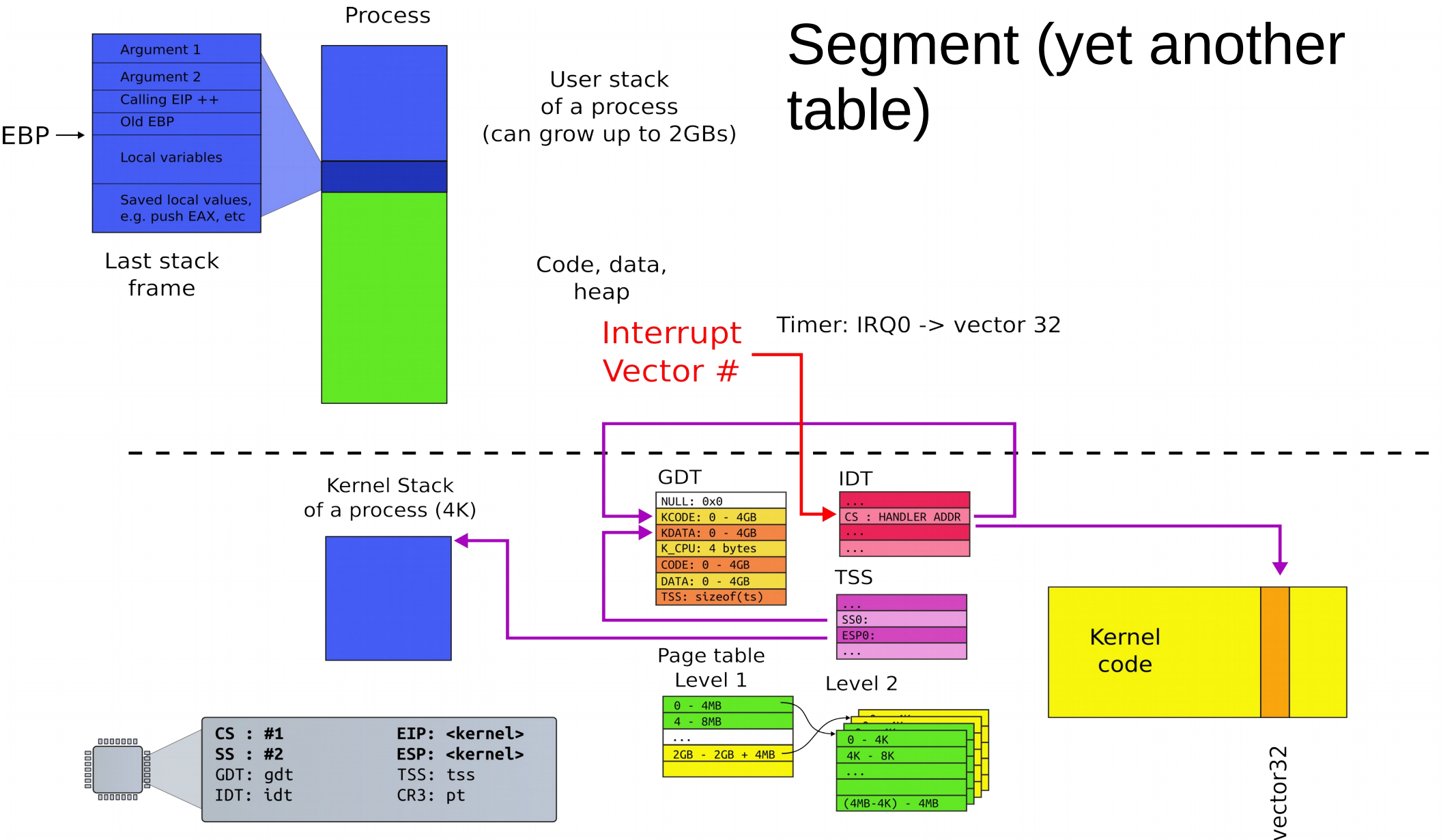


Stack

- But how the hardware knows where it is?



TSS: Task State Segment (yet another table)



Task State Segment

- Another magic control block
 - Pointed to by special task register (TR)
- Lots of fields for rarely-used features
- A feature we care about in a modern OS:
 - Location of kernel stack (fields SS/ESP)
 - Stack segment selector
 - Location of the stack in that segment

Processing of interrupt (cross PL)

1. Save ESP and SS in a CPU-internal register
- 2. Load SS and ESP from TSS**
3. Push user SS, user ESP, user EFLAGS, user CS, user EIP onto new stack (kernel stack)
4. Set CS and EIP from IDT descriptor's segment selector and offset
5. If the call is through an interrupt gate clear interrupts enabled EFLAGS bit
6. Begin execution of a handler

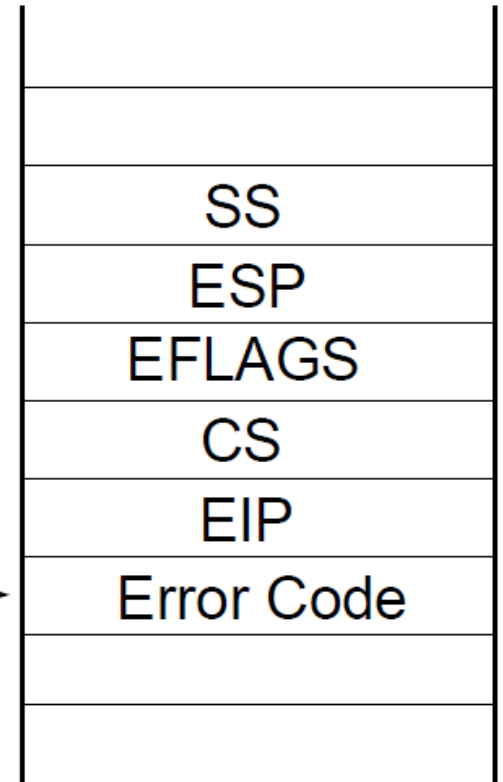
Stack Usage with Privilege-Level Change

Interrupted Procedure's
Stack



ESP Before
Transfer to Handler

Handler's Stack

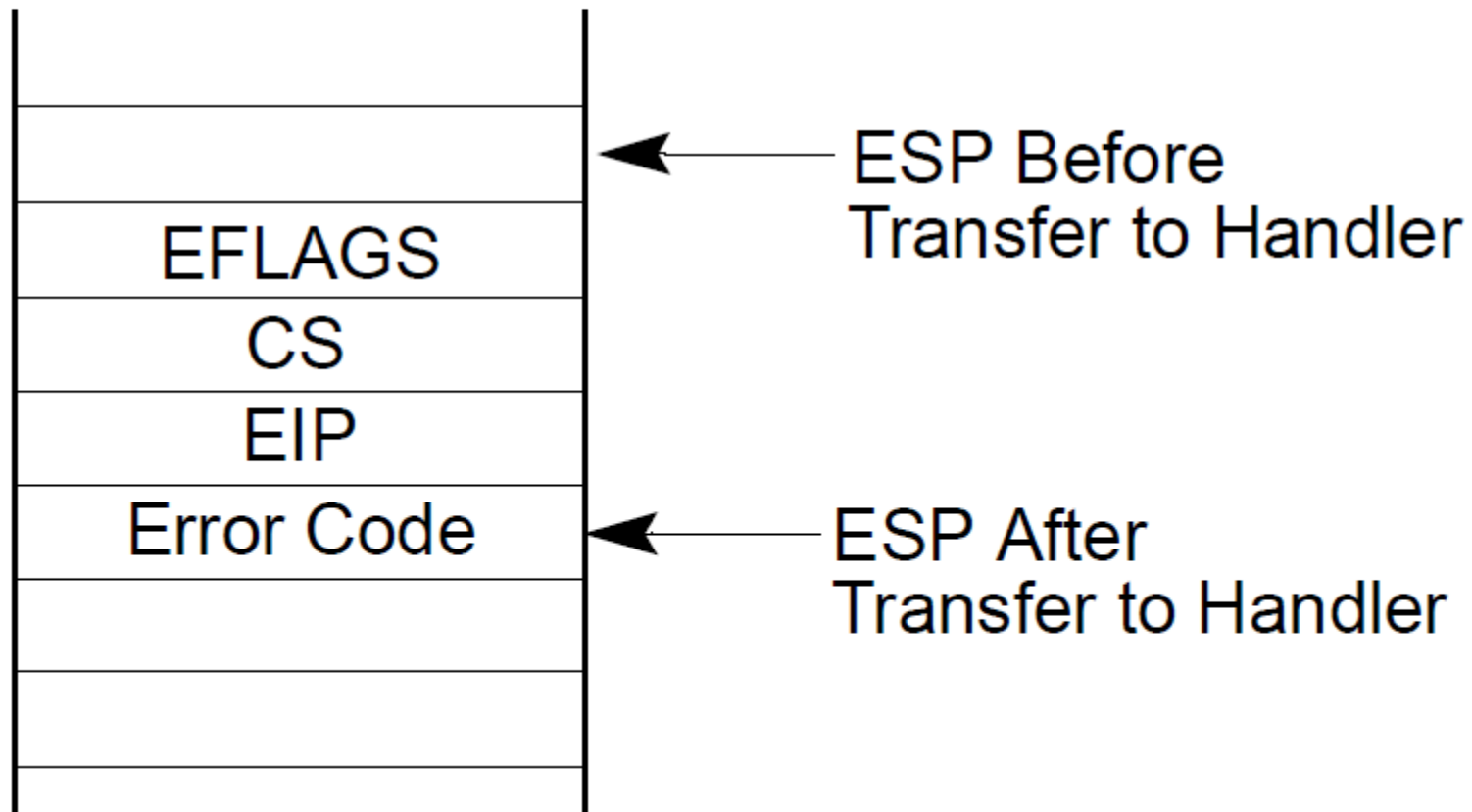


ESP After
Transfer to Handler

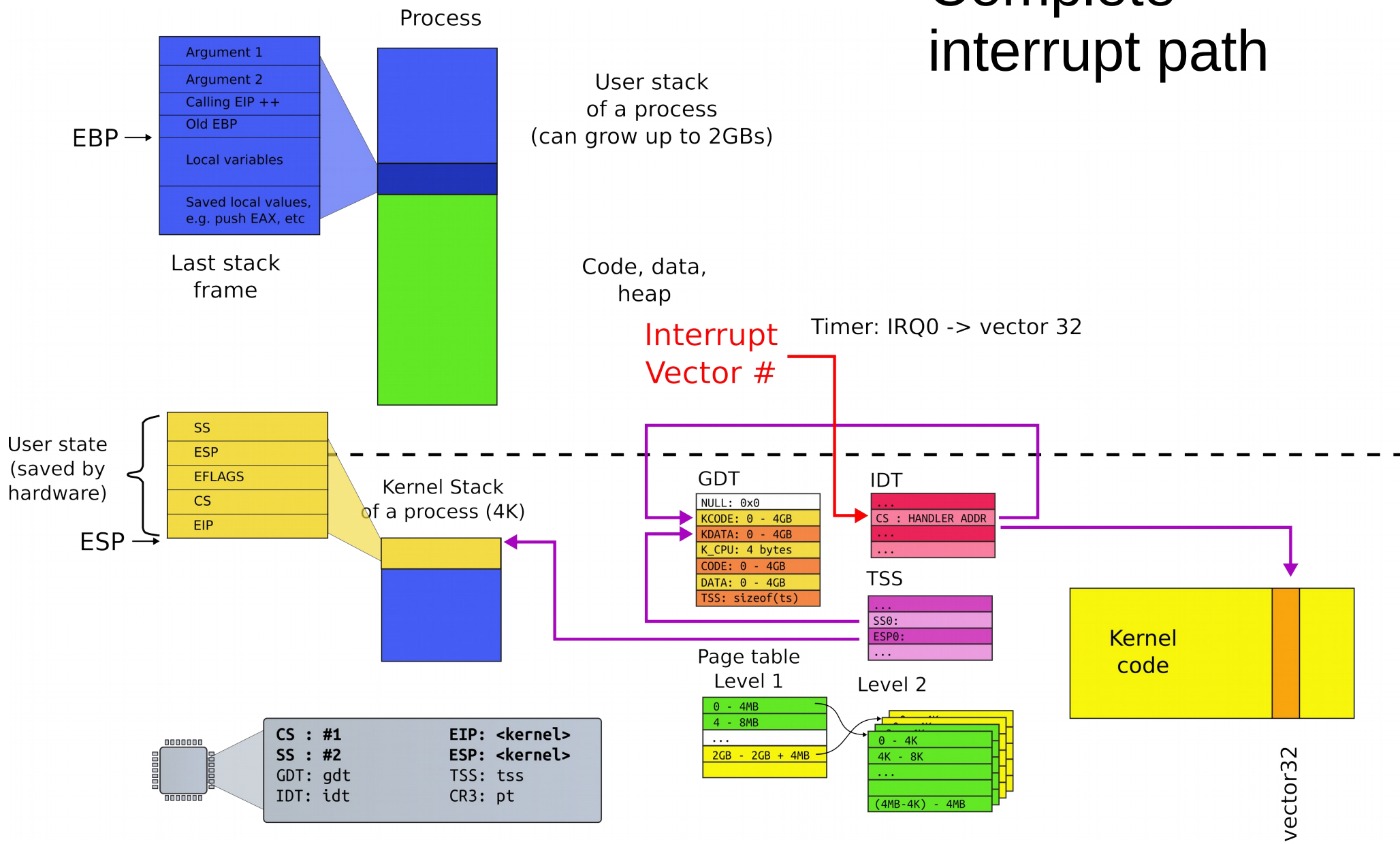


Stack Usage with No Privilege-Level Change

Interrupted Procedure's
and Handler's Stack

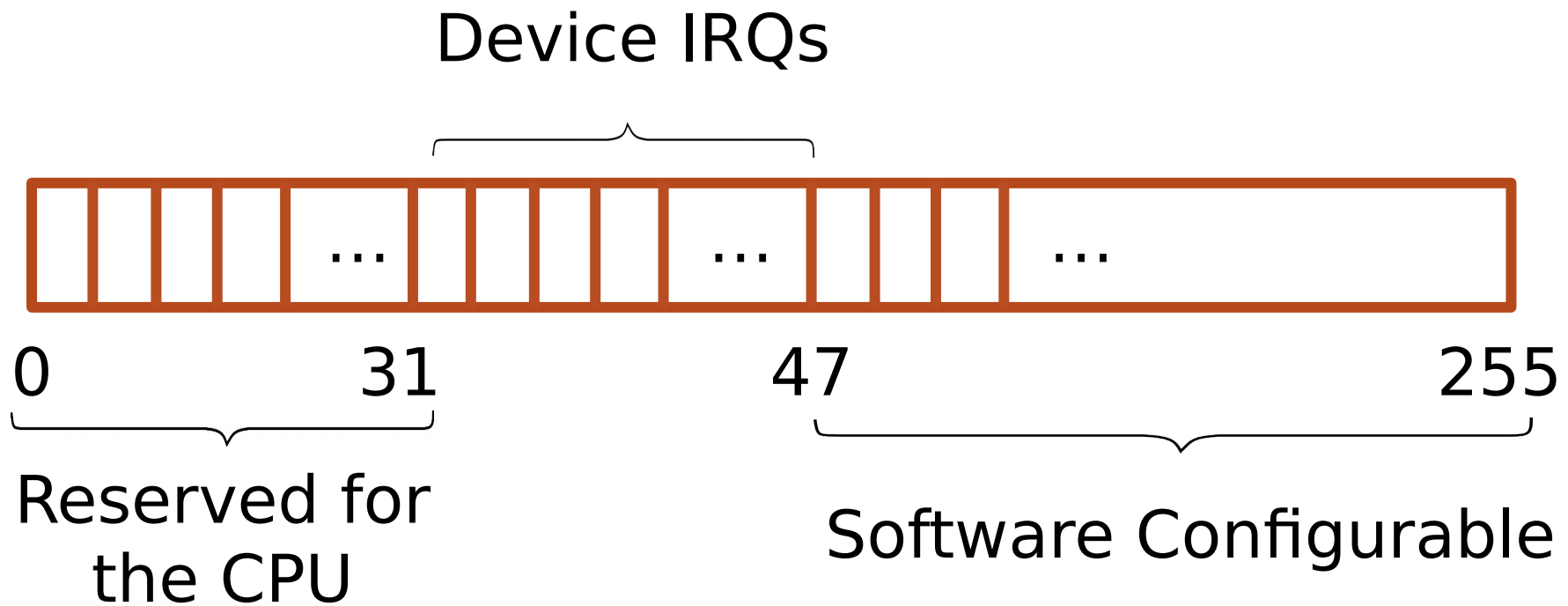


Complete interrupt path



Interrupt descriptor table (IDT)

x86 interrupt descriptor table



Vector No.	Mnemonic	Description	Source
0	#DE	Divide Error	DIV and IDIV instructions.
1	#DB	Debug	Any code or data reference.
2		NMI Interrupt	Non-maskable external interrupt.
3	#BP	Breakpoint	INT 3 instruction.
4	#OF	Overflow	INTO instruction.
5	#BR	BOUND Range Exceeded	BOUND instruction.
6	#UD	Invalid Opcode (UnDefined Opcode)	UD2 instruction or reserved opcode. ¹
7	#NM	Device Not Available (No Math Coprocessor)	Floating-point or WAIT/FWAIT instruction.
8	#DF	Double Fault	Any instruction that can generate an exception, an NMI, or an INTR.
9	#MF	CoProcessor Segment Overrun (reserved)	Floating-point instruction. ²
10	#TS	Invalid TSS	Task switch or TSS access.
11	#NP	Segment Not Present	Loading segment registers or accessing system segments.
12	#SS	Stack Segment Fault	Stack operations and SS register loads.
13	#GP	General Protection	Any memory reference and other protection checks.
14	#PF	Page Fault	Any memory reference.
15		Reserved	
16	#MF	Floating-Point Error (Math Fault)	Floating-point or WAIT/FWAIT instruction.
17	#AC	Alignment Check	Any data reference in memory. ³
18	#MC	Machine Check	Error codes (if any) and source are model dependent. ⁴
19	#XM	SIMD Floating-Point Exception	SIMD Floating-Point Instruction ⁵
20-31		Reserved	
32-255		Maskable Interrupts	External interrupt from INTR pin or INT <i>n</i> instruction.

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4	#OF	Overflow	INTO instruction.
5	#BR	BOUND Range Exceeded	BOUND instruction.
6	#UD	Invalid Opcode (UnDefined Opcode)	UD2 instruction or reserved opcode. ¹
7	#NM	Device Not Available (No Math Coprocessor)	Floating-point or WAIT/FWAIT instruction.
8	#DF	Double Fault	Any instruction that can generate an exception, an NMI, or an INTR.
9	#MF	CoProcessor Segment Overrun (reserved)	Floating-point instruction. ²
10	#TS	Invalid TSS	Task switch or TSS access.
11	#NP	Segment Not Present	Loading segment registers or accessing system segments.
12	#SS	Stack Segment Fault	Stack operations and SS register loads.
13	#GP	General Protection	Any memory reference and other protection checks.
14	#PF	Page Fault	Any memory reference.
15		Reserved	
16	#MF	Floating-Point Error (Math Fault)	Floating-point or WAIT/FWAIT instruction.
17	#AC	Alignment Check	Any data reference in memory. ³
18	#MC	Machine Check	Error codes (if any) and source are model dependent. ⁴
19	#XM	SIMD Floating-Point Exception	SIMD Floating-Point Instruction ⁵
20-31		Reserved	
32-255		Maskable Interrupts	External interrupt from INTR pin or INT <i>n</i> instruction.

Interrupts

- Each type of interrupt is assigned an index from 0—255.
 - 0—31 are for processor interrupts fixed by Intel
 - E.g., 14 is always for page faults
- 32—255 are software configured
 - 32—47 are often used for device interrupts (IRQs)
 - Most device IRQ lines can be configured
 - Look up APICs for more info (Ch 4 of Bovet and Cesati)
 - **0x80 issues system call in Linux**
 - **Xv6 uses 0x40 (64) for the system call**

Disabling interrupts

- Delivery of interrupts can be disabled with IF (interrupt flag) in EFLAGS register
- There is a couple of exceptions
 - Synchronous interrupts cannot be disabled
 - It doesn't make sense to disable a page fault
 - INT n – cannot be masked as it is synchronous
 - Non-maskable interrupts (see next slide)
 - Interrupt #2 in the IDT

Vector No.	Mnemonic	Description	Source
0	#DE	Divide Error	DIV and IDIV instructions.
1	#DB	Debug	Any code or data reference
2		NMI Interrupt	Non-maskable external interrupt.
3	#BP	Breakpoint	INT 3 instruction.
4	#OF	Overflow	INTO instruction.
5	#BR	BOUND Range Exceeded	BOUND instruction.
6	#UD	Invalid Opcode (UnDefined Opcode)	UD2 instruction or reserved opcode. ¹
7	#NM	Device Not Available (No Math Coprocessor)	Floating-point or WAIT/FWAIT instruction.
8	#DF	Double Fault	Any instruction that can generate an exception, an NMI, or an INTR.
9	#MF	CoProcessor Segment Overrun (reserved)	Floating-point instruction. ²
10	#TS	Invalid TSS	Task switch or TSS access.
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12	#SS	Stack Segment Fault	Stack operations and SS register loads.
13	#GP	General Protection	Any memory reference and other protection checks.
14	#PF	Page Fault	Any memory reference.
15		Reserved	
16	#MF	Floating-Point Error (Math Fault)	Floating-point or WAIT/FWAIT instruction.
17	#AC	Alignment Check	Any data reference in memory. ³
18	#MC	Machine Check	Error codes (if any) and source are model dependent. ⁴
19	#XM	SIMD Floating-Point Exception	SIMD Floating-Point Instruction ⁵
20-31		Reserved	
32-255		Maskable Interrupts	External interrupt from INTR pin or INT <i>n</i> instruction.

Nonmaskable interrupts (NMI)

- Delivered even if IF is clear, e.g. interrupts disabled
 - CPU blocks subsequent NMI interrupts until IRET
- Sources
 - External hardware asserts the NMI pin
 - Processor receives a message on the system bus, or the APIC serial bus with NMI delivery mode
- Delivered via vector #2

Xv6 source

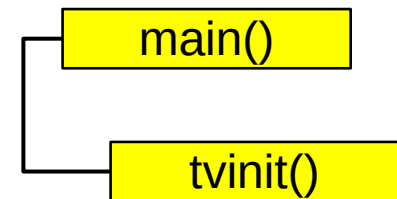
```
1317 main(void)
1318 {
1319     kinit1(end, P2V(4*1024*1024)); // phys page allocator
1320     kvmalloc(); // kernel page table
1321     mpinit(); // detect other processors
1322     lapicinit(); // interrupt controller
1323     seginit(); // segment descriptors
1324     cprintf("\ncpu%d: starting xv6\n\n", cpunum());
1325     picinit(); // another interrupt controller
1326     ioapicinit(); // another interrupt controller
1327     consoleinit(); // console hardware
1328     uartinit(); // serial port
1329     pinit(); // process table
1330     tvinit(); // trap vectors
1331     binit(); // buffer cache
1332     fileinit(); // file table
1333     ideinit(); // disk
1334     if(!ismp)
1335         timerinit(); // uniprocessor timer
1336     startothers(); // start other processors
1337     kinit2(P2V(4*1024*1024), P2V(PHYSTOP)); // must come after startothers()
1338     userinit(); // first user process
1339     mpmain(); // finish this processor's setup
1340 }
```

main()

Initialize IDT

```
3316 void
3317 tvinit(void)
3318 {
3319     int i;
3320
3321     for(i = 0; i < 256; i++)
3322         SETGATE(idt[i], 0, SEG_KCODE<<3, vectors[i], 0);
3323     SETGATE(idt[T_SYSCALL], 1, SEG_KCODE<<3,
              vectors[T_SYSCALL], DPL_USER);
3324
3325     initlock(&tickslock, "time");
3326 }
```

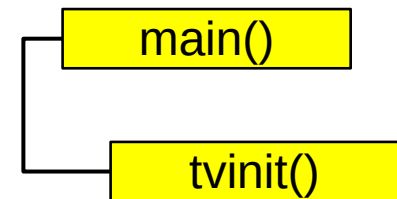
- tvinit() is called from main()



Initialize IDT

- System call interrupt vector (T_SYSCALL)

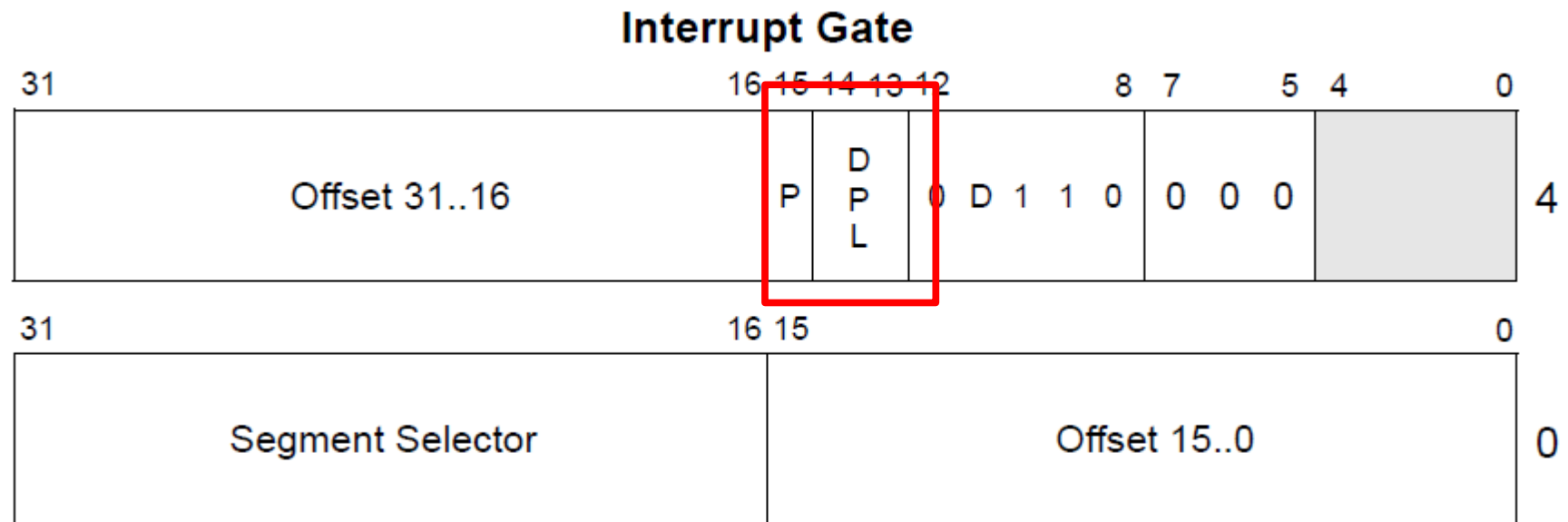
```
3316 void
3317 tvinit(void)
3318 {
3319     int i;
3320
3321     for(i = 0; i < 256; i++)
3322         SETGATE(idt[i], 0, SEG_KCODE<<3, vectors[i], 0);
3323     SETGATE(idt[T_SYSCALL], 1, SEG_KCODE<<3,
              vectors[T_SYSCALL], DPL_USER);
3324
3325     initlock(&tickslock, "time");
3326 }
```



Protection

- Generally user code cannot invoke int X
 - i.e., can't issue int 14 (a page fault)
 - OS configures the IDT in such a manner that invocation of all int X instructions besides 0x40 triggers a general protection fault exception
 - Interrupt vector 13

Remember this slide: interrupt descriptor (an entry in the IDT)

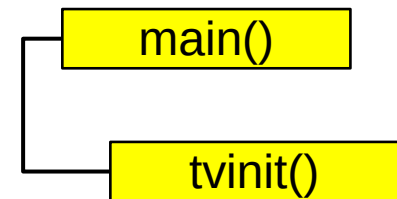


- Interrupt is allowed if...
 - current privilege level (CPL) is less or equal to descriptor privilege level (DPL)
- The kernel protects device interrupts from user

Initialize IDT

- A couple of important details

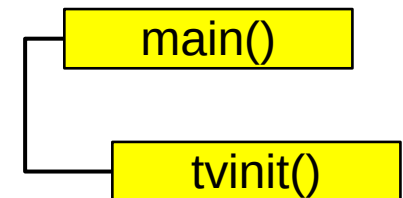
```
3316 void
3317 tvinit(void)
3318 {
3319     int i;
3320
3321     for(i = 0; i < 256; i++)
3322         SETGATE(idt[i], 0, SEG_KCODE<<3, vectors[i], 0);
3323     SETGATE(idt[T_SYSCALL], 1, SEG_KCODE<<3,
3324             vectors[T_SYSCALL], DPL_USER);
3325     initlock(&tickslock, "time");
3326 }
```



```
3316 void
3317 tvinit(void)
3318 {
3319     int i;
3320
3321     for(i = 0; i < 256; i++)
3322         SETGATE(idt[i], 0, SEG_KCODE<<3, vectors[i], 0);
3323     SETGATE(idt[T_SYSCALL], 1, SEG_KCODE<<3,
3324             vectors[T_SYSCALL], DPL_USER);
3325
3326     initlock(&tickslock, "time");
3327 }
```

Initialize IDT

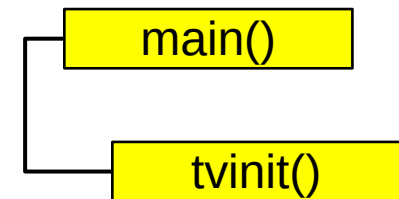
- Only int T_SYSCALL can be called from user-level



```
3316 void
3317 tvinit(void)
3318 {
3319     int i;
3320
3321     for(i = 0; i < 256; i++)
3322         SETGATE(idt[i], 0, SEG_KCODE<<3, vectors[i], 0);
3323     SETGATE(idt[T_SYSCALL], 1, SEG_KCODE<<3,
3324             vectors[T_SYSCALL], DPL_USER);
3325
3326     initlock(&tickslock, "time");
3327 }
```

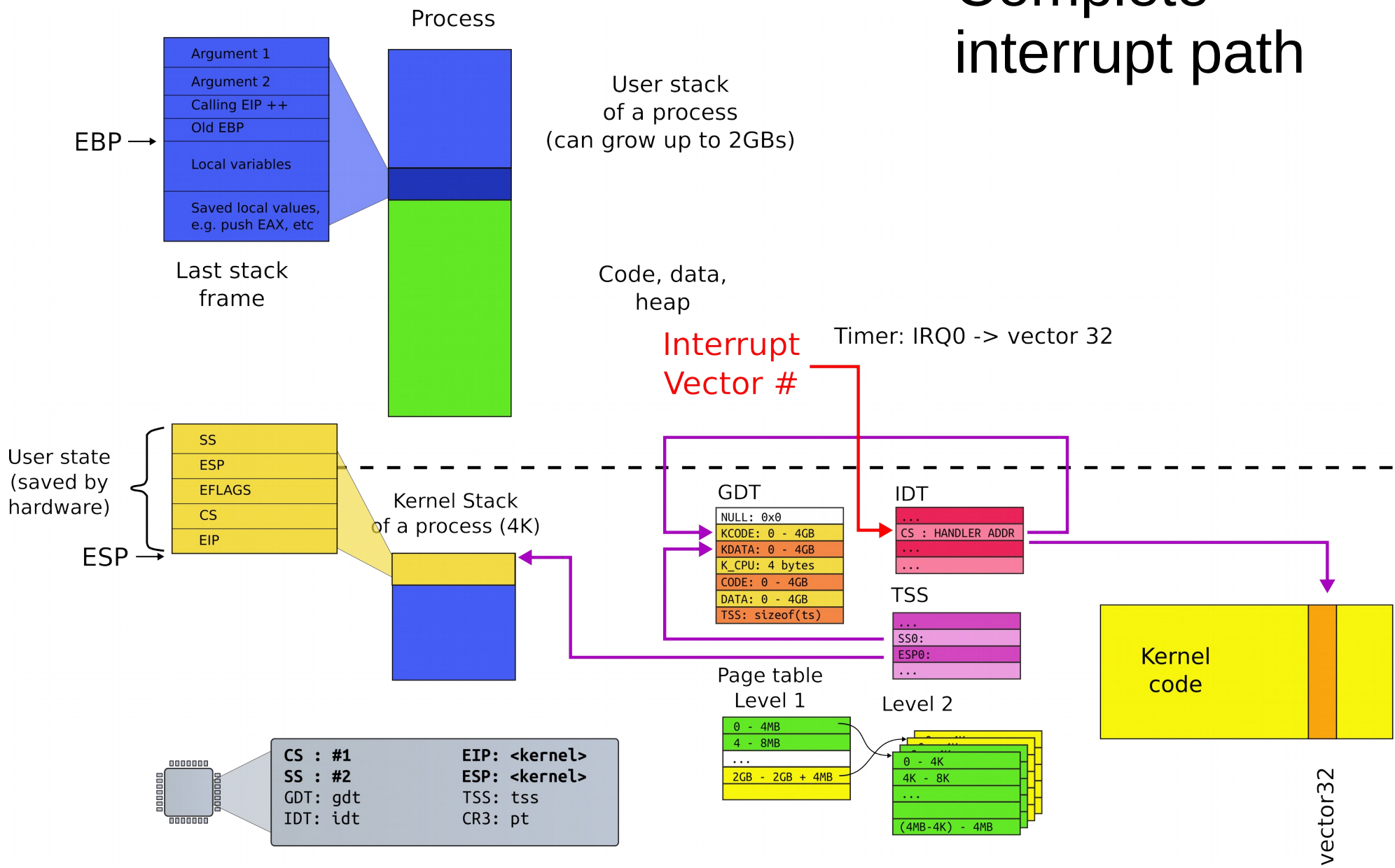
Initialize IDT

- Syscall is a “trap”
- i.e., doesn't disable interrupts



Interrupt path through the xv6 kernel

Complete interrupt path



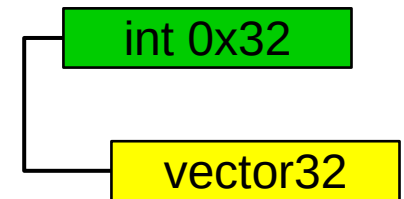
Timer Interrupt (int 0x32)

vector32:

```
pushl $0      // error code
```

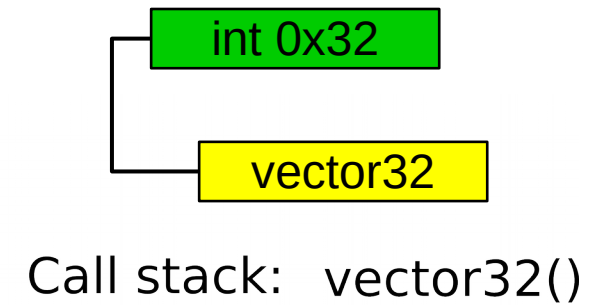
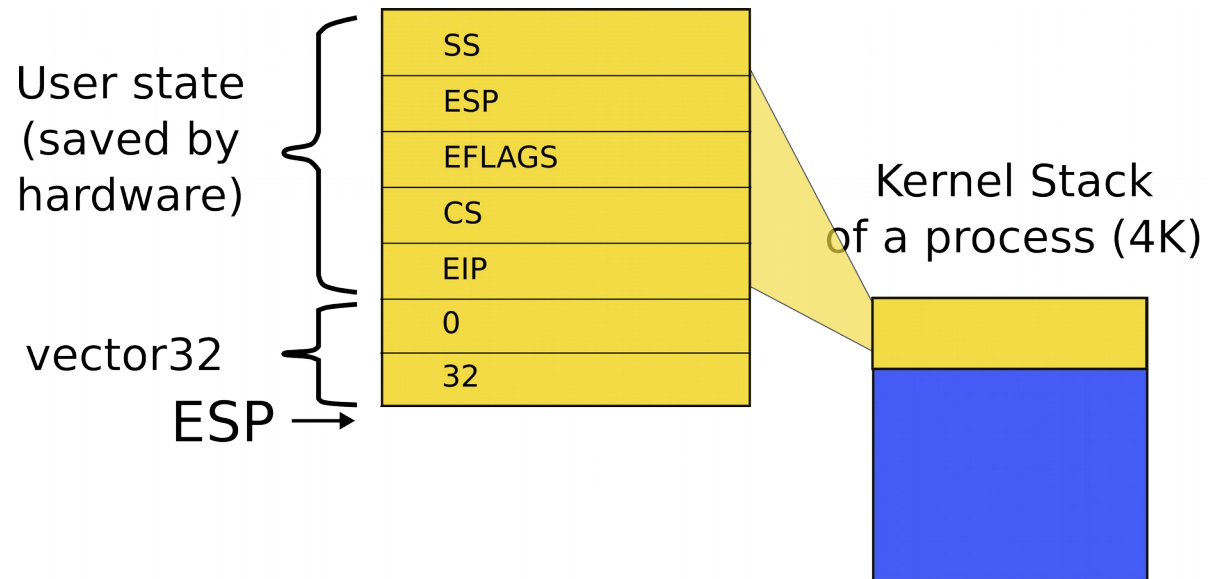
```
pushl $32     // vector #
```

```
jmp alltraps
```



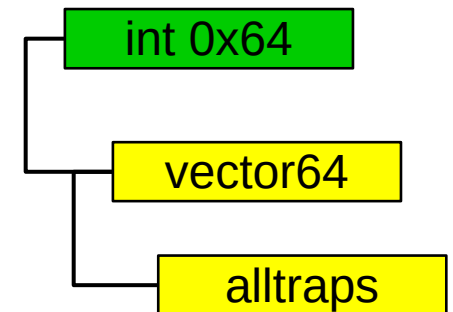
- Automatically generated
- From vectors.pl
 - vector.S

Kernel stack after interrupt



alltraps()

```
3254 alltraps:
3255 # Build trap frame.
3256 pushl %ds
3257 pushl %es
3258 pushl %fs
3259 pushl %gs
3260 pushal
3261
3262 # Set up data segments.
3263 movw $(SEG_KDATA<<3), %ax
3264 movw %ax, %ds
3265 movw %ax, %es
3266
3267 # Call trap(tf), where tf=%esp
3268 pushl %esp
3269 call trap
```



pusha

- An assembler instruction that saves all registers on the stack
 - https://c9x.me/x86/html/file_module_x86_id_270.html

```
Temporary = ESP;
```

```
Push(EAX);
```

```
Push(ECX);
```

```
Push(EDX);
```

```
Push(EBX);
```

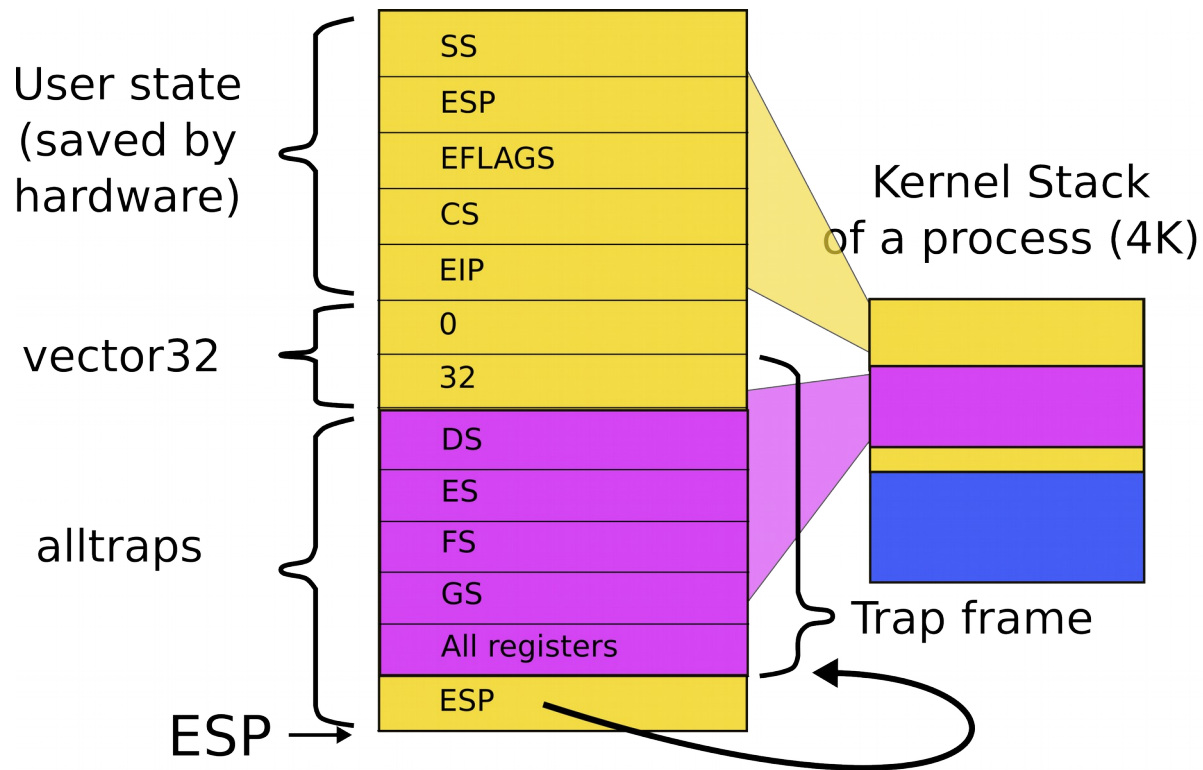
```
Push(Temporary);
```

```
Push(EBP);
```

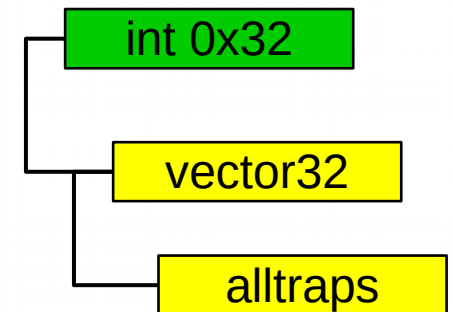
```
Push(ESI);
```

```
Push(EDI);
```

Kernel stack after interrupt

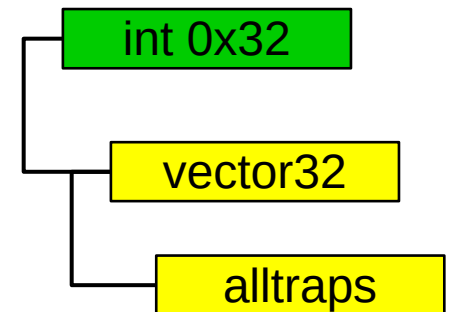


Call stack: vector32()
alltraps()



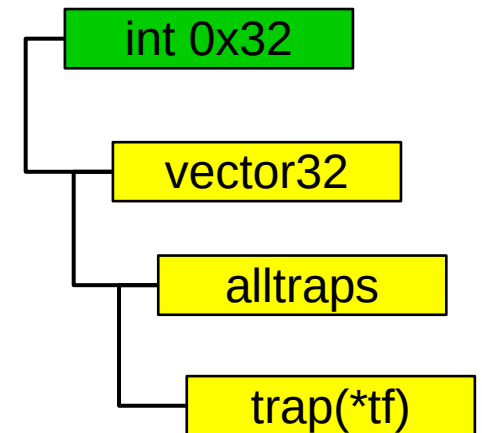
The end result: call trap()

```
3254 alltraps:
3255 # Build trap frame.
3256 pushl %ds
3257 pushl %es
3258 pushl %fs
3259 pushl %gs
3260 pushal
3261
3262 # Set up data and per-cpu segments.
3263 movw $(SEG_KDATA<<3), %ax
3264 movw %ax, %ds
3265 movw %ax, %es
3266 movw $(SEG_KCPU<<3), %ax
3267 movw %ax, %fs
3268 movw %ax, %gs
3269
3270 # Call trap(tf), where tf=%esp
3271 pushl %esp
3272 call trap
```



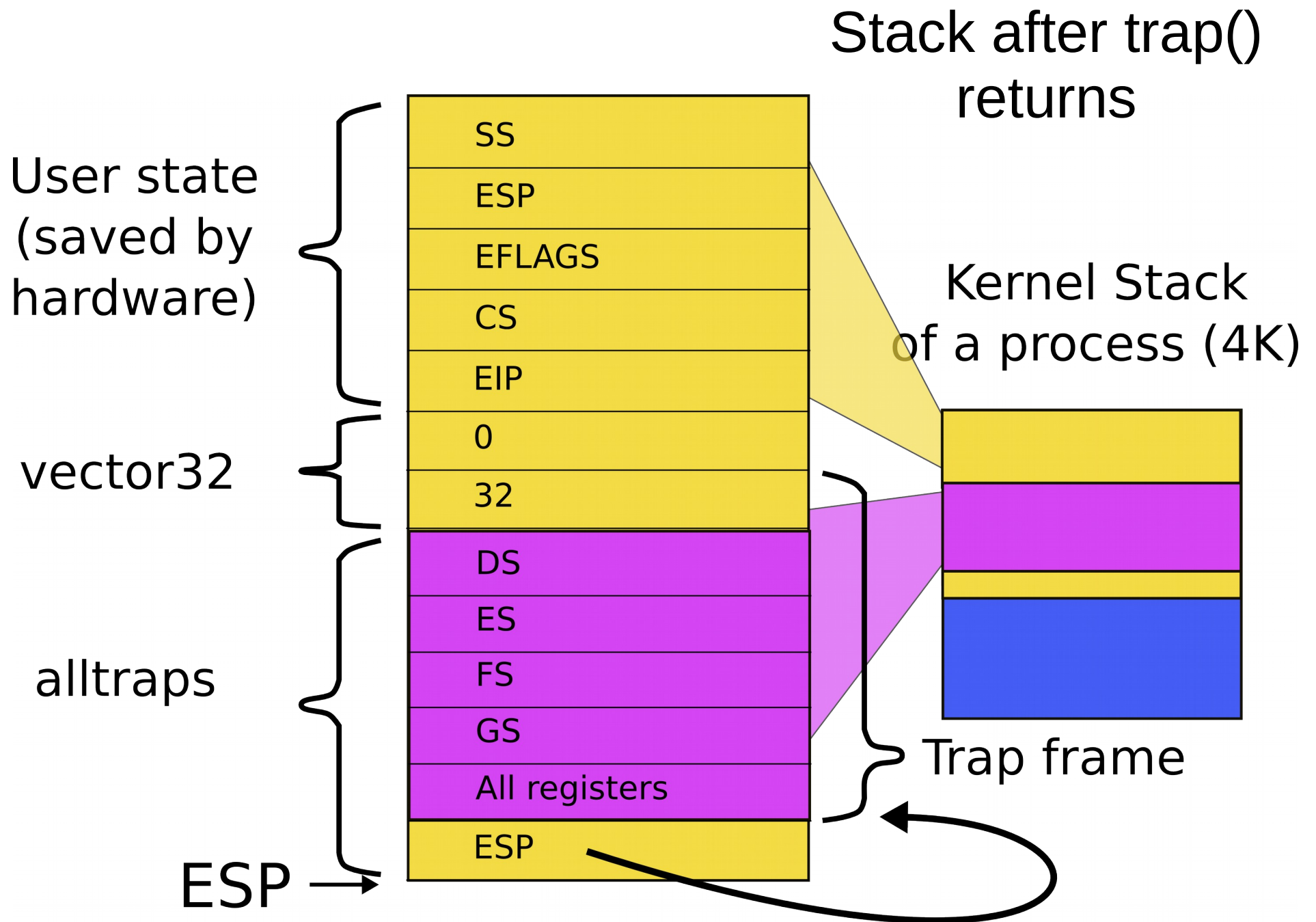
All interrupts, e.g. timer interrupt end up in a single function: trap()

```
3351 trap(struct trapframe *tf)
3352 {
...
3363     switch(tf->trapno){
3364     case T_IRQ0 + IRQ_TIMER:
3365         if(cpu->id == 0){
3366             acquire(&tickslock);
3367             ticks++;
3368             wakeup(&ticks);
3369             release(&tickslock);
3370         }
3372     break;
...
3423     if(proc && proc->state == RUNNING
        && tf->trapno == T_IRQ0+IRQ_TIMER)
3424         yield();
```



```
3004 alltraps:
...
3020 # Call trap(tf), where tf=%esp
3021 pushl %esp
3022 call trap
3023 addl $4, %esp
3024
3025 # Return falls through to trapret...
3026 .globl trapret
3027 trapret:
3028 popal
3029 popl %gs
3030 popl %fs
3031 popl %es
3032 popl %ds
3033 addl $0x8, %esp # trapno and errcode
3034 iret
```

alltraps(): exit from the interrupt



alltraps(): exiting

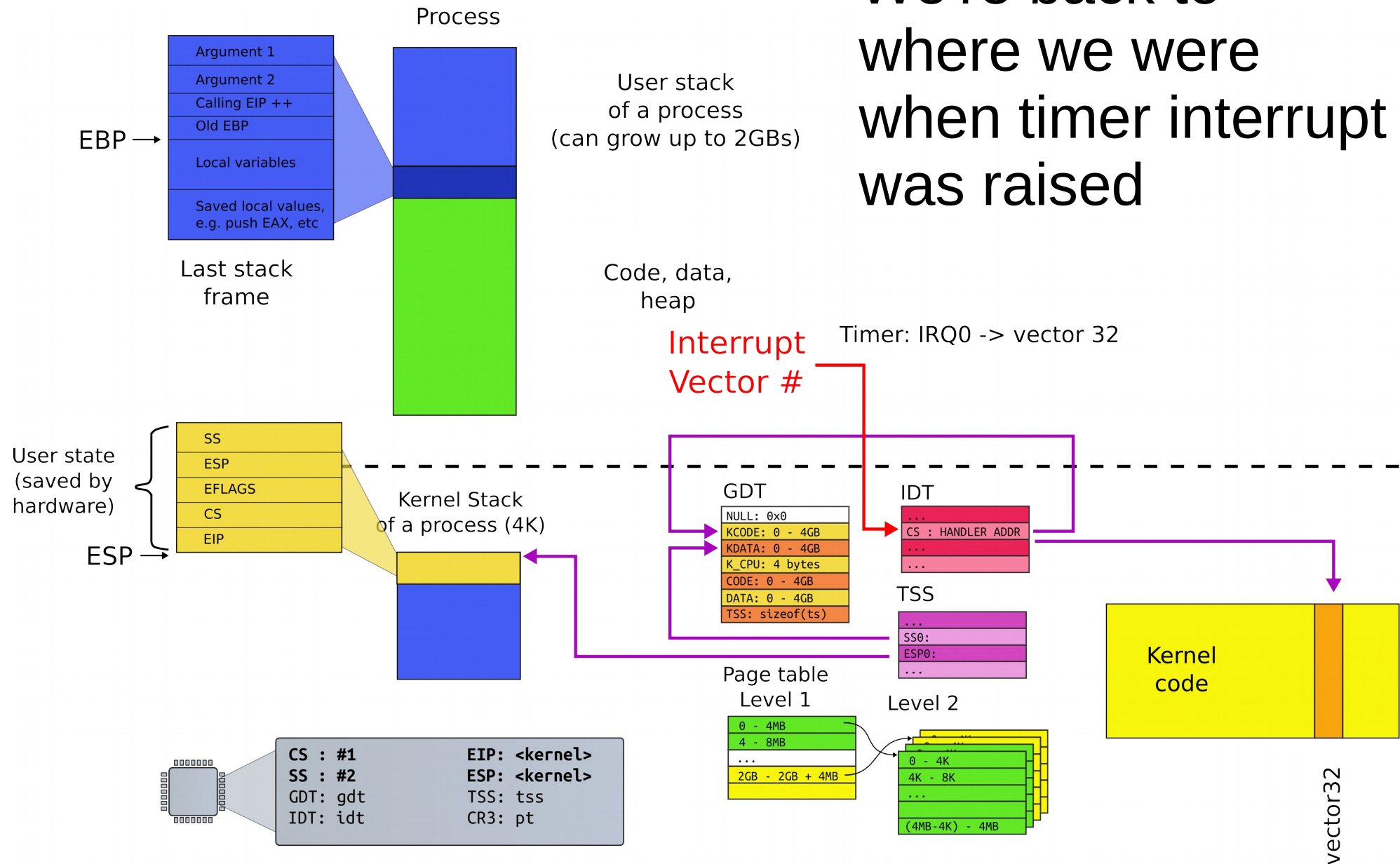
```
3004 alltraps:
...
3020 # Call trap(tf), where tf=%esp
3021 pushl %esp
3022 call trap
3023 addl $4, %esp
3024
3025 # Return falls through to trapret...
3026 .globl trapret
3027 trapret:
3028 popal
3029 popl %gs
3030 popl %fs
3031 popl %es
3032 popl %ds
3033 addl $0x8, %esp # trapno and errcode
3034 iret
```

- Restore all registers
- Exit into user
 - iret

Return from an interrupt

- Starts with IRET
 1. Restore the CS and EIP registers to their values prior to the interrupt or exception
 2. Restore EFLAGS
 3. Restore SS and ESP to their values prior to interrupt
 - This results in a stack switch
 4. Resume execution of interrupted procedure

We're back to where we were when timer interrupt was raised

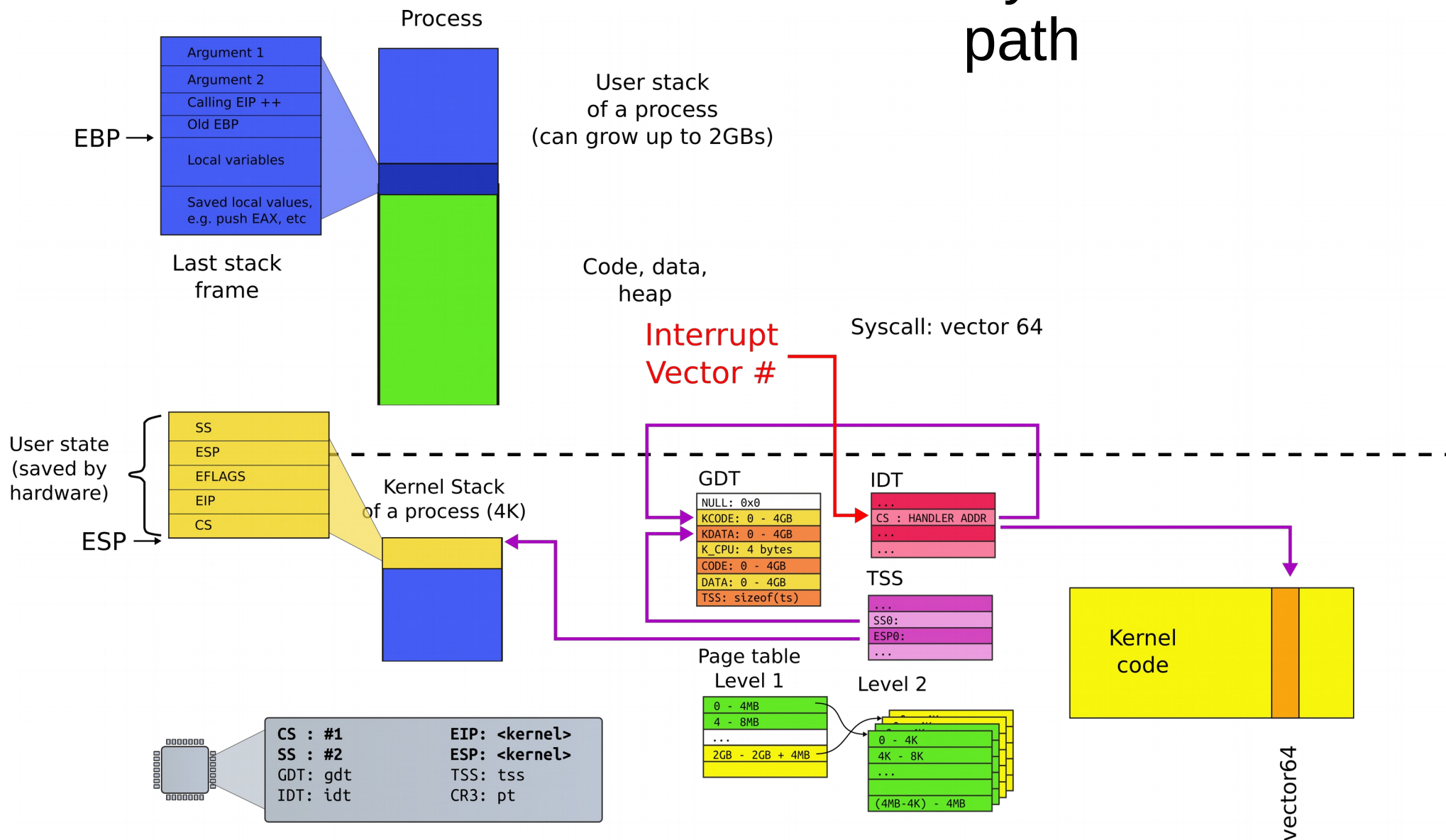


System Calls
(int 0x40)

Software interrupts can be used to implement system calls

- The int N instruction provides a secure mechanism for kernel invocation
 - i.e., user can enter the kernel
 - But through a well-defined entry point
 - System call handler
- Xv6 uses vector 0x40 (or 64)
 - You can choose any other unused vector
 - Linux uses 0x80
 - Well now it uses sysenter instead of int 0x80 as it is faster

System call path



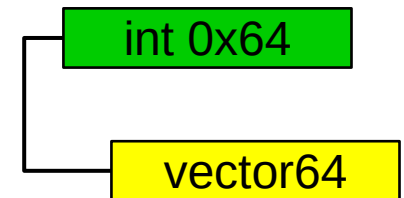
Where does IDT (entry 64) point to?

vector64:

```
pushl $0      // error code
```

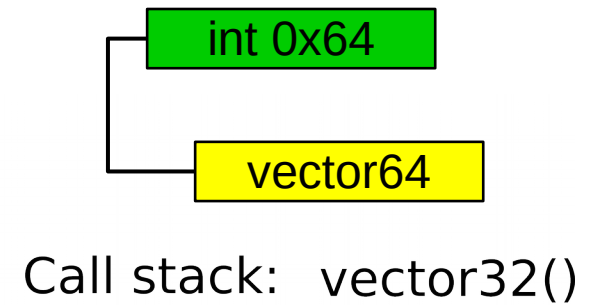
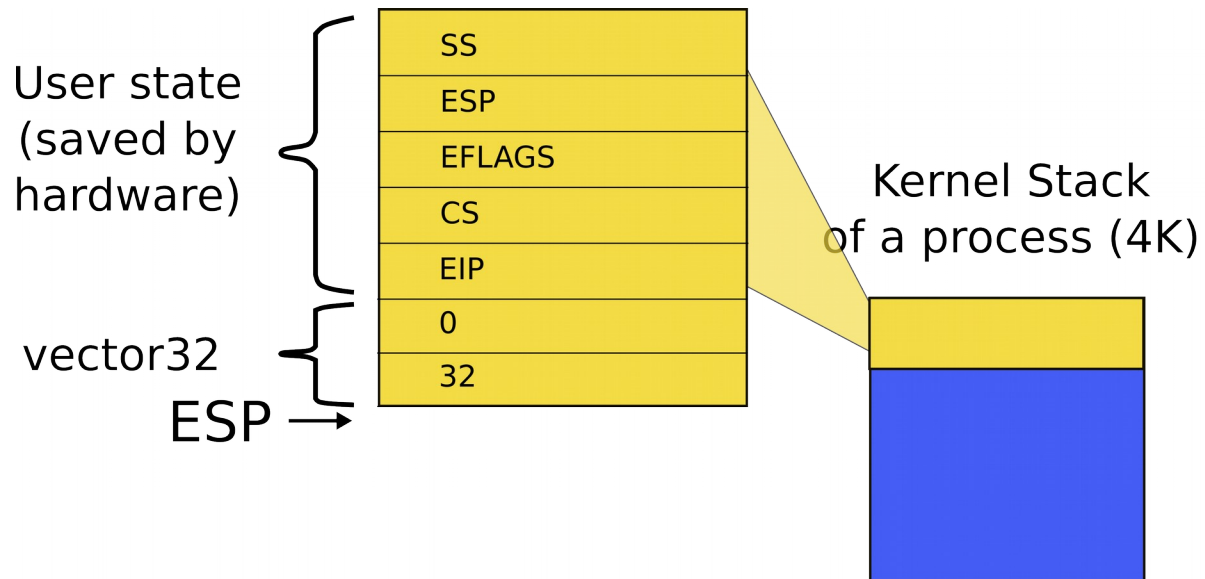
```
pushl $64     // vector #
```

```
jmp alltraps
```



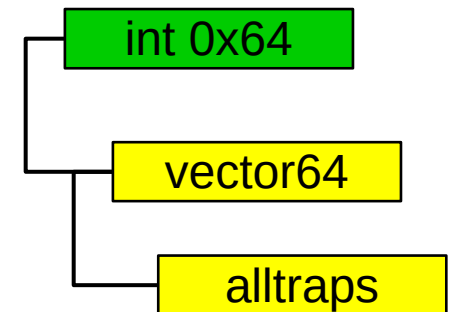
- Automatically generated
- From vectors.pl
 - vector.S

Kernel stack inside system call

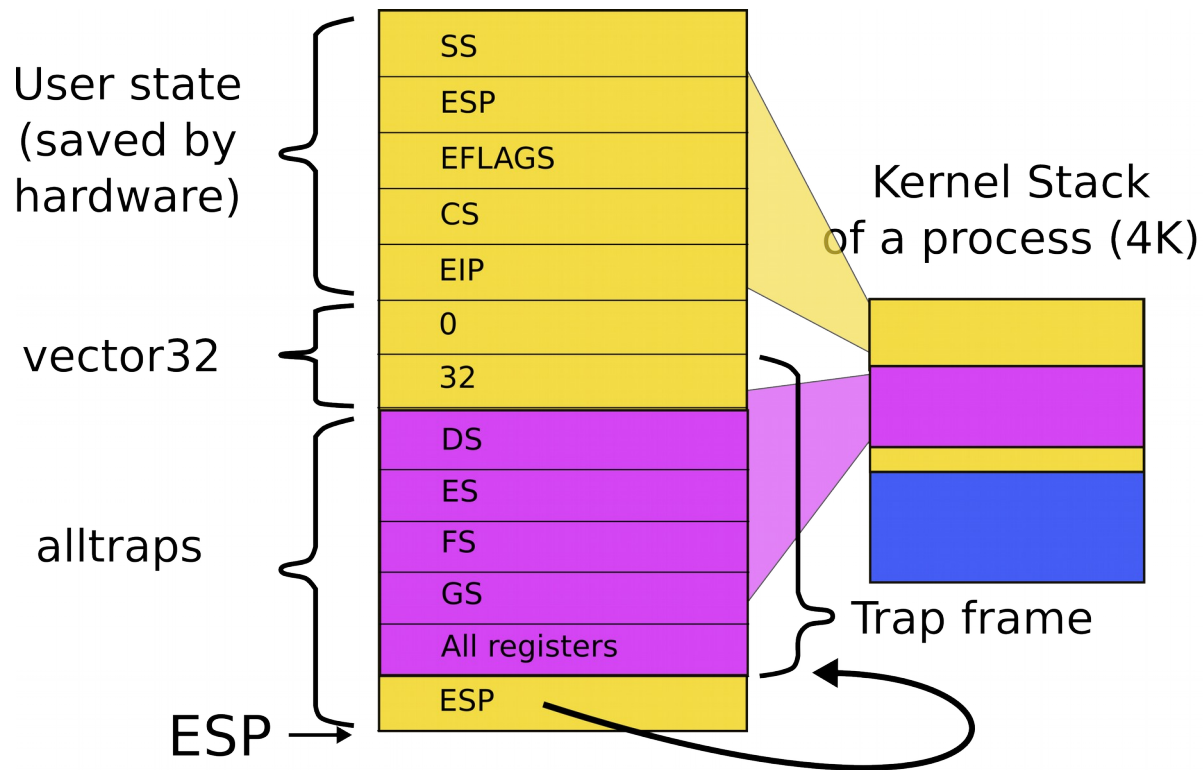


alltraps()

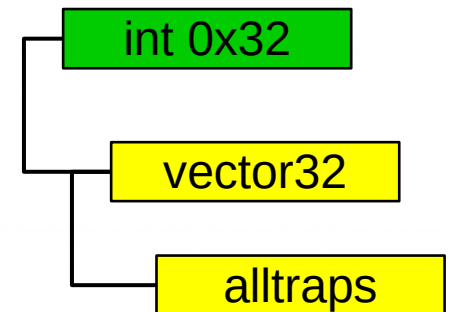
```
3254 alltraps:
3255 # Build trap frame.
3256 pushl %ds
3257 pushl %es
3258 pushl %fs
3259 pushl %gs
3260 pushal
3261
3262 # Set up data and per-cpu segments.
3263 movw $(SEG_KDATA<<3), %ax
3264 movw %ax, %ds
3265 movw %ax, %es
3266 movw $(SEG_KCPU<<3), %ax
3267 movw %ax, %fs
3268 movw %ax, %gs
3269
3270 # Call trap(tf), where tf=%esp
3271 pushl %esp
3272 call trap
```



Kernel stack inside system call

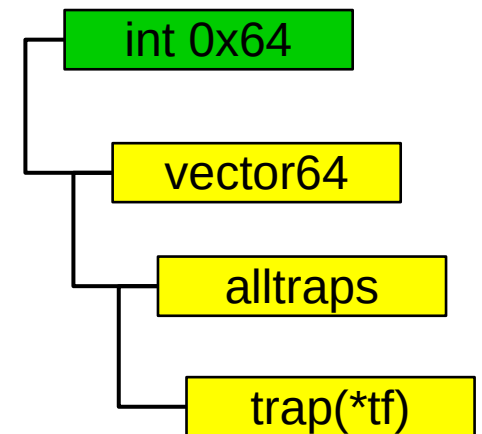


Call stack: vector32()
alltraps()



```
3351 trap(struct trapframe *tf)
3352 {
3353     if(tf->trapno == T_SYSCALL){
3354         if(proc->killed)
3355             exit();
3356         proc->tf = tf;
3357         syscall();
3358         if(proc->killed)
3359             exit();
3360         return;
3361     }
3362
3363     switch(tf->trapno){
3364     case T_IRQ0 + IRQ_TIMER:
```

System call handling inside trap()

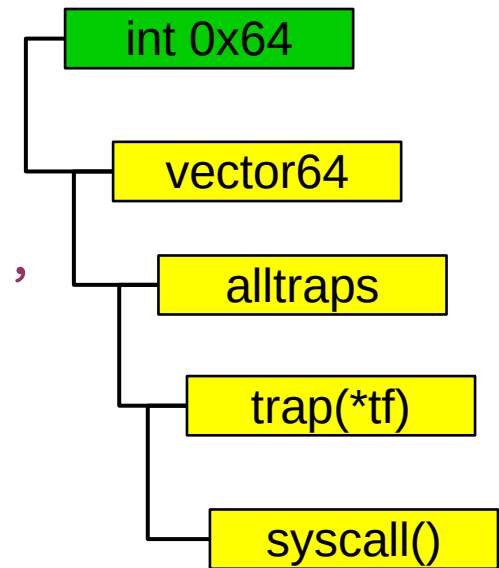


Syscall number

- System call number is passed in the %eax register
 - To distinguish which syscall to invoke,
 - e.g., sys_read, sys_exec, etc.
- alltrap() saves it along with all other registers

syscall(): get the number from the trap frame

```
3625 syscall(void)
3626 {
3627     int num;
3628
3629     num = proc->tf->eax;
3630     if(num > 0 && num < NELEM(syscalls) && syscalls[num])
3631     {
3632         proc->tf->eax = syscalls[num]();
3633     } else {
3634         cprintf("%d %s: unknown sys call %d\n",
3635             proc->pid, proc->name, num);
3636         proc->tf->eax = -1;
3637     }
3638 }
```



syscall(): process a syscall from the table

```
3625 syscall(void)
3626 {
3627     int num;
3628
3629     num = proc->tf->eax;
3630     if(num > 0 && num < NELEM(syscalls) && syscalls[num])
3631     {
3632         proc->tf->eax = syscalls[num]();
3633     } else {
3634         cprintf("%d %s: unknown sys call %d\n",
3635             proc->pid, proc->name, num);
3636         proc->tf->eax = -1;
3637     }
3638 }
```

System call table

```
3600 static int (*syscalls[])(void) = {
3601     [SYS_fork] sys_fork,
3602     [SYS_exit] sys_exit,
3603     [SYS_wait] sys_wait,
3604     [SYS_pipe] sys_pipe,
3605     [SYS_read] sys_read,
3606     [SYS_kill] sys_kill,
3607     [SYS_exec] sys_exec,
3608     [SYS_fstat] sys_fstat,
3609     [SYS_chdir] sys_chdir,
3610     [SYS_dup] sys_dup,
3611     [SYS_getpid] sys_getpid,
3612     [SYS_sbrk] sys_sbrk,
3613     [SYS_sleep] sys_sleep,
3614     [SYS_uptime] sys_uptime,
3615     [SYS_open] sys_open,
3616     [SYS_write] sys_write,
3617     [SYS_mknod] sys_mknod,
3618     [SYS_unlink] sys_unlink,
3619     [SYS_link] sys_link,
3620     [SYS_mkdir] sys_mkdir,
3621     [SYS_close] sys_close,
3622 };
```

How do user programs access system calls?

- It would be weird to write

```
8410    pushl $argv
```

```
8411    pushl $init
```

```
8412    pushl $0 // where caller pc would be
```

```
8413    movl $SYS_exec, %eax
```

```
8414    int $T_SYSCALL
```

- ... every time we want to invoke a system call
- This is an example for the `exec()` system call

```
// system calls
int fork(void);
int exit(void) __attribute__((noreturn));
int wait(void);
int pipe(int*);
int write(int, void*, int);
int read(int, void*, int);
int close(int);
int kill(int);
int exec(char*, char**);
int open(char*, int);
int mknod(char*, short, short);
int unlink(char*);
int fstat(int fd, struct stat*);
int link(char*, char*);
...
```

user.h

- user.h defines system call prototypes
- Compiler can generate correct system call stacks
 - Remember calling conventions?
 - Arguments on the stack

Example

- From cat.asm
- `if (write(1, buf, n) != n)`

A3:	53	push	ebx
a4:	68 00 0b 00 00	push	0xb00
a9:	6a 01	push	0x1
ab:	e8 c2 02 00 00	call	372 <write>

- Note, different versions of gcc
 - and different optimization levels
- Will generate slightly different code

Example

- From cat.asm
- `if (write(1, buf, n) != n)`

a0:	89 5c 24 08	mov	%ebx, 0x8(%esp)
a4:	c7 44 24 04 00 0b 00	movl	\$0xb00, 0x4(%esp)
ab:	00		
ac:	c7 04 24 01 00 00 00	movl	\$0x1, (%esp)
b3:	e8 aa 02 00 00	call	362 <write>

Example

- From cat.asm
- `if (write(1, buf, n) != n)`

a0:	89 5c 24 08	mov	%ebx, 0x8(%esp)
a4:	c7 44 24 04 00 0b 00	movl	\$0xb00, 0x4(%esp)
ab:	00		
ac:	c7 04 24 01 00 00 00	movl	\$0x1, (%esp)
b3:	e8 aa 02 00 00	call	362 <write>

Example

- From cat.asm
- `if (write(1, buf, n) != n)`

a0: 89 5c 24 08

`mov %ebx, 0x8(%esp)`

a4: c7 44 24 04 00 0b 00

`movl $0xb00, 0x4(%esp)`

ab: 00

ac: c7 04 24 01 00 00 00

`movl $0x1, (%esp)`

b3: e8 aa 02 00 00

`call 362 <write>`

- Still not clear...
 - The header file allows compiler to generate a call side invocation,
 - e.g., push arguments on the stack
 - But where is the system call invocation itself
 - e.g., `int $T_SYSCALL`

usys.S

```
8450 #include "syscall.h"
8451 #include "traps.h"
8452
8453 #define SYSCALL(name) \
8454     .globl name; \
8455     name: \
8456         movl $SYS_ ## name, %eax; \
8457         int $T_SYSCALL; \
8458         ret
8459
8460 SYSCALL(fork)
8461 SYSCALL(exit)
8462 SYSCALL(wait)
8463 SYSCALL(pipe)
8464 SYSCALL(read)
```

- Xv6 uses a SYSCALL macro to define a function for each system call invocation
 - E.g., fork() to invoke the “fork” system call

Example

- Write system call from cat.asm

00000362 <write>:

SYSCALL(write)

362: b8 10 00 00 00 mov \$0x10,%eax

367: cd 40 int \$0x40

369: c3 ret

System call arguments

- Where are the system call arguments?
- How does kernel access them?
 - And returns results?

Example

- Write system call
- `if (write(1, buf, n) != n)`

```
5876 int
5877 sys_write(void)
5878 {
5879     struct file *f;
5880     int n;
5881     char *p;
5882
5883     if(argfd(0, 0, &f) < 0 || argint(2, &n) < 0 || argptr(1, &p, n) < 0)
5884         return -1;
5885     return filewrite(f, p, n);
5886 }
```

Example

- Write system call
- `if (write(1, buf, n) != n)`

```
5876 int
5877 sys_write(void)
5878 {
5879     struct file *f;
5880     int n;
5881     char *p;
5882
5883     if(argfd(0, 0, &f) < 0 || argint(2, &n) < 0 || argptr(1, &p, n) < 0)
5884         return -1;
5885     return filewrite(f, p, n);
5886 }
```

```
3543 // Fetch the nth 32-bit system call argument.
3544 int
3545 argint(int n, int *ip)
3546 {
3547     return fetchint(proc->tf->esp + 4 + 4*n, ip);
3548 }
```

```
3515 // Fetch the int at addr from the current process.
3516 int
3517 fetchint(uint addr, int *ip)
3518 {
3519     if(addr >= proc->sz || addr+4 > proc->sz)
3520         return -1;
3521     *ip = *(int*)(addr);
3522     return 0;
3523 }
```

argint(int n, int *ip)

```
3543 // Fetch the nth 32-bit system call argument.
3544 int
3545 argint(int n, int *ip)
3546 {
3547     return fetchint(proc->tf->esp + 4 + 4*n, ip);
3548 }
```

```
3515 // Fetch the int at addr from the current process.
3516 int
3517 fetchint(uint addr, int *ip)
3518 {
3519     if(addr >= proc->sz || addr+4 > proc->sz)
3520         return -1;
3521     *ip = *(int*)(addr);
3522     return 0;
3523 }
```

argint(int n, int *ip)

```
3543 // Fetch the nth 32-bit system call argument.
```

```
3544 int
```

```
3545 argint(int n, int *ip)
```

```
3546 {
```

```
3547     return fetchint(proc->tf->esp + 4 + 4*n, ip);
```

```
3548 }
```

- Start with the address where current user stack is (esp)

```
3515 // Fetch the int at addr from the current process.
```

```
3516 int
```

```
3517 fetchint(uint addr, int *ip)
```

```
3518 {
```

```
3519     if(addr >= proc->sz || addr+4 > proc->sz)
```

```
3520         return -1;
```

```
3521     *ip = *(int*)(addr);
```

```
3522     return 0;
```

```
3523 }
```

argint(int n, int *ip)

```
3543 // Fetch the nth 32-bit system call argument.
```

```
3544 int
```

```
3545 argint(int n, int *ip)
```

```
3546 {
```

```
3547     return fetchint(proc->tf->esp + 4 + 4*n, ip);
```

```
3548 }
```

- Skip return eip

```
3515 // Fetch the int at addr from the current process.
```

```
3516 int
```

```
3517 fetchint(uint addr, int *ip)
```

```
3518 {
```

```
3519     if(addr >= proc->sz || addr+4 > proc->sz)
```

```
3520         return -1;
```

```
3521     *ip = *(int*)(addr);
```

```
3522     return 0;
```

```
3523 }
```

argint(int n, int *ip)

```
3543 // Fetch the nth 32-bit system call argument.
```

```
3544 int
```

```
3545 argint(int n, int *ip)
```

```
3546 {
```

```
3547     return fetchint(proc->tf->esp + 4 + 4*n, ip);
```

```
3548 }
```

- Fetch n'th argument

```
3515 // Fetch the int at addr from the current process.
```

```
3516 int
```

```
3517 fetchint(uint addr, int *ip)
```

```
3518 {
```

```
3519     if(addr >= proc->sz || addr+4 > proc->sz)
```

```
3520         return -1;
```

```
3521     *ip = *(int*)(addr);
```

```
3522     return 0;
```

```
3523 }
```

argint(int n, int *ip)

```
3543 // Fetch the nth 32-bit system call argument.
3544 int
3545 argint(int n, int *ip)
3546 {
3547     return fetchint(proc->tf->esp + 4 + 4*n, ip);
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3515 // Fetch the int at addr from the current process.
3516 int
3517 fetchint(uint addr, int *ip)
3518 {
3519     if(addr >= proc->sz || addr+4 > proc->sz)
3520         return -1;
3521     *ip = *(int*)(addr);
3522     return 0;
3523 }
```

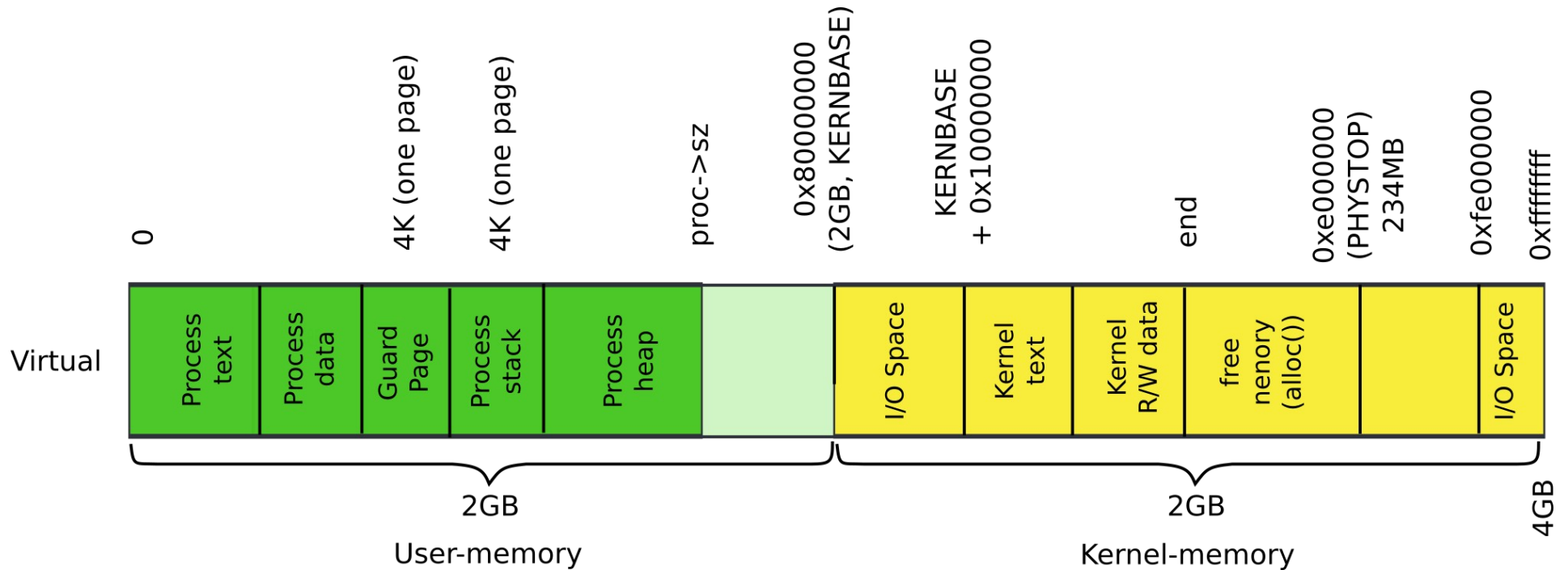
fetchint(uint addr, int *ip)

```
3543 // Fetch the nth 32-bit system call argument.
3544 int
3545 argint(int n, int *ip)
3546 {
3547     return fetchint(proc->tf->esp + 4 + 4*n, ip);
3548 }

3515 // Fetch the int at addr from the current process.
3516 int
3517 fetchint(uint addr, int *ip)
3518 {
3519     if(addr >= proc->sz || addr+4 > proc->sz)
3520         return -1;
3521     *ip = *(int*)(addr);
3522     return 0;
3523 }
```

fetchint(uint addr, int *ip)

Process address space



Any idea for what argptr() shall do?

- Write system call
- `if (write(1, buf, n) != n)`

```
5876 int
5877 sys_write(void)
5878 {
5879     struct file *f;
5880     int n;
5881     char *p;
5882
5883     if(argfd(0, 0, &f) < 0 || argint(2, &n) < 0 || argptr(1, &p, n) < 0)
5884         return -1;
5885     return filewrite(f, p, n);
5886 }
```

- Remember, buf is a pointer to a region of memory
 - i.e., a buffer
- of size n

```
3550 // Fetch the nth word-sized system call argument as a pointer
3551 // to a block of memory of size n bytes. Check that the pointer
3552 // lies within the process address space.
```

```
3553 int
```

```
3554 argptr(int n, char **pp, int size)
```

```
3555 {
```

```
3556     int i;
```

```
3557
```

```
3558     if(argint(n, &i) < 0)
```

```
3559         return -1;
```

```
3560     if((uint)i >= proc->sz || (uint)i+size > proc->sz)
```

```
3561         return -1;
```

```
3562     *pp = (char*)i;
```

```
3563     return 0;
```

```
3564 }
```

- Check that the pointer to the buffer is sound

argptr(uint addr, int *ip)

```
3550 // Fetch the nth word-sized system call argument as a pointer
3551 // to a block of memory of size n bytes. Check that the pointer
3552 // lies within the process address space.
```

```
3553 int
```

```
3554 argptr(int n, char **pp, int size)
```

```
3555 {
```

```
3556     int i;
```

```
3557
```

```
3558     if(argint(n, &i) < 0)
```

```
3559         return -1;
```

```
3560     if((uint)i >= proc->sz || (uint)i+size > proc->sz)
```

```
3561         return -1;
```

```
3562     *pp = (char*)i;
```

```
3563     return 0;
```

```
3564 }
```

- Check that the buffer is in user memory

argptr(uint addr, int *ip)

Summary

- We've learned how system calls work

Printing on the console

```
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());
1325     picinit(); // another interrupt controller
1326     ioapicinit(); // another interrupt controller
1327     consoleinit(); // console hardware
1328     uartinit(); // serial port
1329     pinit(); // process table
1330     tvinit(); // trap vectors
1331     binit(); // buffer cache
1332     fileinit(); // file table
1333     ideinit(); // disk
1334     if(!ismp)
1335         timerinit(); // uniprocessor timer
1336     startothers(); // start other processors
1337     kinit2(P2V(4*1024*1024), P2V(PHYSTOP)); // must come after startothers()
1338     userinit(); // first user process
1339     mpmain(); // finish this processor's setup
1340 }
```

main()

```
8000 // Print to the console. only understands %d, %x, %p, %s.
```

```
8001 void
```

```
8002 cprintf(char *fmt, ...)
```

```
8003 {
```

```
...
```

```
8012     if (fmt == 0)
```

```
8013         panic("null fmt");
```

```
8014
```

```
8015     argp = (uint*)(void*)&fmt + 1;
```

```
8016     for(i = 0; (c = fmt[i] & 0xff) != 0; i++){
```

```
8017         if(c != '%'){
```

```
8018             consputc(c);
```

```
8019             continue;
```

```
8020         }
```

```
8021         c = fmt[++i] & 0xff;
```

```
8022         if(c == 0)
```

```
8023             break;
```

```
8024         switch(c){
```

```
...
```

```
8032         case 's':
```

```
8033             if((s = (char*)argp++) == 0)
```

```
8034                 s = "(null)";
```

```
8035             for(; *s; s++)
```

```
8036                 consputc(*s);
```

```
8037             break;
```

```
...
```

```
8047     }
```

Print on the screen

Print one character

```
8150 void
8151 consputc(int c)
8152 {
...
8159     if(c == BACKSPACE){
8160         uartputc('\b'); uartputc(' '); uartputc('\b');
8161     } else
8162         uartputc(c);
8163     cgaputc(c);
8164 }
...
8350 void
8351 uartputc(int c)
8352 {
8353     int i;
8354
8355     if(!uart)
8356         return;
8357     for(i = 0; i < 128 && !(inb(COM1+5) & 0x20); i++)
8358         microdelay(10);
8359     outb(COM1+0, c);
8360 }
```

```
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());
1325     picinit(); // another interrupt controller
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1327     consoleinit(); // console hardware
1328     uartinit(); // serial port
1329     pinit(); // process table
1330     tvinit(); // trap vectors
1331     binit(); // buffer cache
1332     fileinit(); // file table
1333     ideinit(); // disk
1334     if(!ismp)
1335         timerinit(); // uniprocessor timer
1336     startothers(); // start other processors
1337     kinit2(P2V(4*1024*1024), P2V(PHYSTOP)); // must come after startothers()
1338     userinit(); // first user process
1339     mpmain(); // finish this processor's setup
1340 }
```

main()

```
8000 // Print to the console. only understands %d, %x, %p, %s.
```

```
8001 void
```

```
8002 cprintf(char *fmt, ...)
```

```
8003 {
```

```
...
```

```
8012     if (fmt == 0)
```

```
8013         panic("null fmt");
```

```
8014
```

```
8015     argp = (uint*)(void*)&fmt + 1;
```

```
8016     for(i = 0; (c = fmt[i] & 0xff) != 0; i++){
```

```
8017         if(c != '%'){
```

```
8018             consputc(c);
```

```
8019             continue;
```

```
8020         }
```

```
8021         c = fmt[++i] & 0xff;
```

```
8022         if(c == 0)
```

```
8023             break;
```

```
8024         switch(c){
```

```
...
```

```
8032         case 's':
```

```
8033             if((s = (char*)argp++) == 0)
```

```
8034                 s = "(null)";
```

```
8035             for(; *s; s++)
```

```
8036                 consputc(*s);
```

```
8037             break;
```

```
...
```

```
8047     }
```

Print on the screen

Print one character (serial line)

```
8150 void
8151 consputc(int c)
8152 {
...
8159     if(c == BACKSPACE){
8160         uartputc('\b'); uartputc(' '); uartputc('\b');
8161     } else
8162         uartputc(c);
8163     cgaputc(c);
8164 }
...
8350 void
8351 uartputc(int c)
8352 {
8353     int i;
8354
8355     if(!uart)
8356         return;
8357     for(i = 0; i < 128 && !(inb(COM1+5) & 0x20); i++)
8358         microdelay(10);
8359     outb(COM1+0, c);
8360 }
```

```
8102 static ushort *crt = (ushort*)P2V(0xb8000); // CGA memory
```

```
8103
```

```
8104 static void
```

```
8105 cgaputc(int c)
```

```
8106 {
```

```
8107     int pos;
```

```
8108
```

```
...
```

```
8115     if(c == '\n')
```

```
8116         pos += 80 - pos%80;
```

```
8117     else if(c == BACKSPACE){
```

```
8118         if(pos > 0) --pos;
```

```
8119     } else
```

```
8120         crt[pos++] = (c&0xff) | 0x0700; // black on white
```

```
8121
```

```
...
```

```
8124
```

```
8125     if((pos/80) >= 24){ // Scroll up.
```

```
8126         memmove(crt, crt+80, sizeof(crt[0])*23*80);
```

```
8127         pos -= 80;
```

```
8128         memset(crt+pos, 0, sizeof(crt[0])*(24*80 - pos));
```

```
8129     }
```

```
8130
```

```
...
```

```
8136 }
```

Print one character (display)

Thank you