143A: Principles of Operating Systems

Lecture 11: Interrupts and Exceptions

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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()

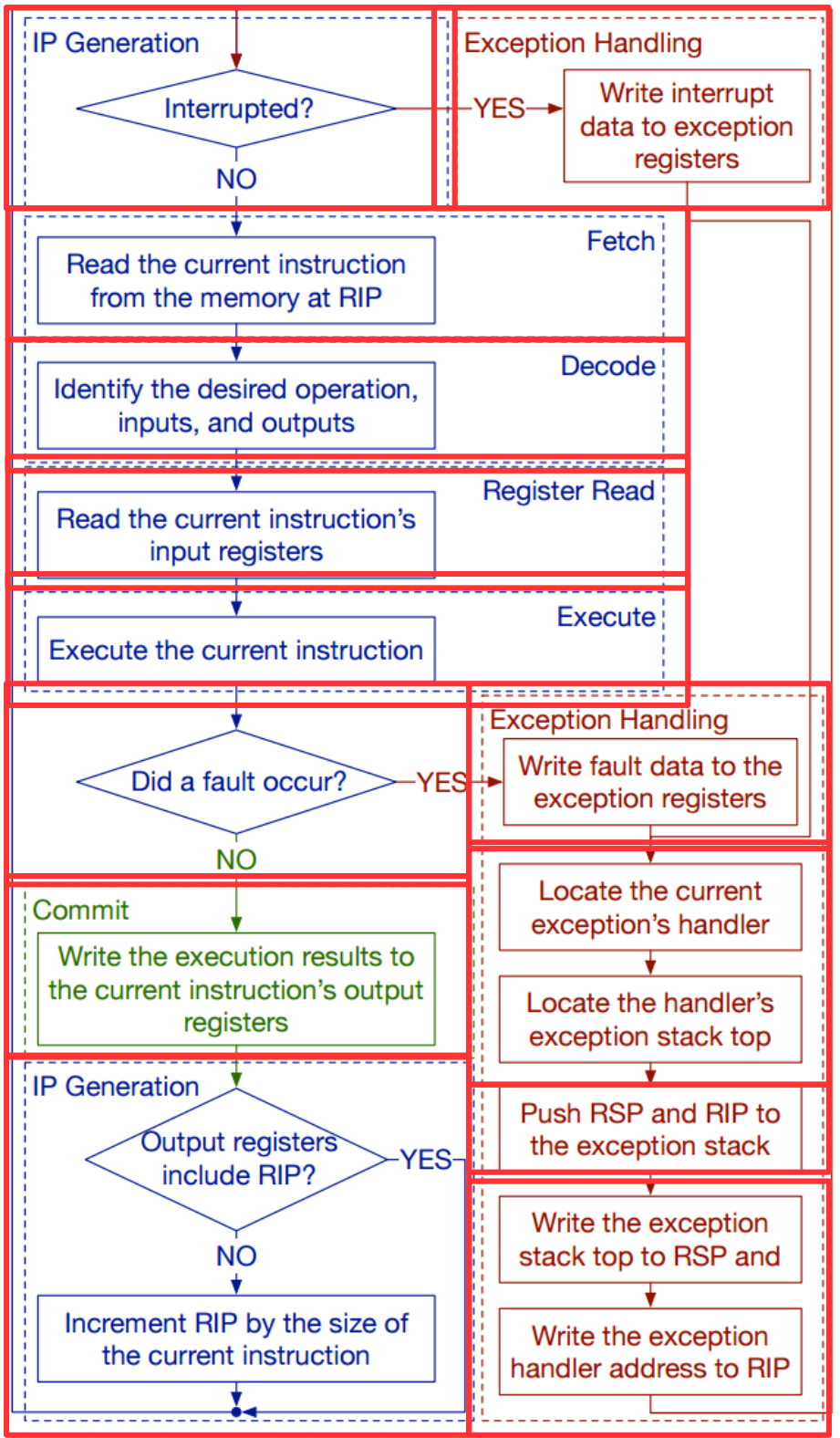
Why do we need interrupts?

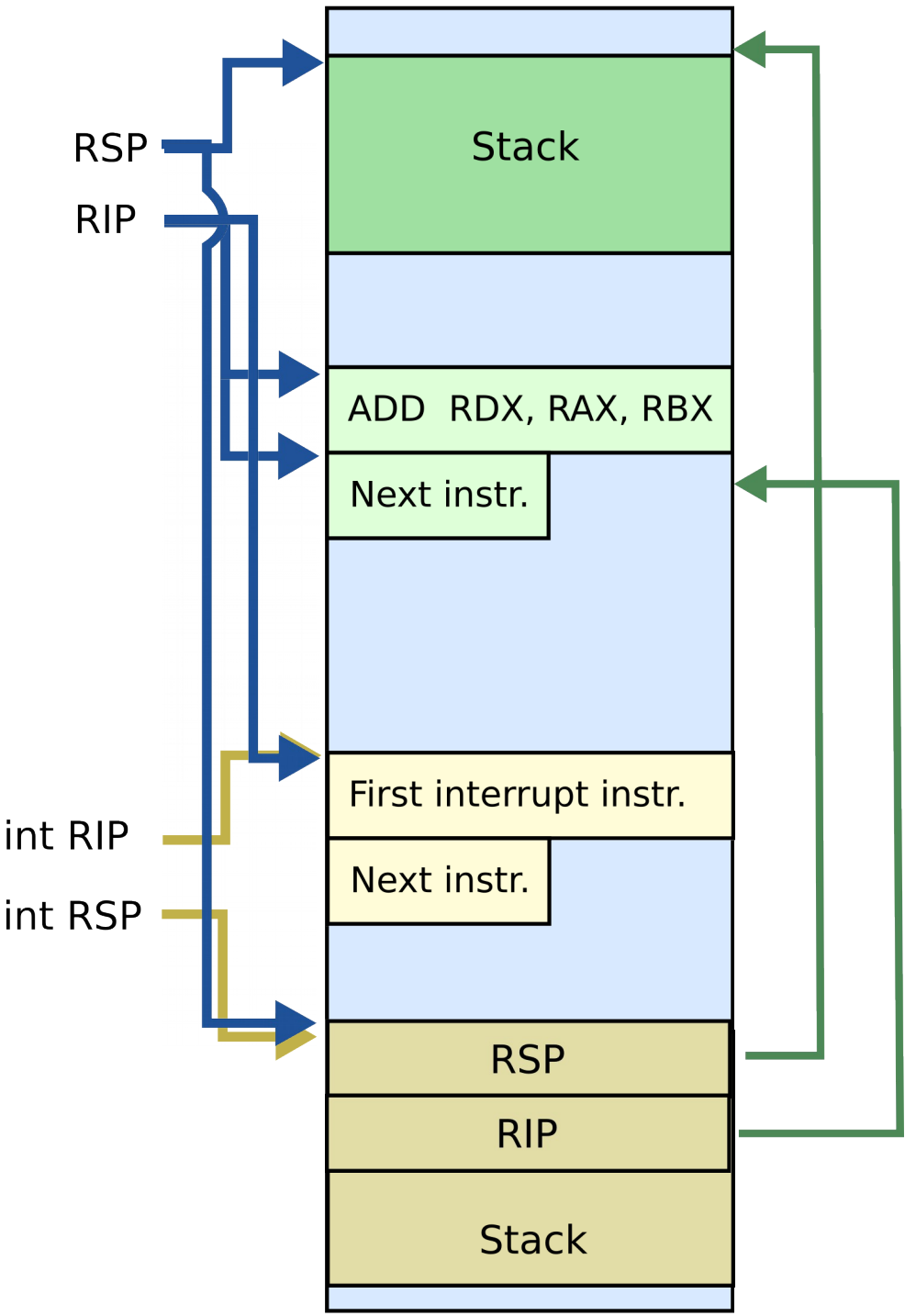
Remember:
hardware interface is designed to help OS

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?


IP Generation
Interrupted?
YES
NO
Exception Handling
Write interrupt data to exception registers
Fetch
Read the current instruction from the memory at RIP
Decode
Identify the desired operation, inputs, and outputs
Register Read
Read the current instruction's input registers
Execute
Execute the current instruction
Did a fault occur?
YES
NO
Exception Handling
Write fault data to the exception registers
Locate the current exception's handler
Locate the handler's exception stack top
Push RSP and RIP to the exception stack
Write the exception stack top to RSP and
Write the exception handler address to RIP
Commit
Write the execution results to the current instruction's output registers
IP Generation
Output registers include RIP?
YES
NO
Increment RIP by the size of the current instruction


RSP
RIP
int RIP
int RSP
Stack
ADD RDX, RAX, RBX
Next instr.
First interrupt instr.
Next instr.
RSP
RIP
Stack

Handling interrupts and exceptions

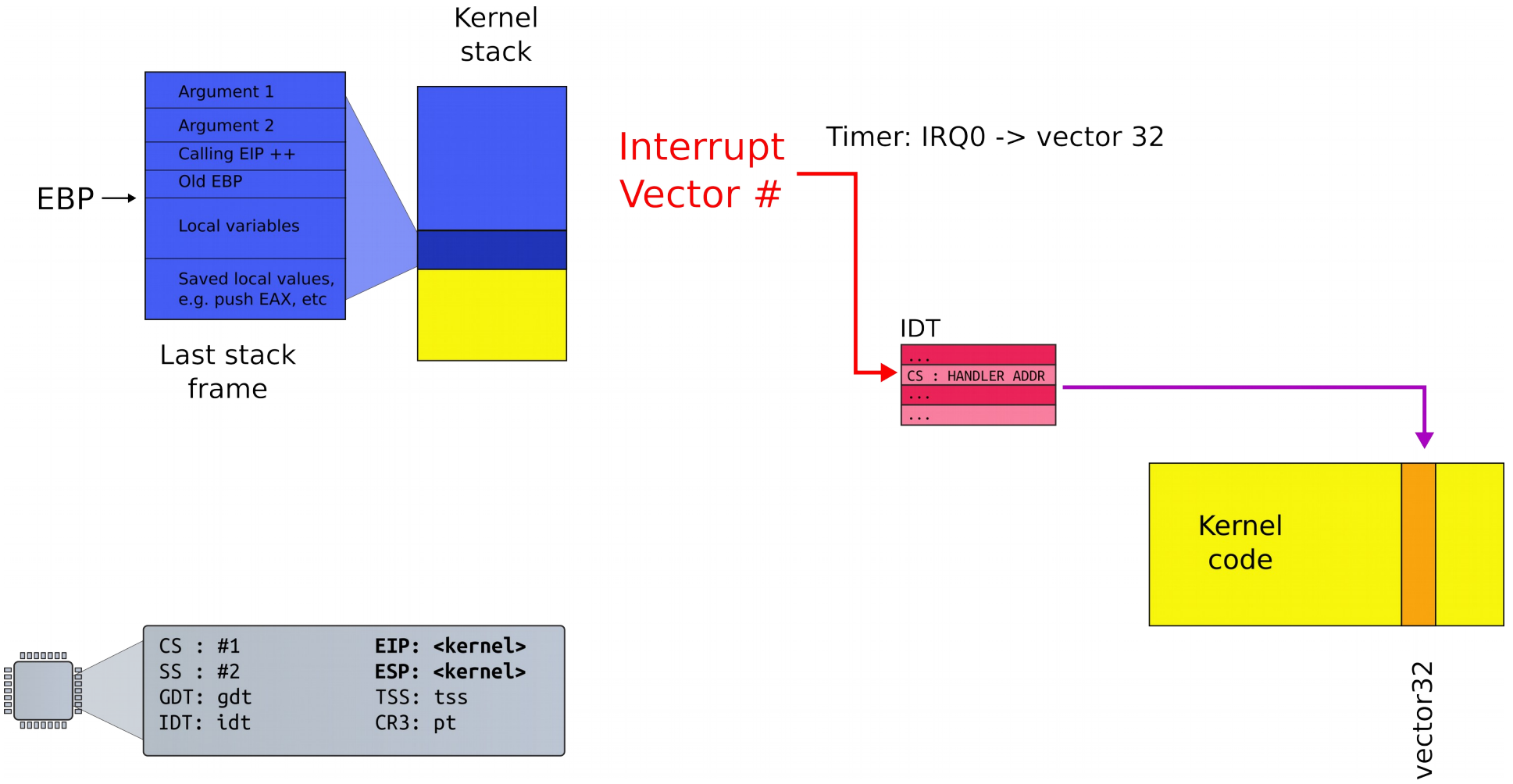
- In both synchronous and asynchronous cases the CPU follows the **same procedure**
  - Stop execution of the current program
  - Start execution of a handler
  - Processor accesses the handler through an entry in the Interrupt Descriptor Table (IDT)
- Each interrupt is defined by a number
  - E.g.,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

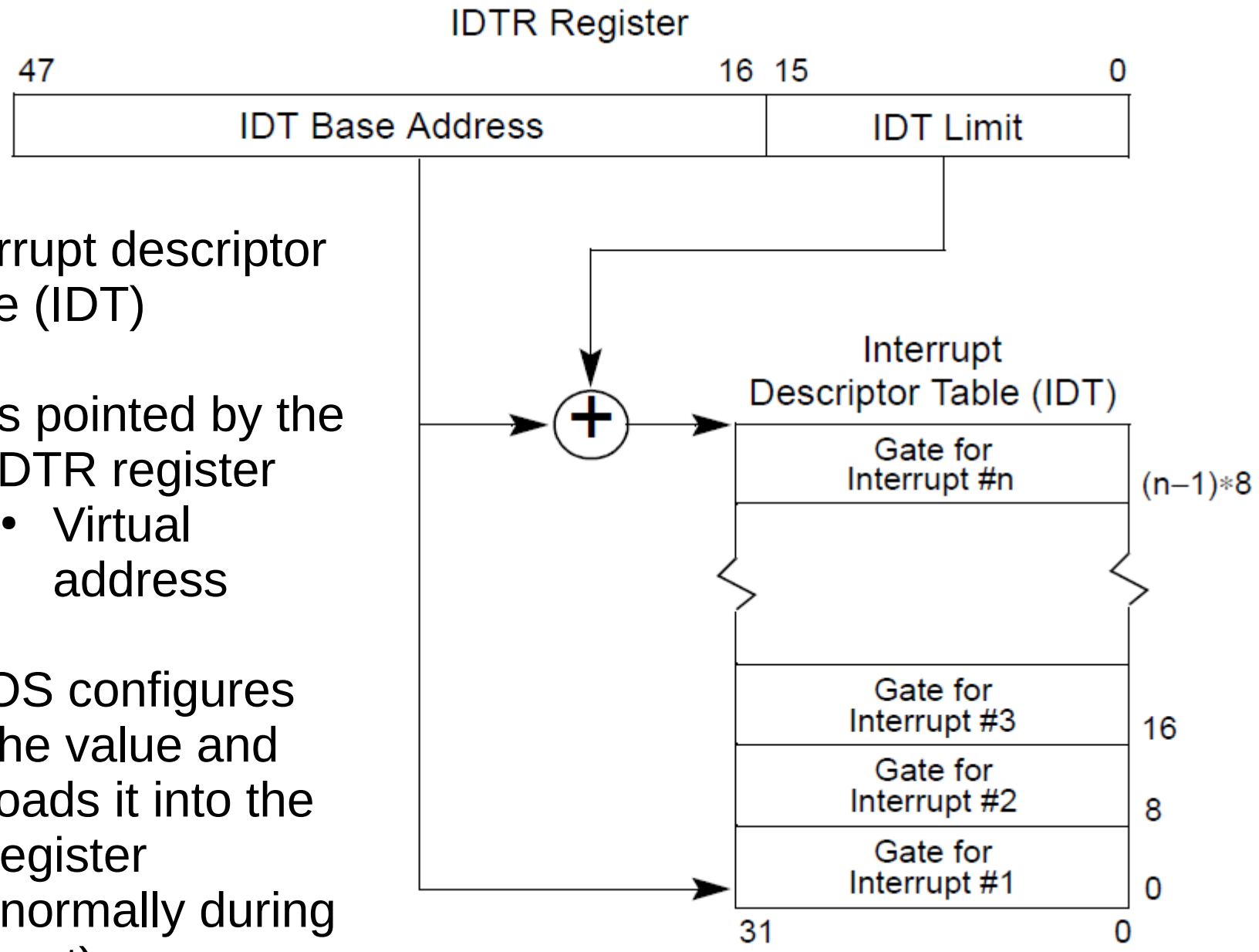
Case #1: Interrupt path no change in privilege level

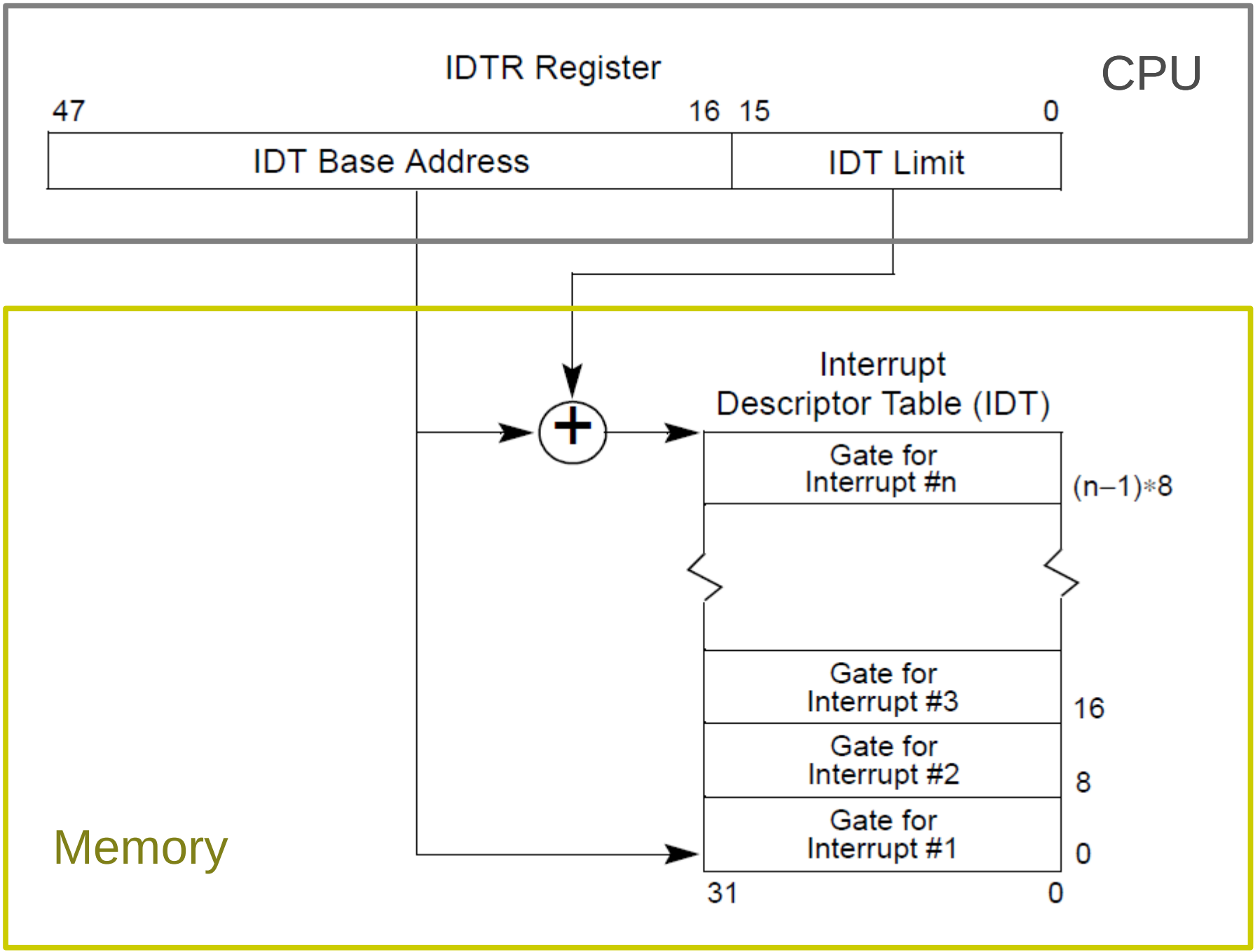
- e.g., we're already running in the kernel



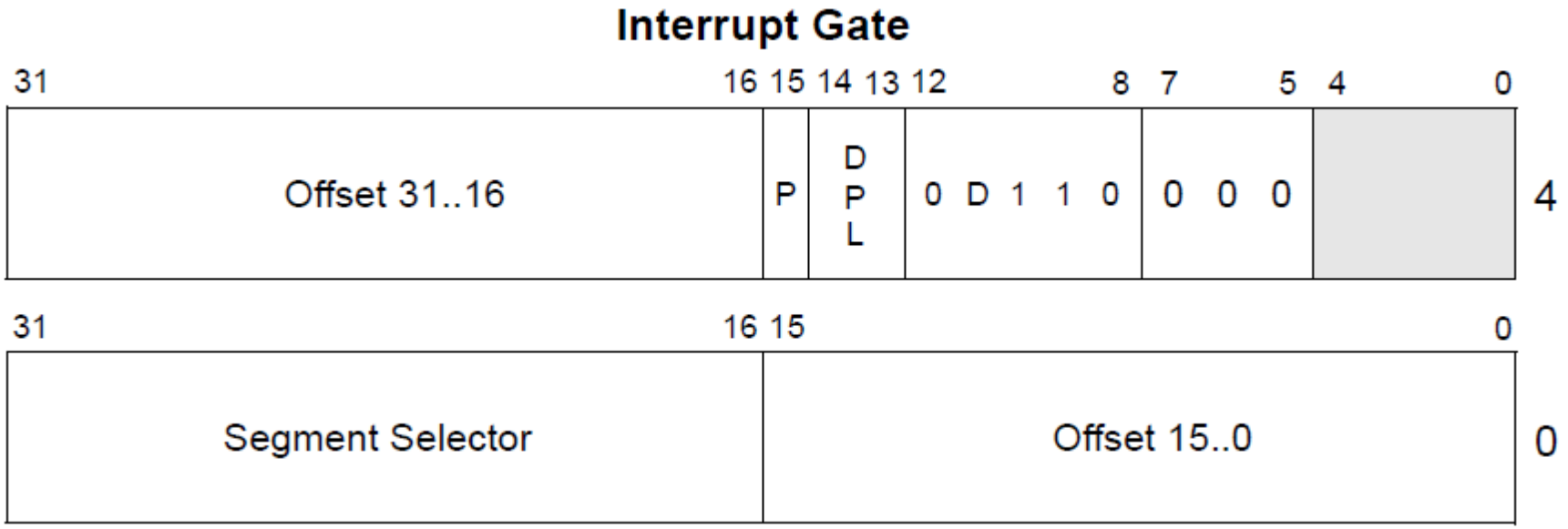
Interrupt descriptor table (IDT)

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

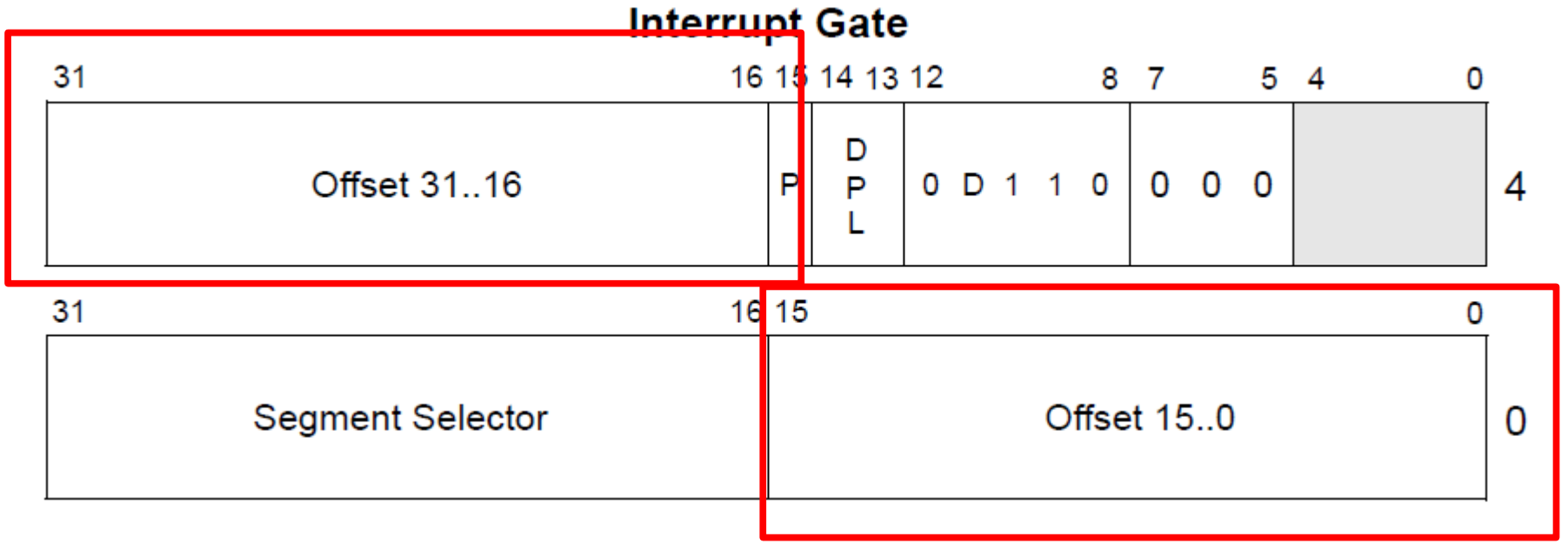



IDTR Register
CPU
47
16
15
0
IDT Base Address
IDT Limit
Interrupt
Descriptor Table (IDT)
Gate for
Interrupt #n
(n–1)*8
Gate for
Interrupt #3
16
Gate for
Interrupt #2
8
Gate for
Interrupt #1
0
31
0
Memory

Interrupt descriptor



Interrupt descriptor

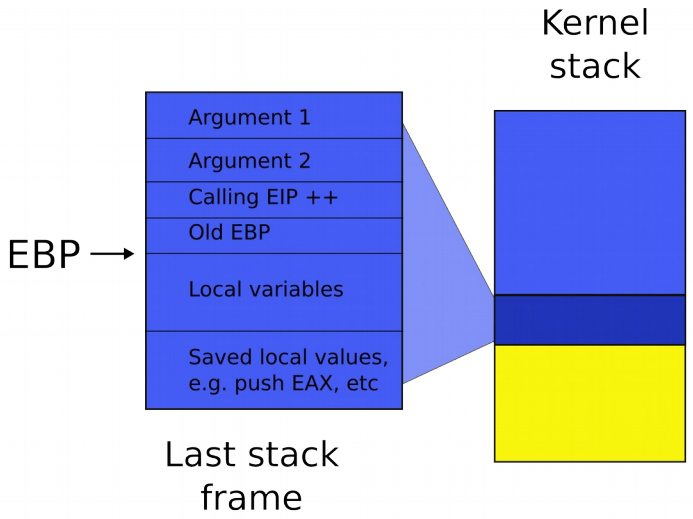


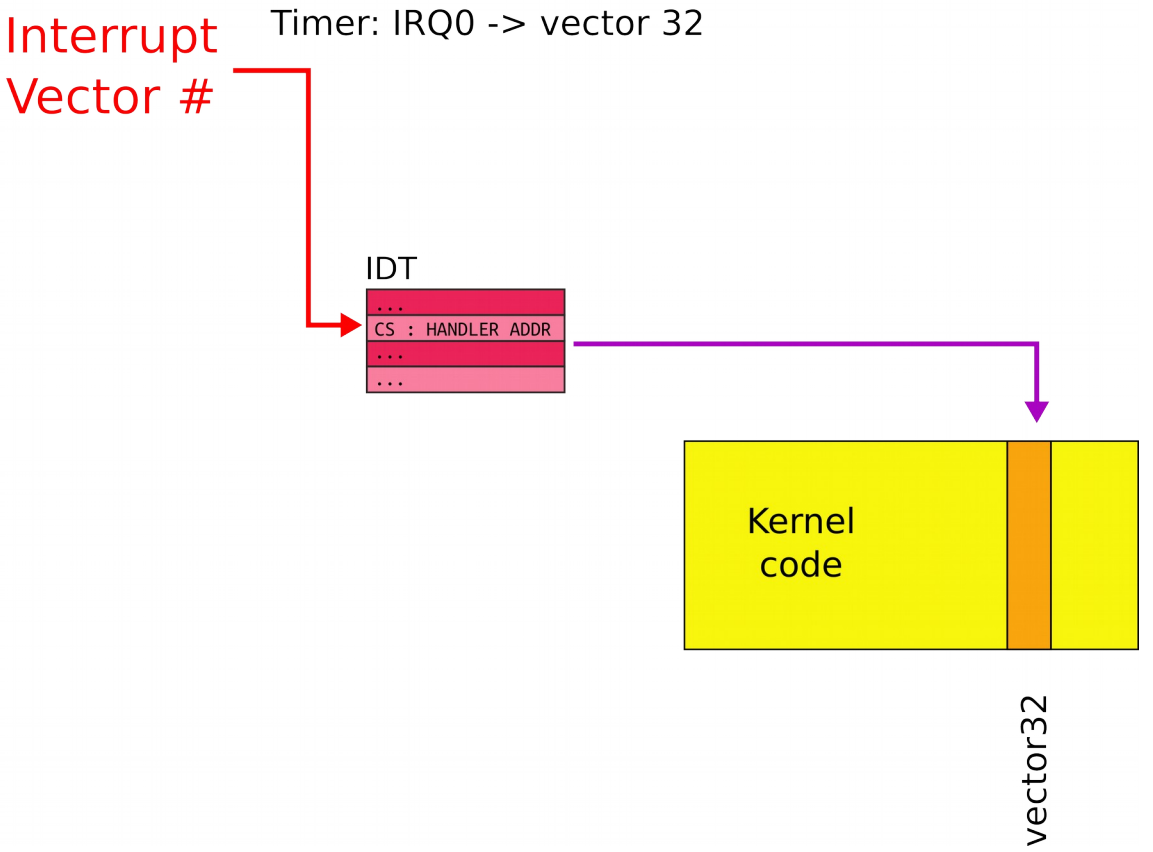
- We will walk through these fields gradually
  - For now we care about vector offset
  - Pointer to the interrupt handler

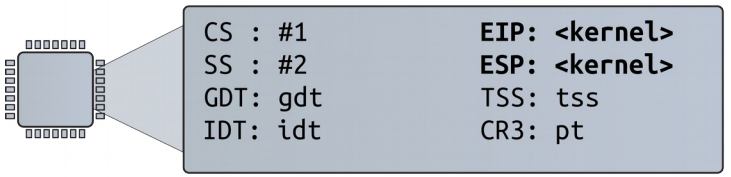
Interrupt handlers

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

Interrupt path



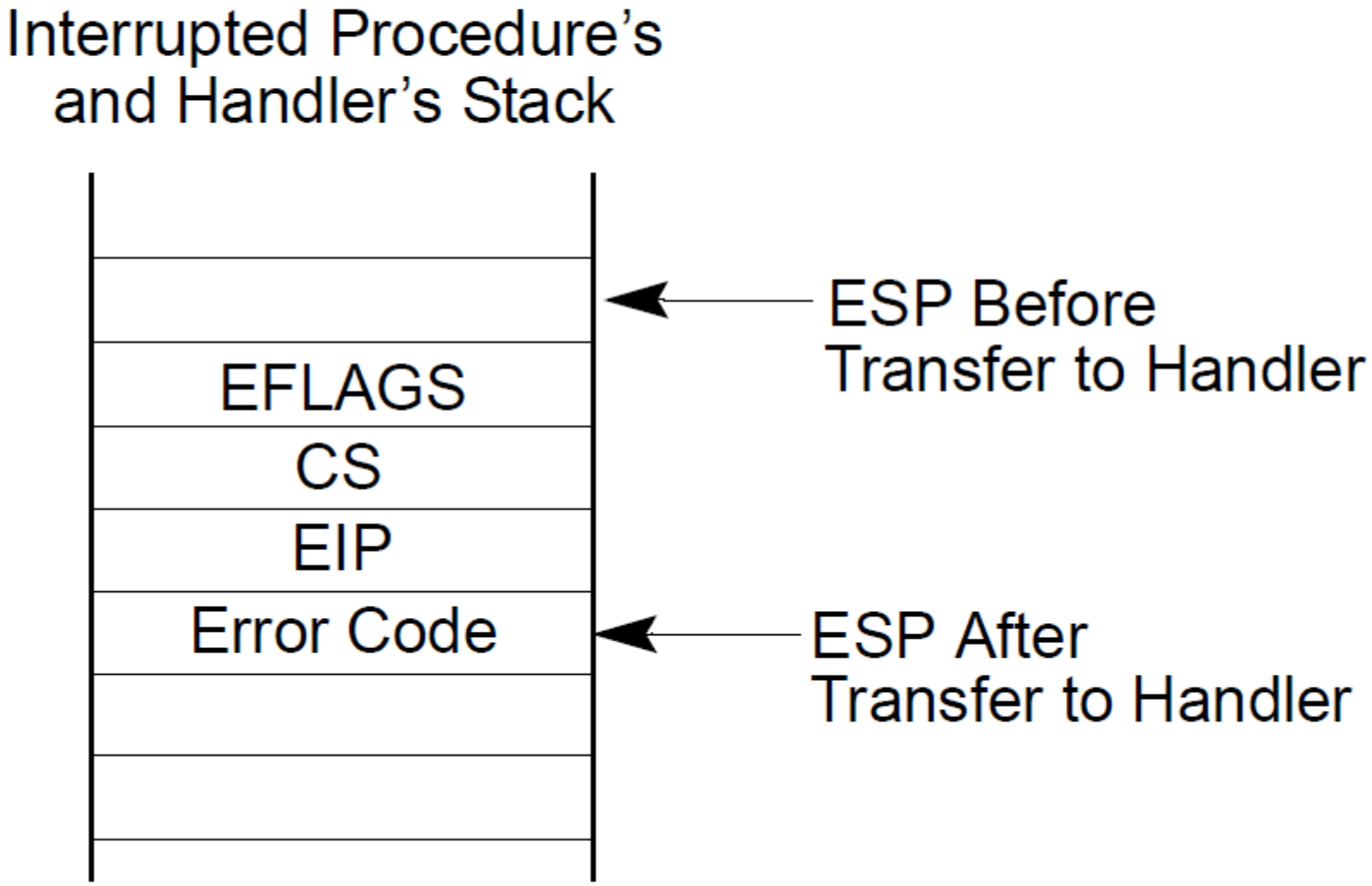




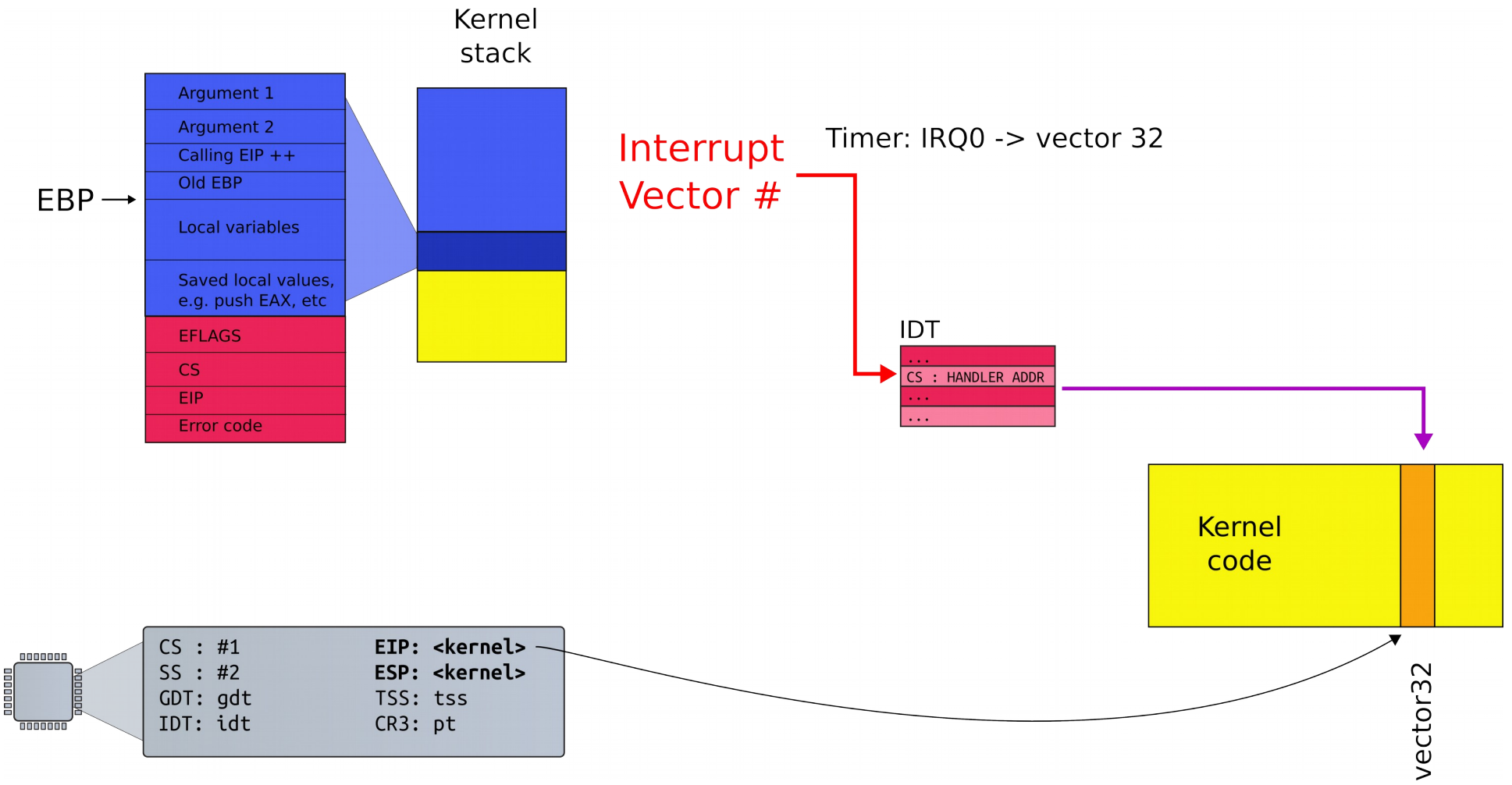
Processing of interrupt (same PL)

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



Interrupt path

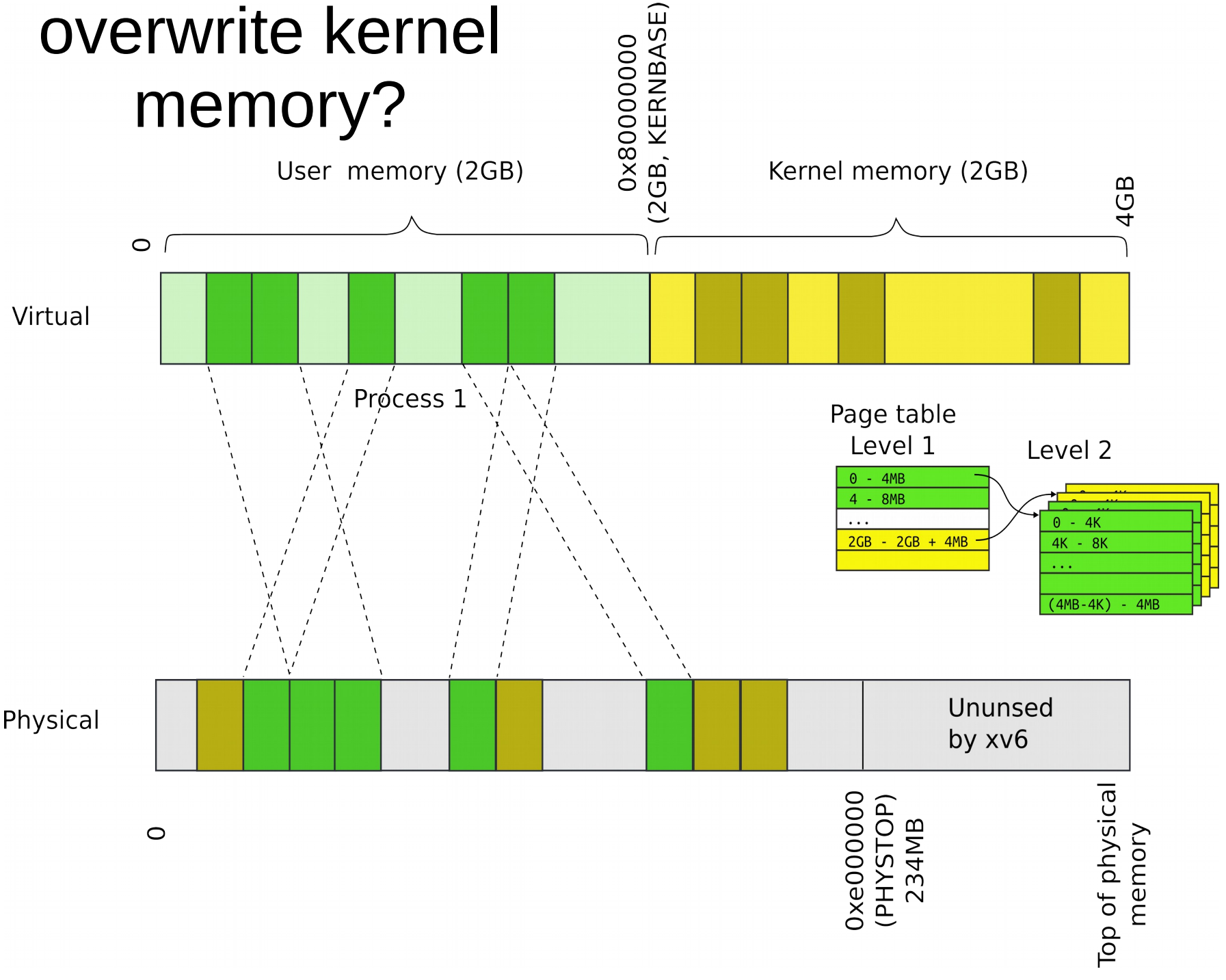


Processing of interrupt (cross PL)

- Need to change privilege level...

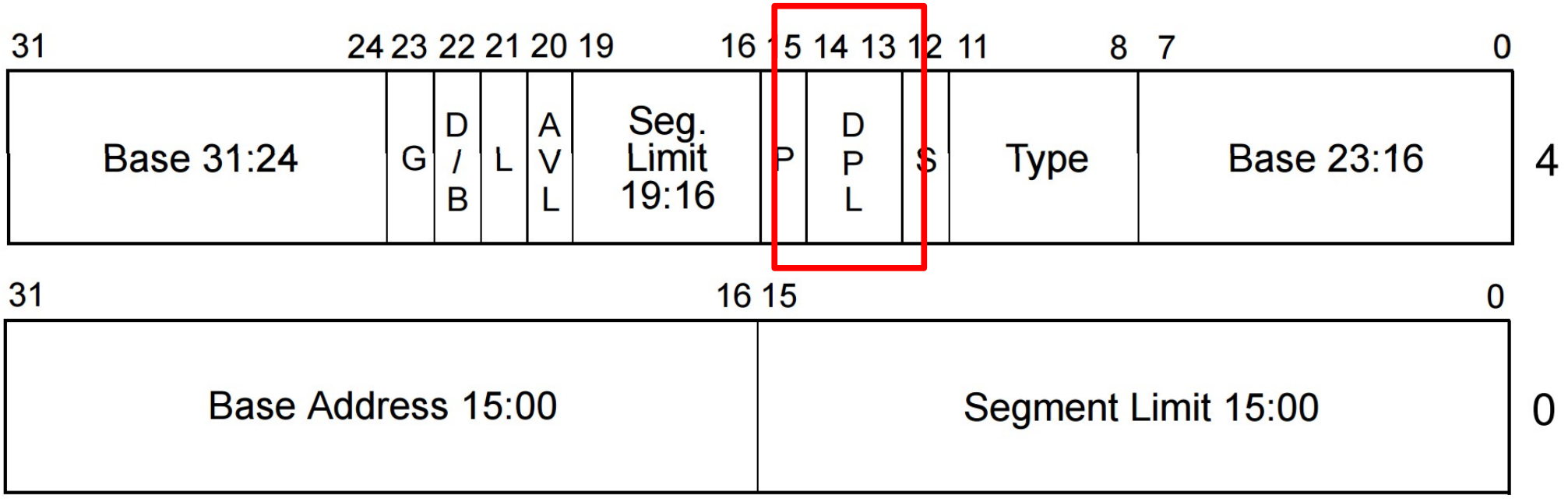
Detour:
What are those privilege levels?

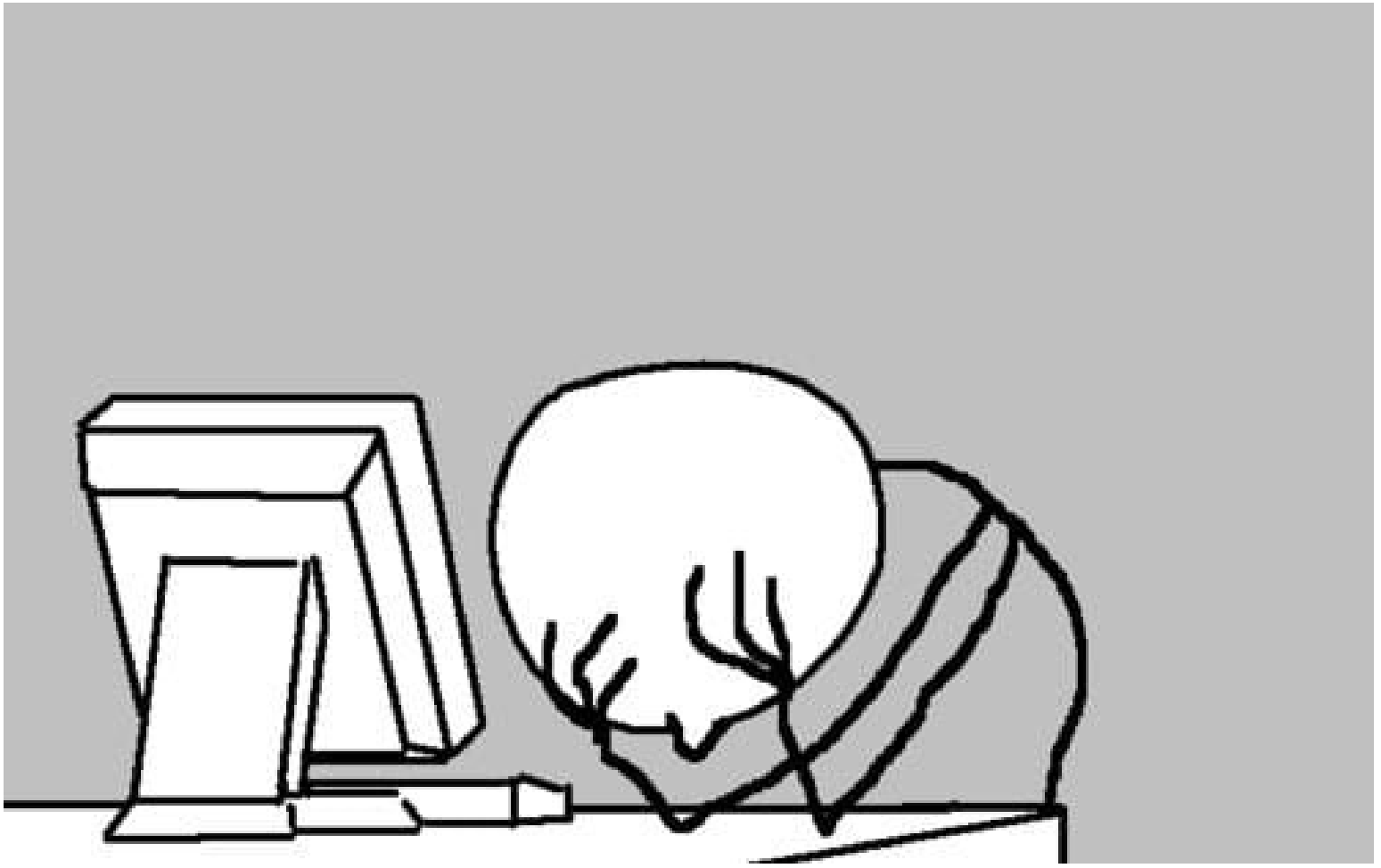
Recap: Can a process overwrite kernel memory?

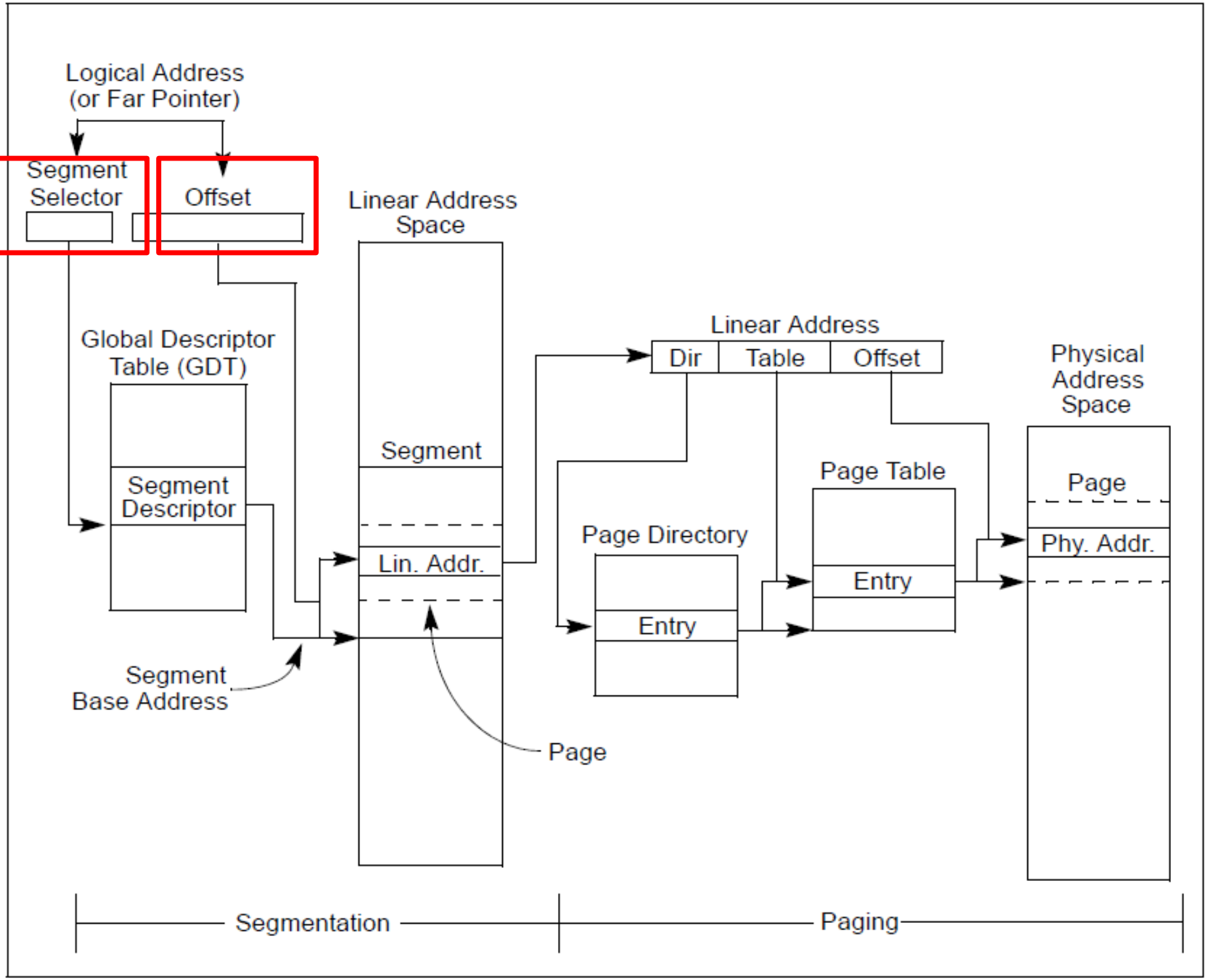


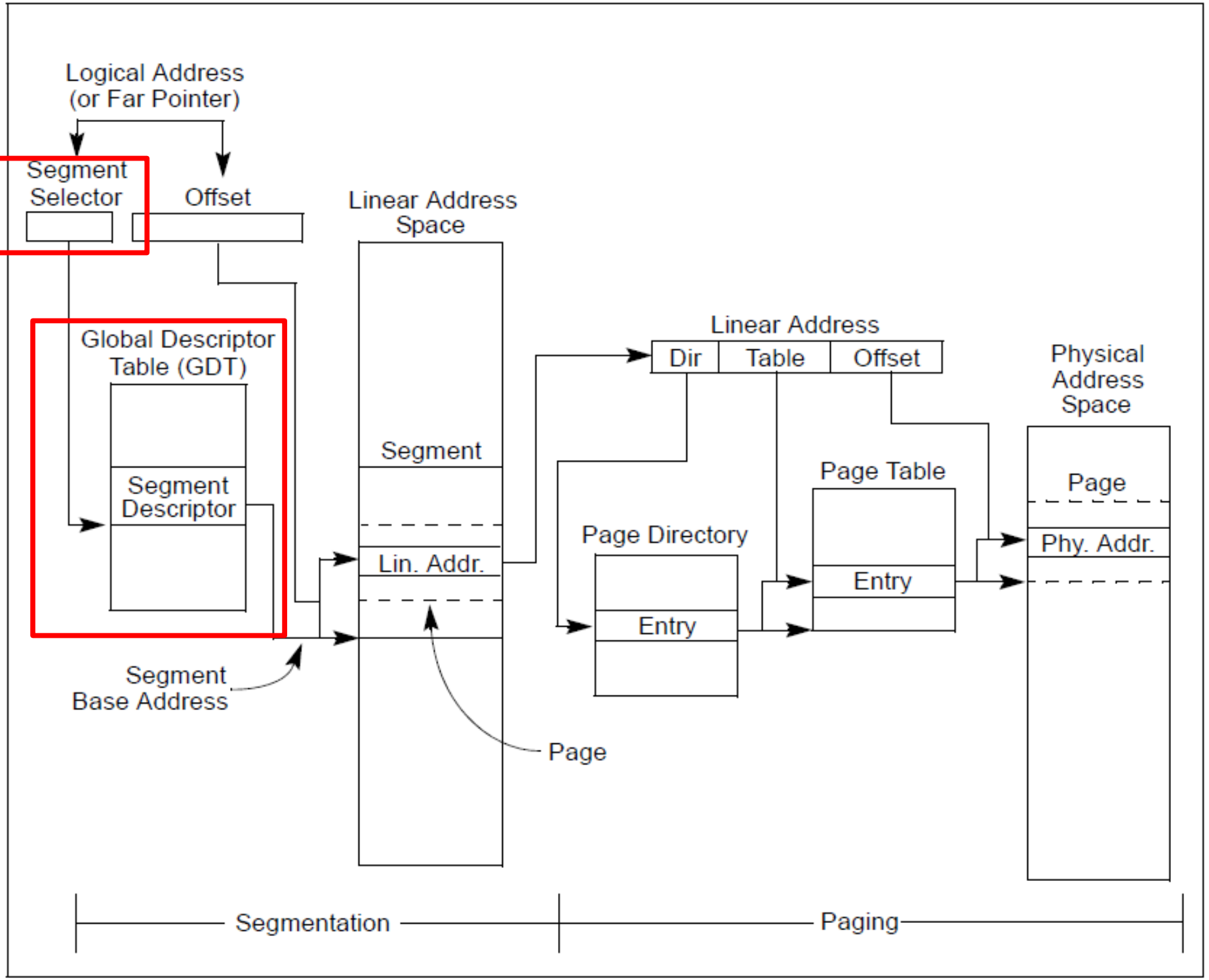
Privilege levels

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






Logical Address
(or Far Pointer)
Segment
Selector
Offset
Linear Address
Space
Global Descriptor
Table (GDT)
Segment
Descriptor
Segment
Lin. Addr.
Linear Address
Dir
Table
Offset
Physical
Address
Space
Page Table
Page
Phy. Addr.
Page Directory
Entry
Entry
Segment
Base Address
Page
Segmentation
Paging


Logical Address
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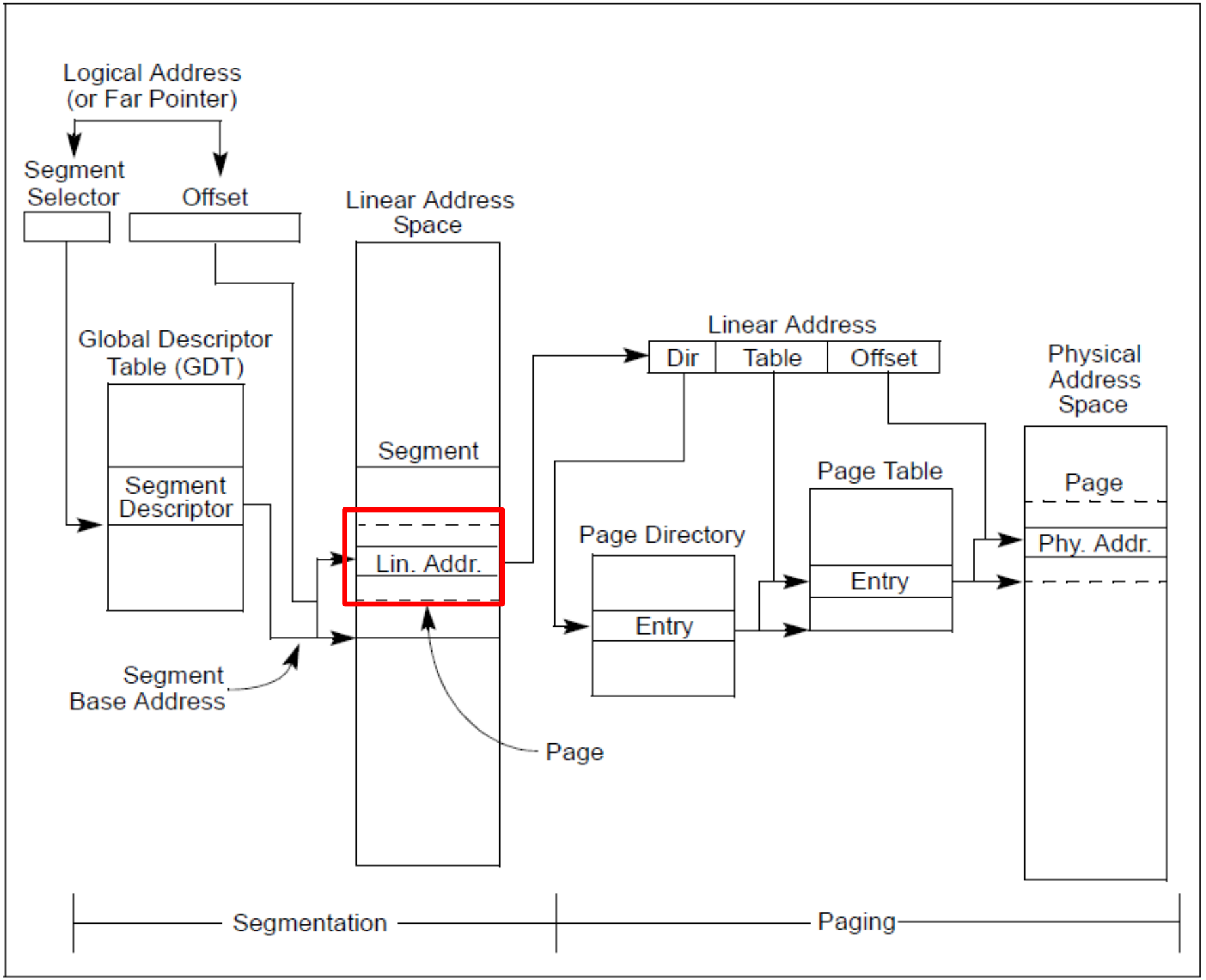
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Privilege levels

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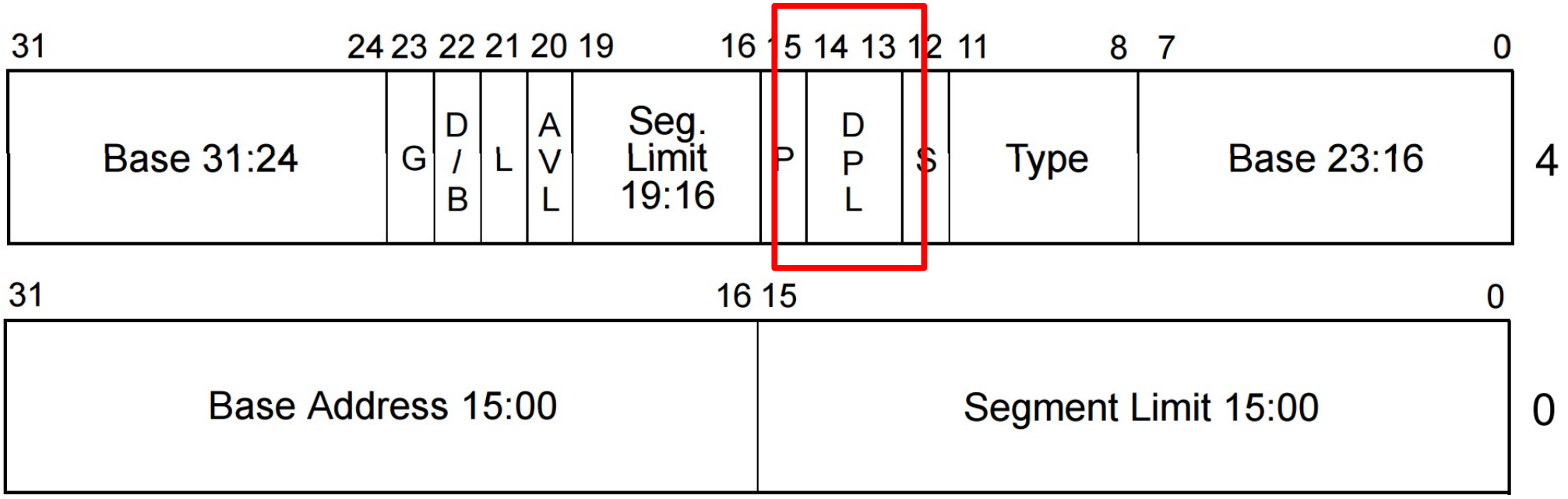


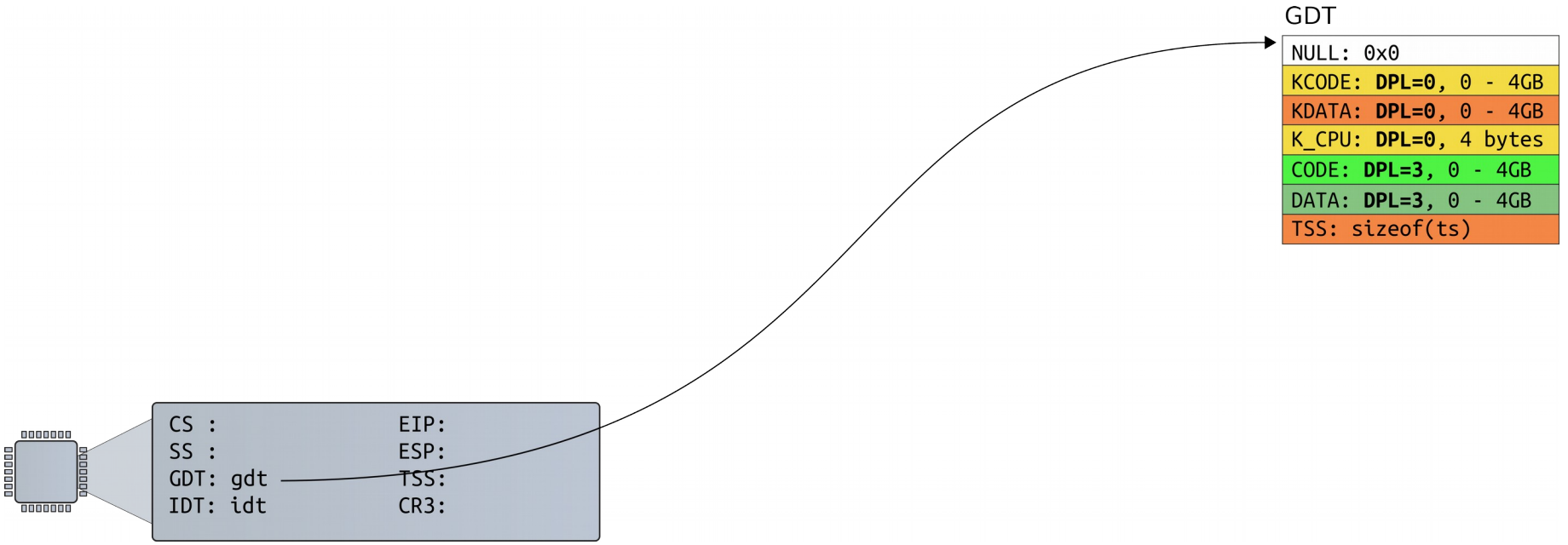
Privilege levels

- 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

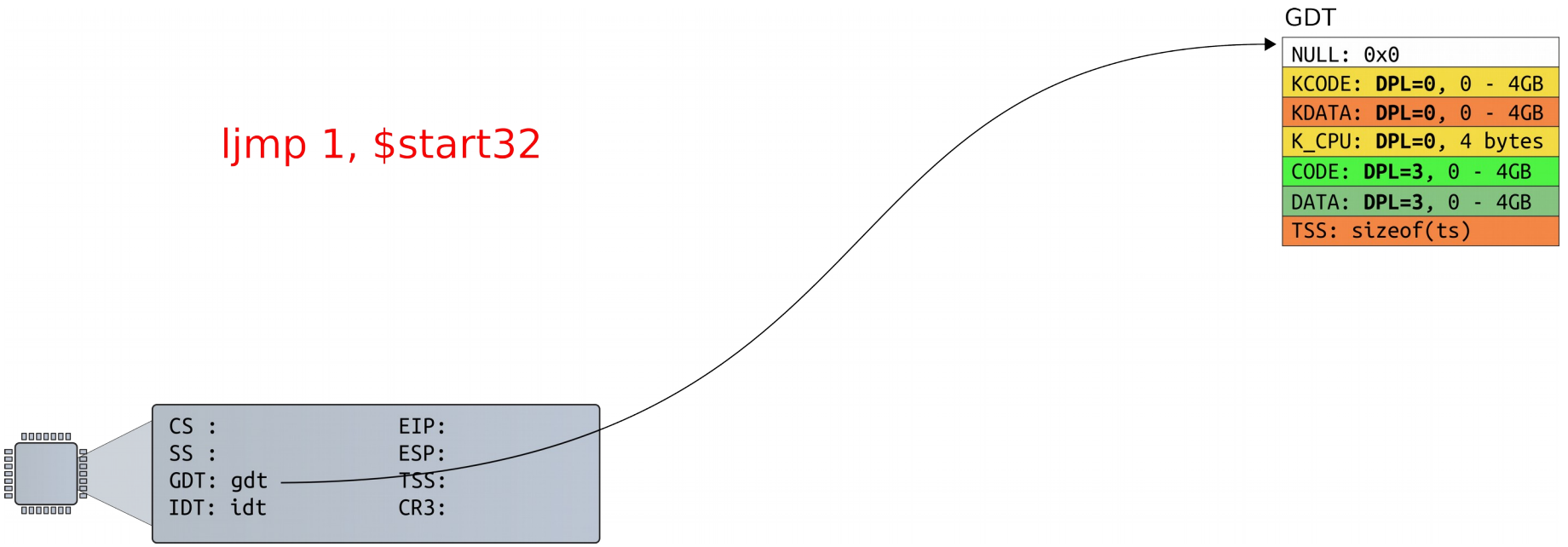
Privilege level transitions

- CPL can access only less privileged segments
  - E.g., 0 can access 1, 2, 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



Privilege levels

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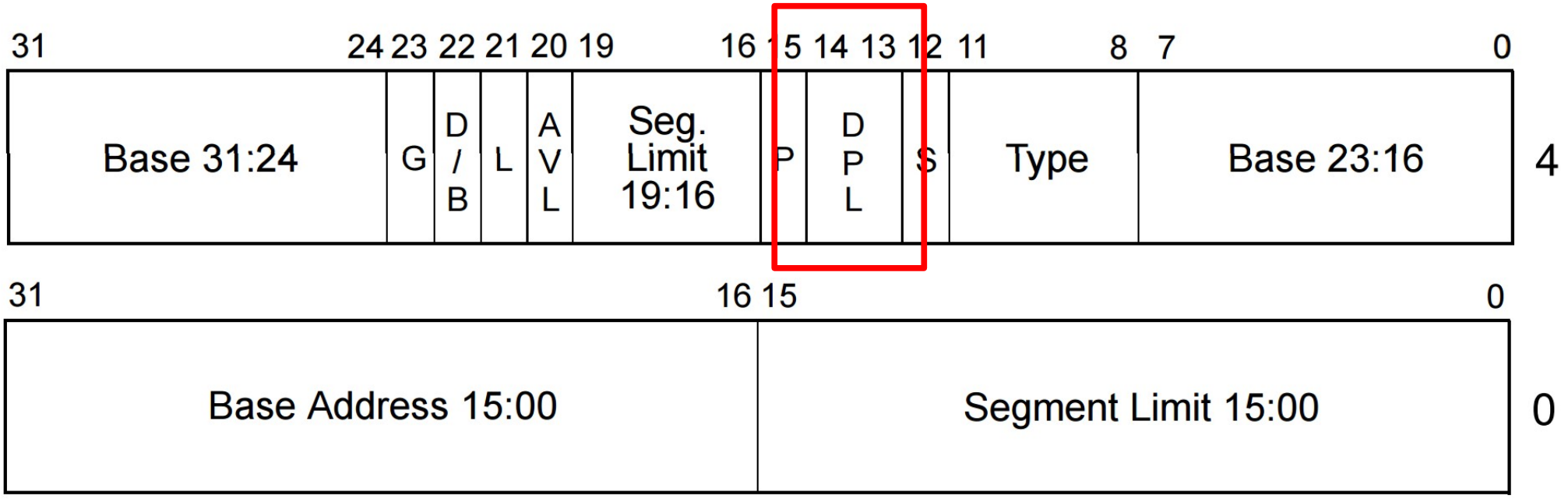
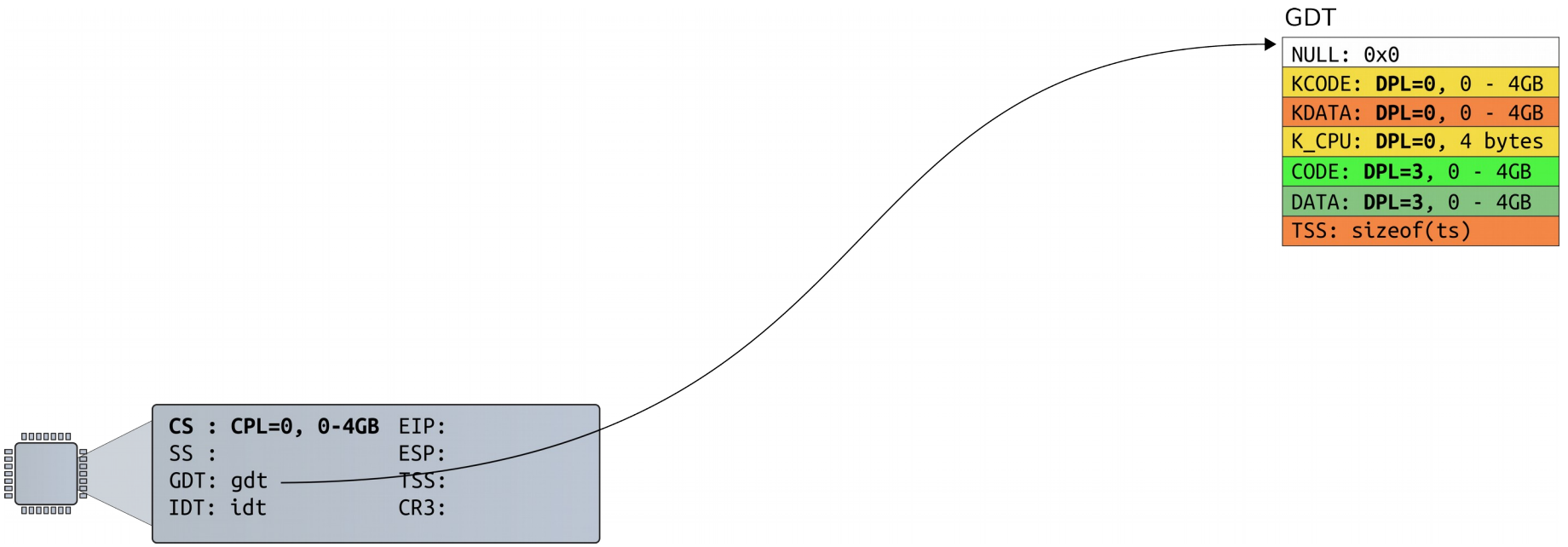


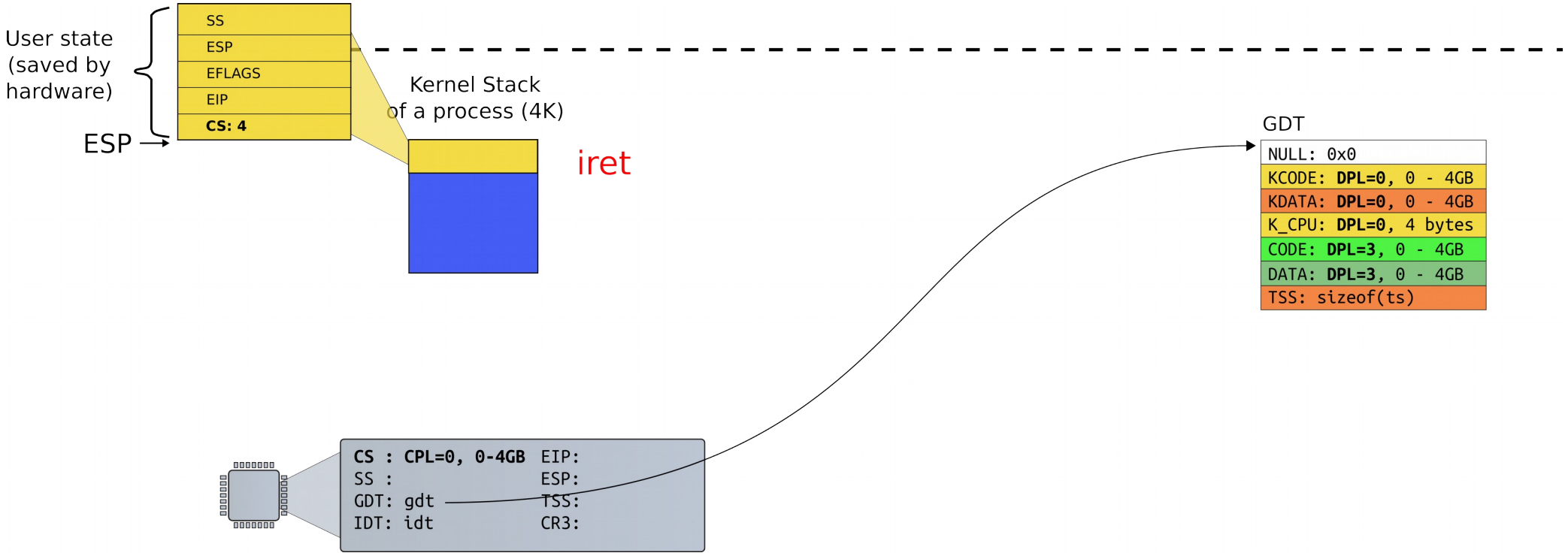
How GDT is defined

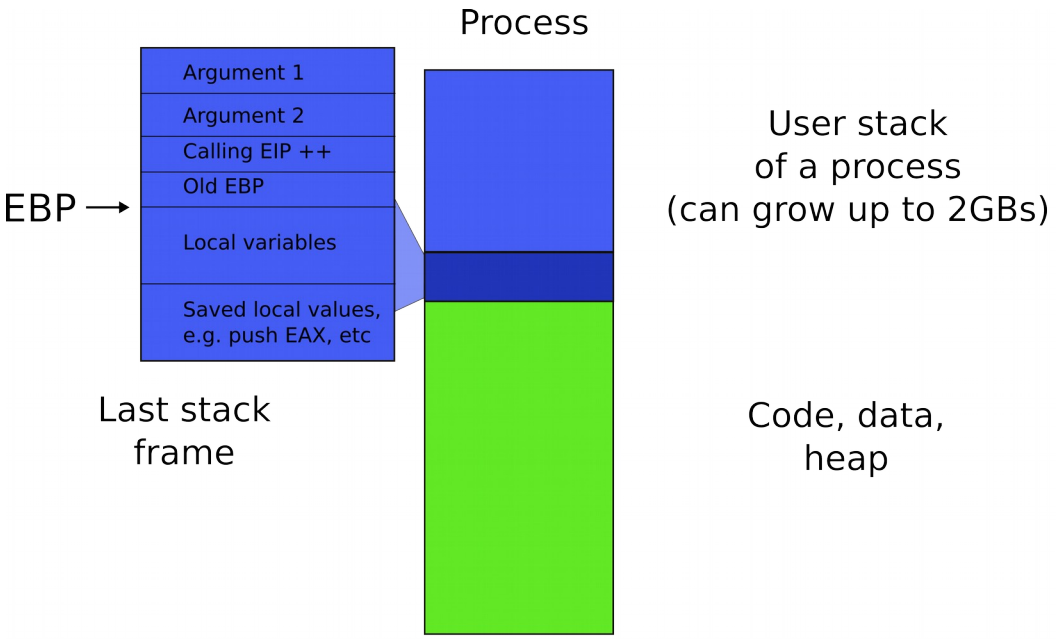
```
9180 # Bootstrap GDT
9181 .p2align 2 # force 4 byte alignment
9182 gdt:
9183   SEG_NULLASM # null seg
9184   SEG_ASM(STA_X|STA_R, 0x0, 0xffffffff) # code
seg
9185   SEG_ASM(STA_W, 0x0, 0xffffffff) # data seg
9186
9187 gdtdesc:
9188   .word (gdtdesc - gdt - 1) # sizeof(gdt) - 1
9189   .long gdt
```

Now CPL=0. We run in the kernel

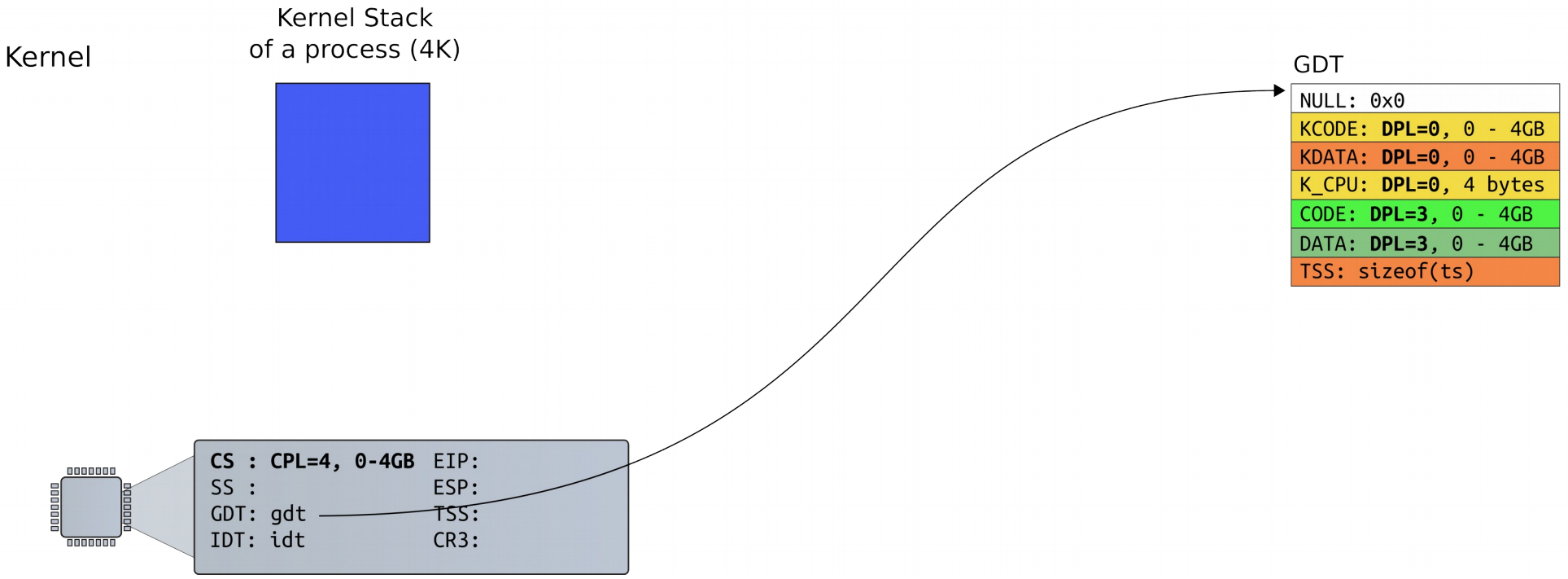


iret: return to user, load GDT #4





Run in user, CPL=3



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

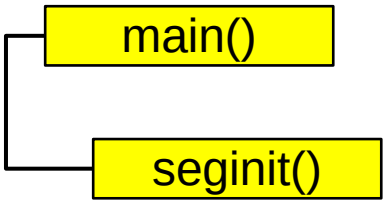
How GDT is initialized in xv6?

```
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

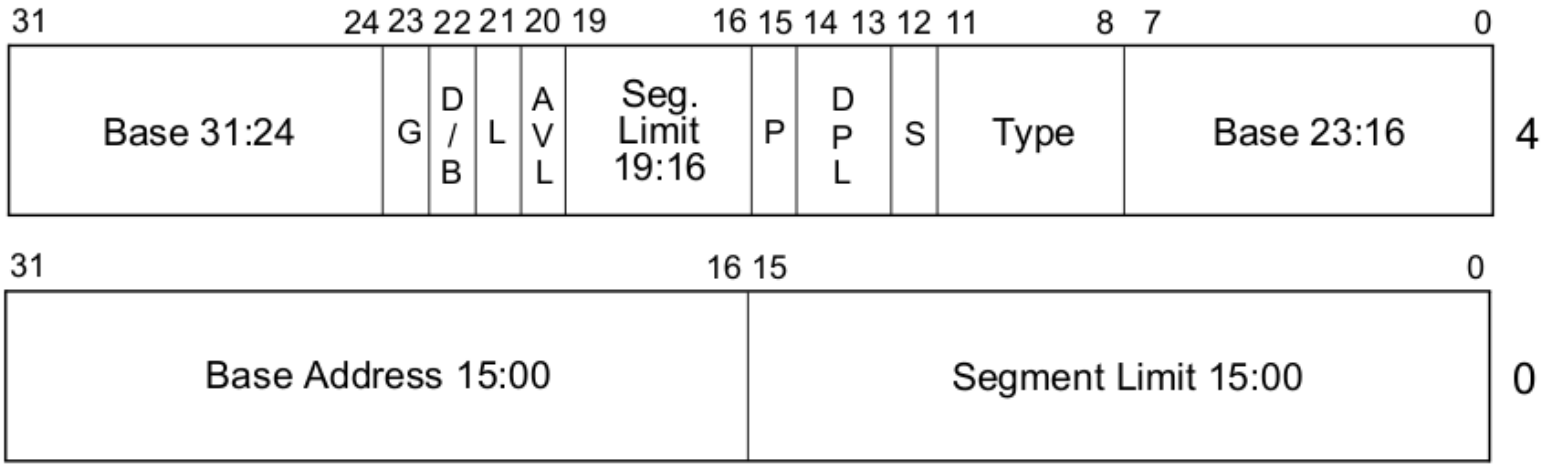
```
1712 // Set up CPU's kernel segment descriptors.
1713 // Run once on entry on each CPU.
1714 void
1715 seginit(void)
1716 {
1717   struct cpu *c;
1718
1719   // Map "logical" addresses to virtual addresses using identity map.
1720   // Cannot share a CODE descriptor for both kernel and user
1721   // 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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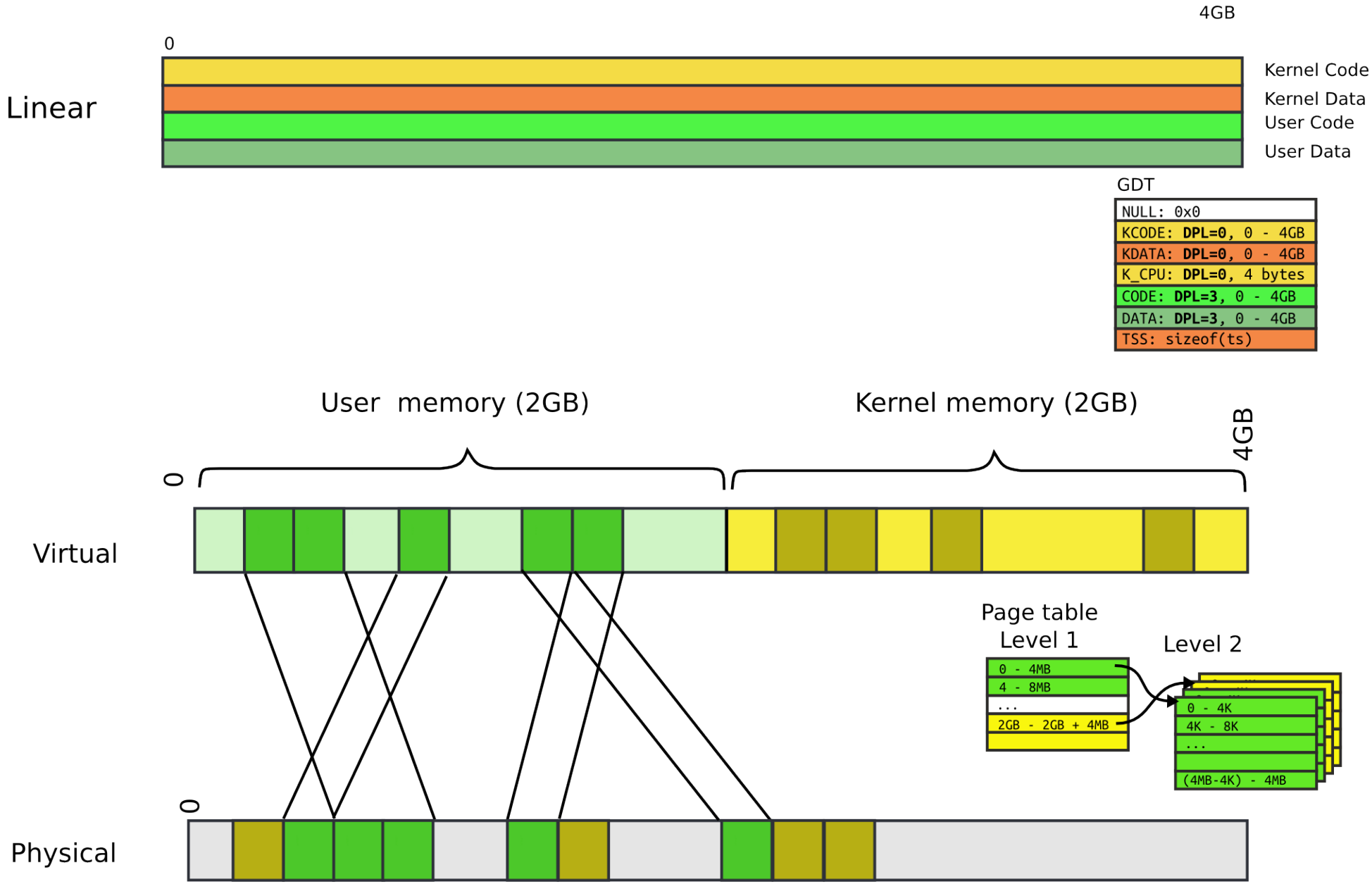
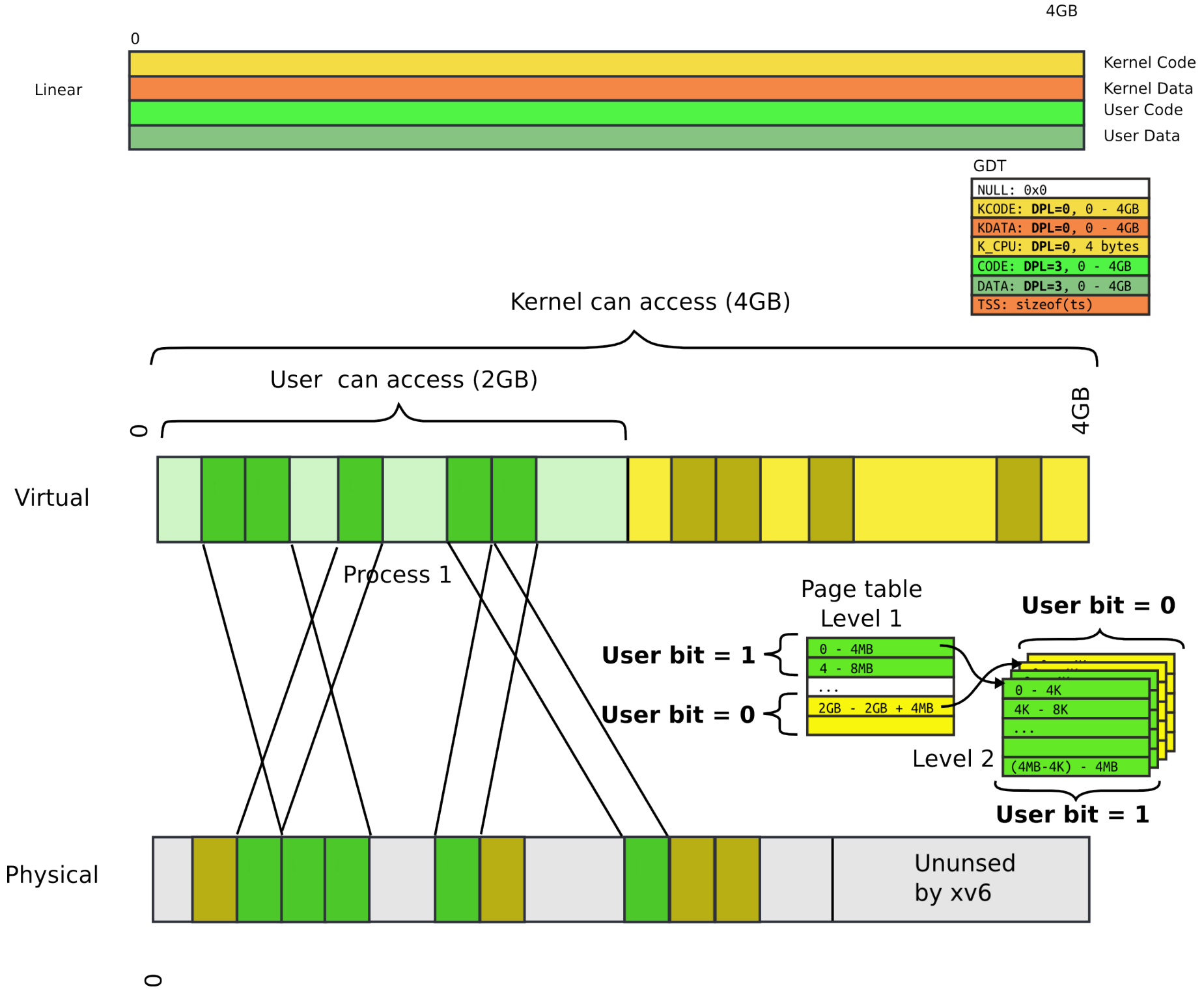
- But then... how the kernel is protected?
  - **Page tables**


4GB
0
Linear
Kernel Code
Kernel Data
User Code
User Data
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)
User memory (2GB)
Kernel memory (2GB)
4GB
0
Virtual
Page table
Level 1
Level 2
0 - 4MB
4 - 8MB
...
2GB - 2GB + 4MB
0 - 4K
4K - 8K
...
(4MB-4K) - 4MB
0
Physical

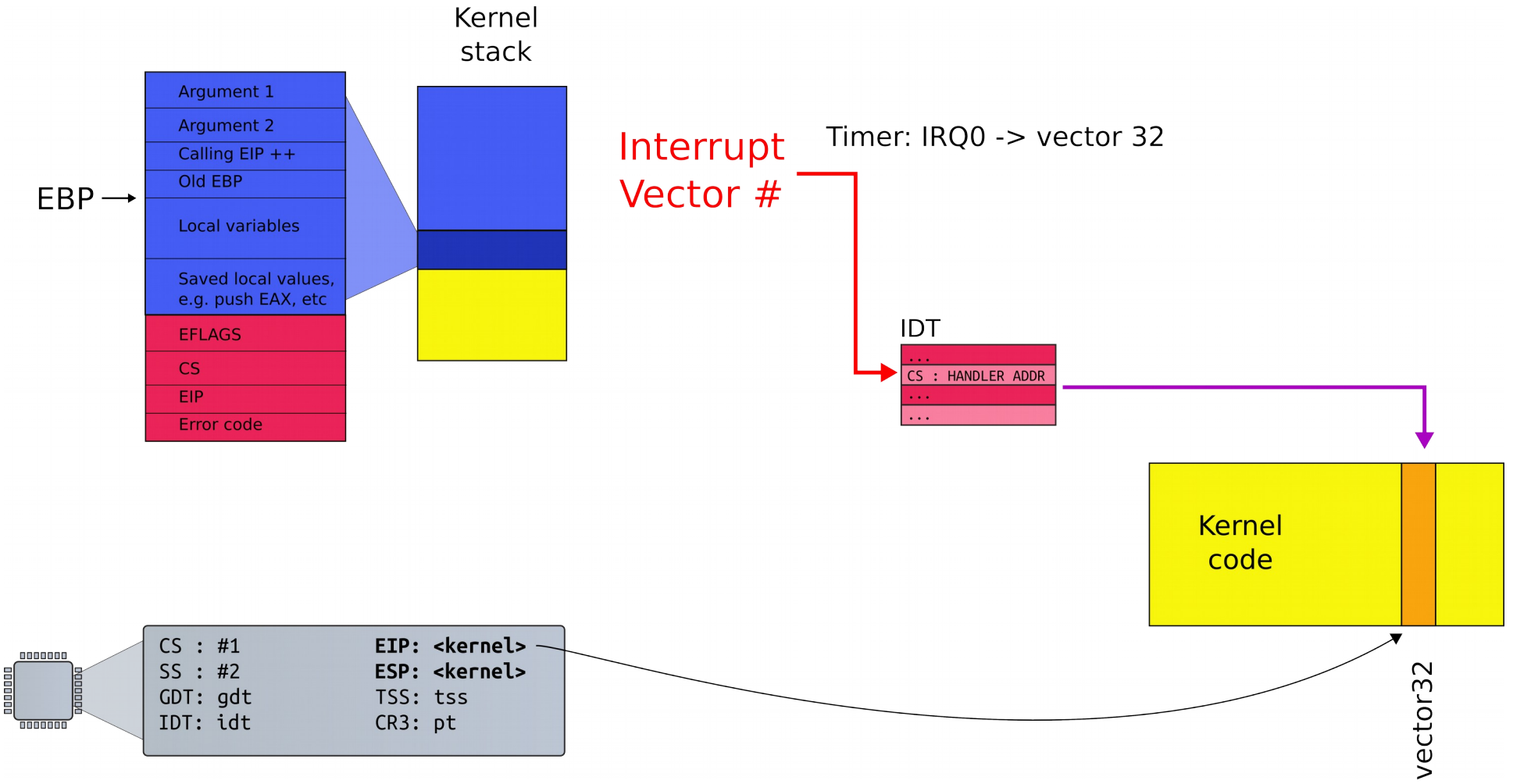
Page table: user bit

- 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


4GB
0
Linear
Kernel Code
Kernel Data
User Code
User Data
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)
Kernel can access (4GB)
User can access (2GB)
0
4GB
Virtual
Process 1
Page table
Level 1
User bit = 1
User bit = 0
0 - 4MB
4 - 8MB
...
2GB - 2GB + 4MB
User bit = 0
0 - 4K
4K - 8K
...
(4MB-4K) - 4MB
Level 2
User bit = 1
Physical
Ununsed
by xv6
0

End of detour:
Back to handling interrupts

Recap: interrupt path, no PL change

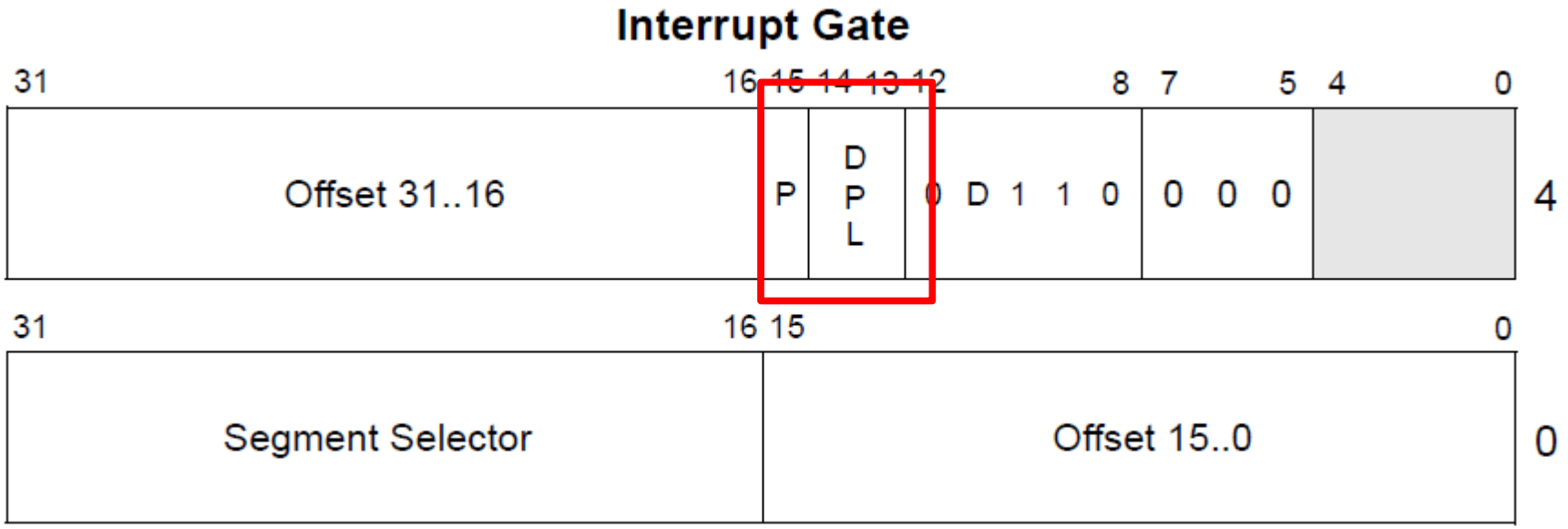


Processing of an interrupt when change of a privilege level is required

Processing of interrupt (cross PL)

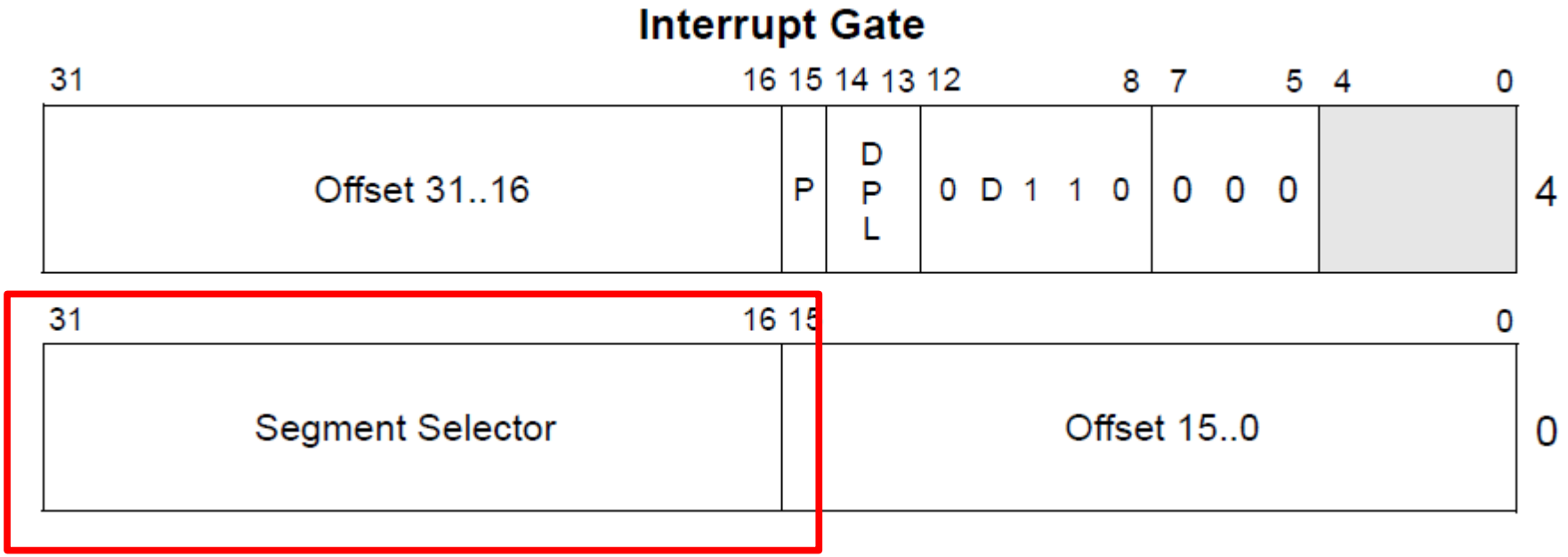
- Assume we're at CPL =3 (user)

Interrupt descriptor (an entry in the IDT)



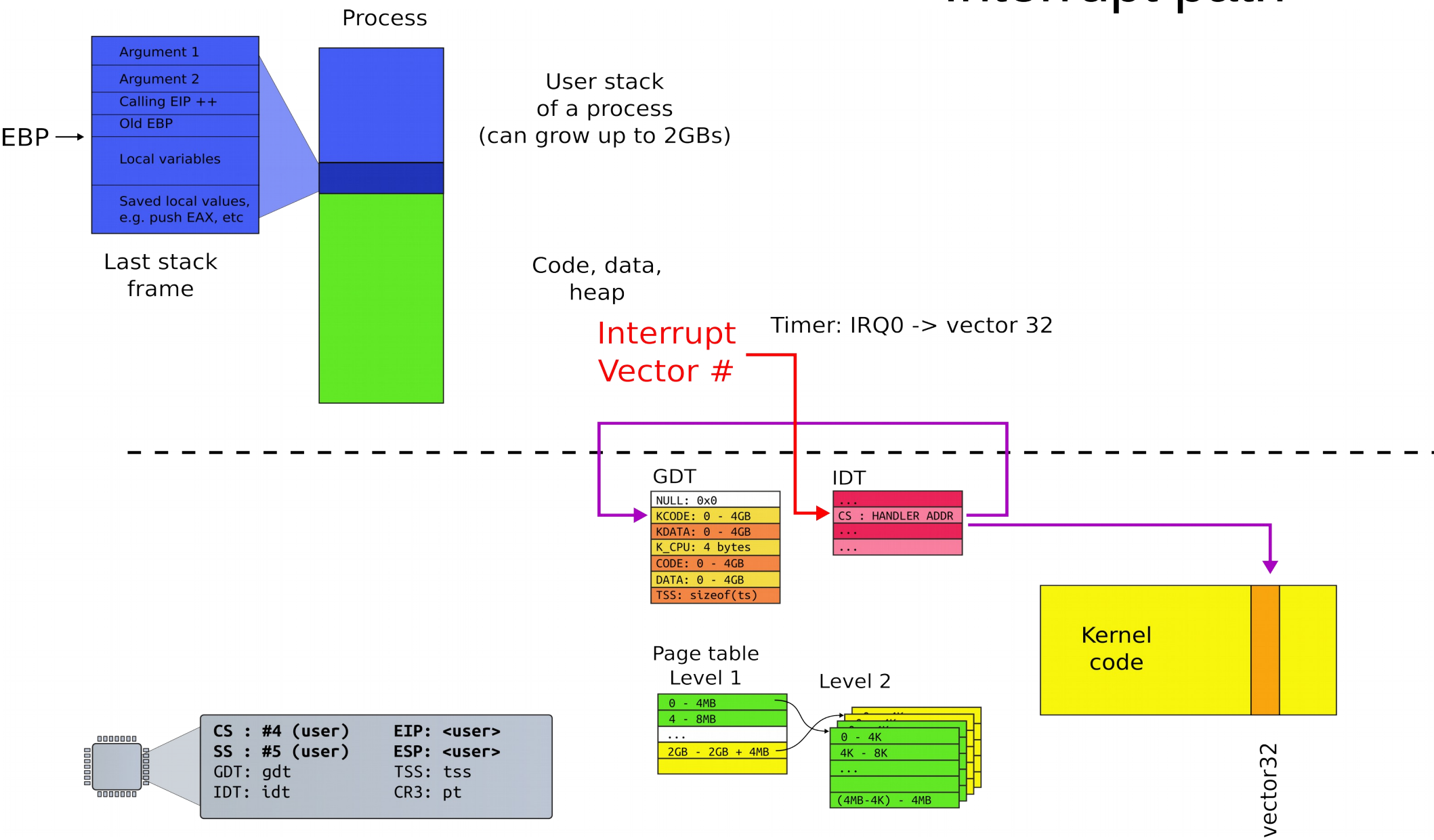
- Interrupt is allowed if...
  - current privilege level (CPL) is less or equal to descriptor privilege level (DPL)
- The kernel protects device interrupts from user

Interrupt descriptor (an entry in the IDT)



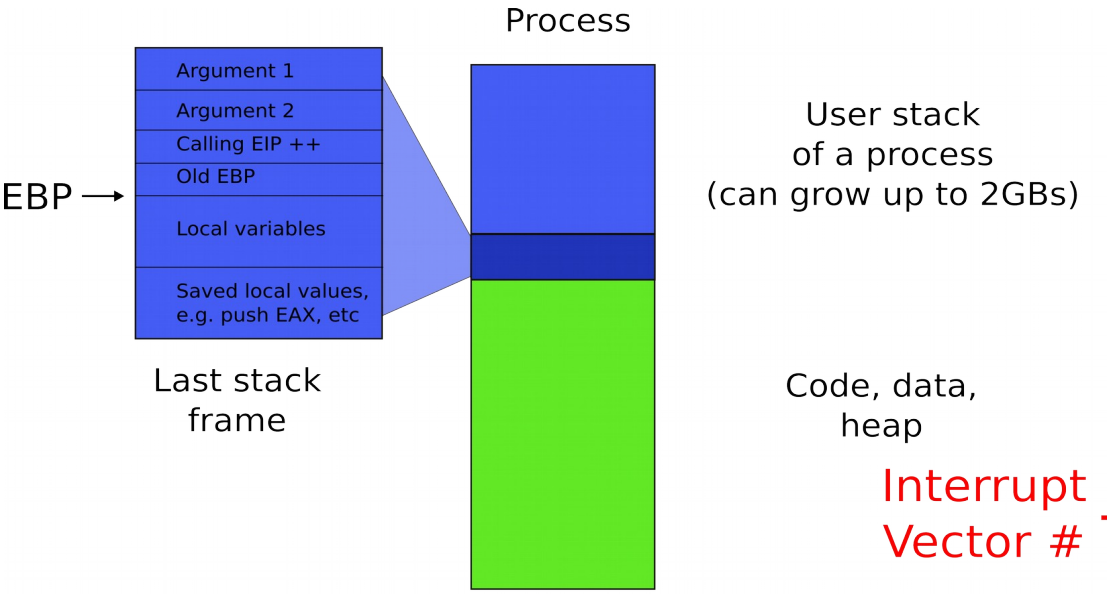
- Note that this new segment can be more privileged
  - E.g., CPL = 3, DPL = 3, new segment can be PL = 0
  - This is how user-code (PL=3) transitions into kernel (PL=0)

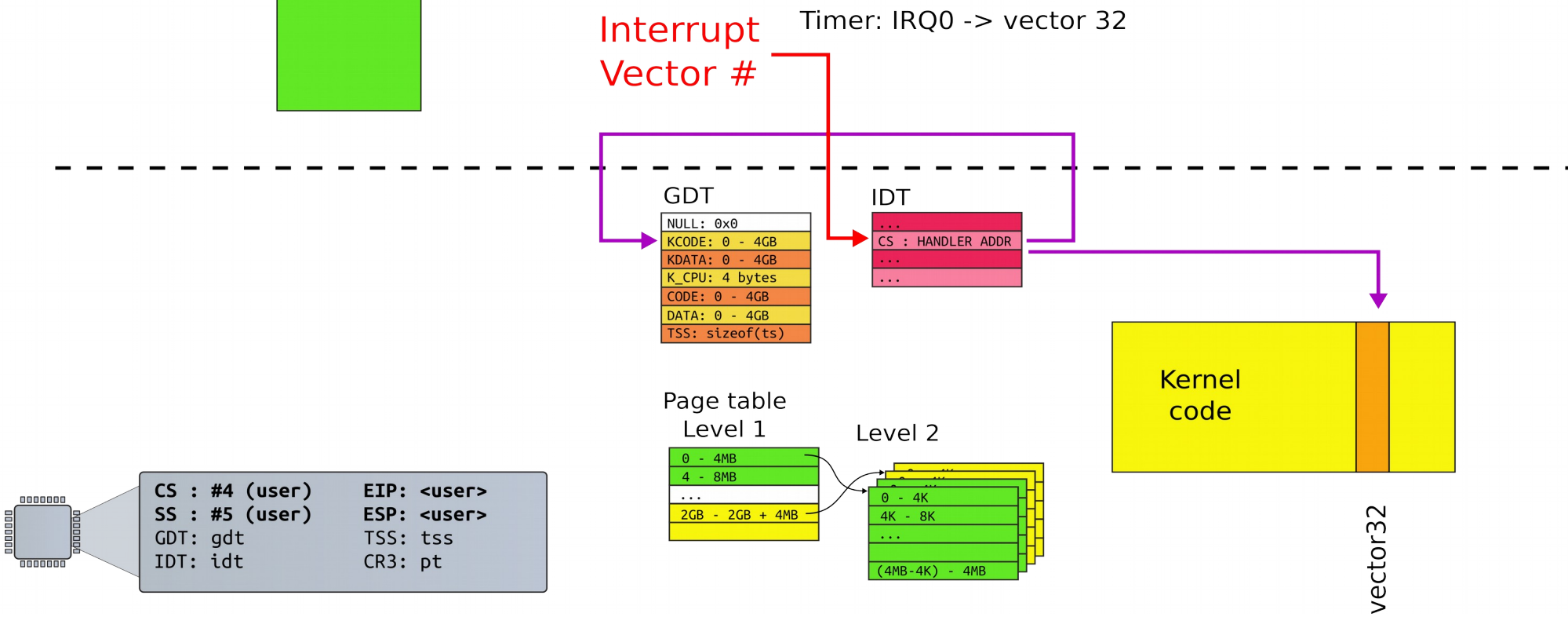
Interrupt path



Stack

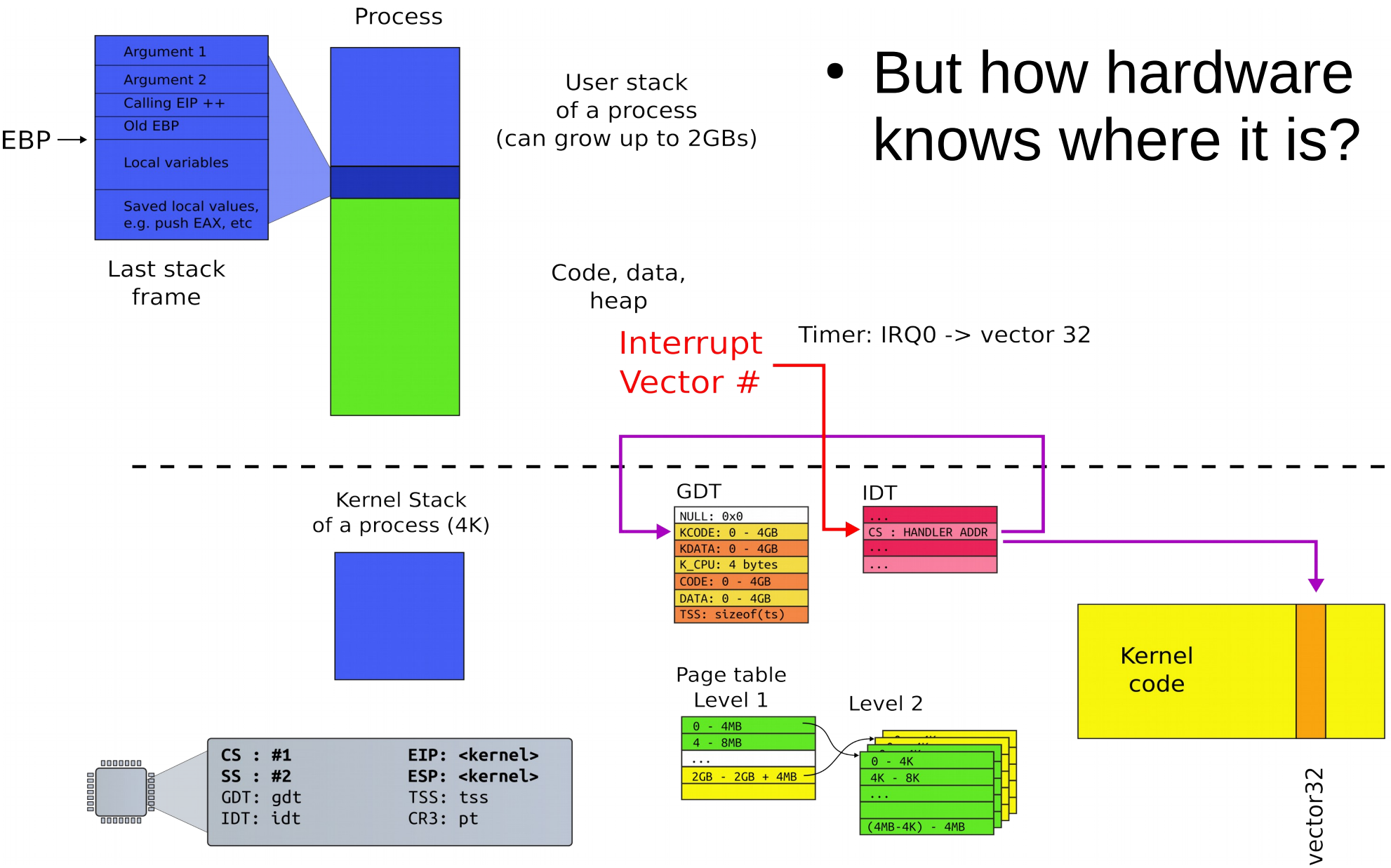
- Can we continue on the same stack?



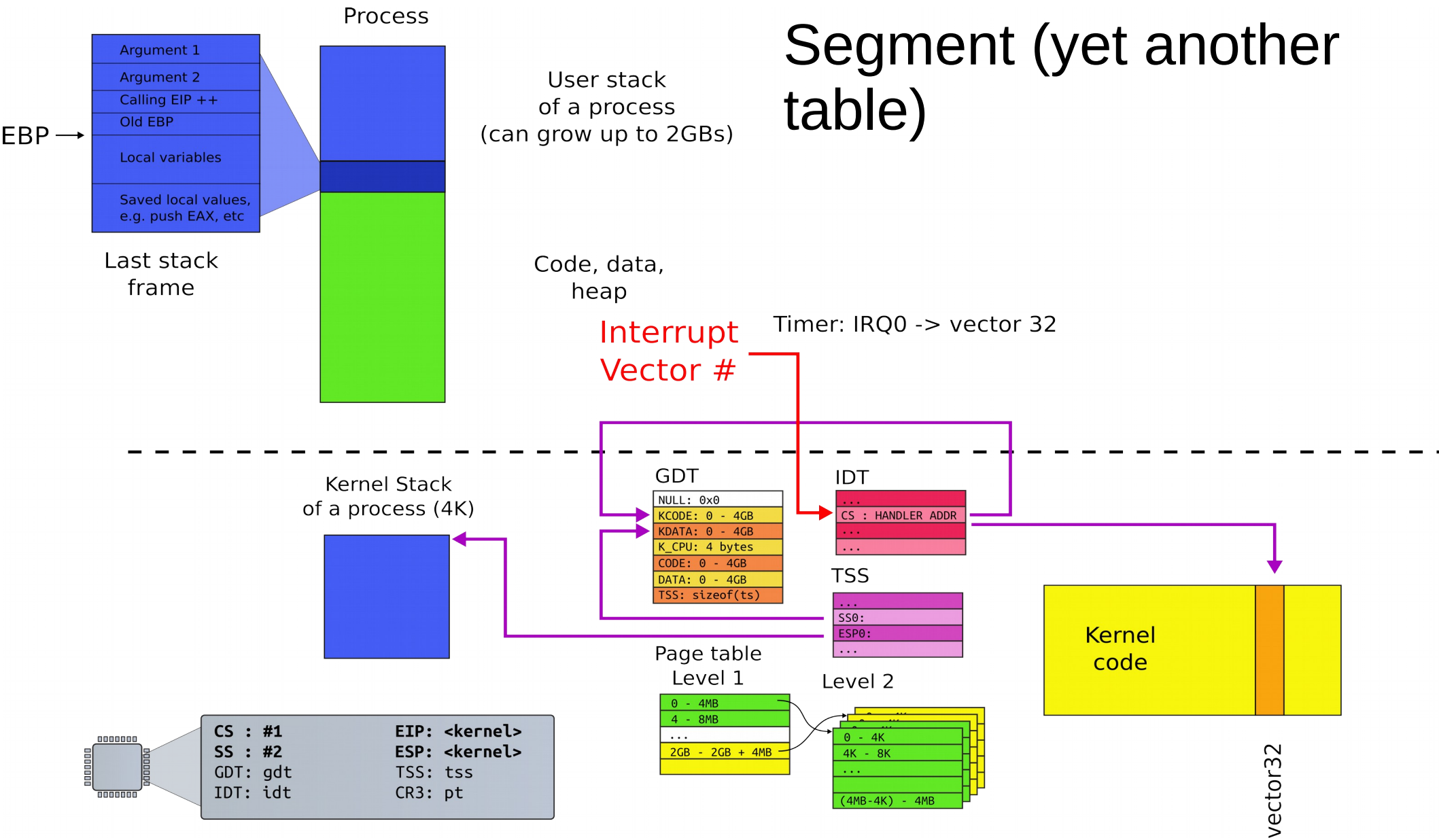


Stack

- But how hardware knows where it is?



TSS: Task State Segment (yet another table)

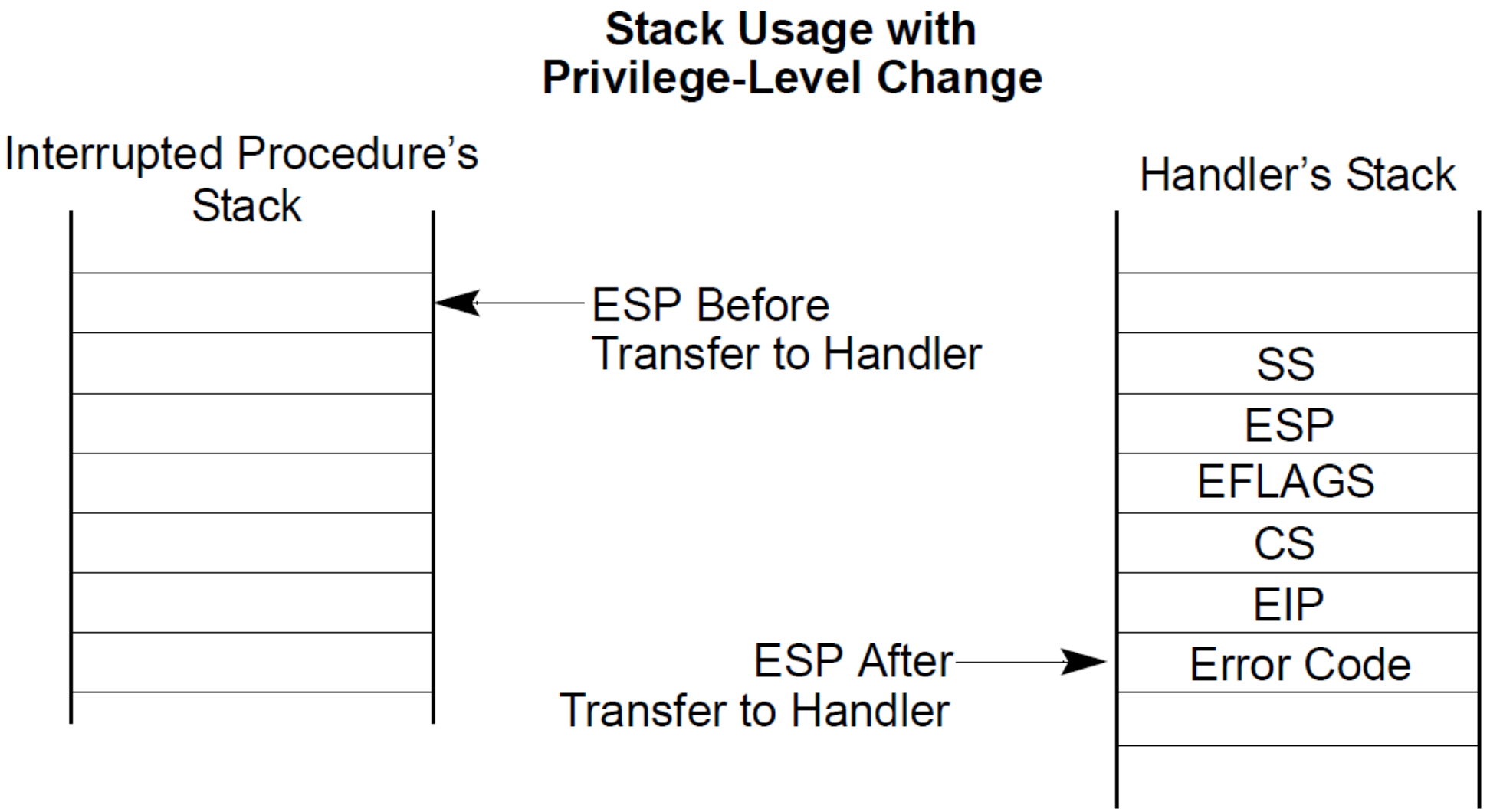


Task State Segment

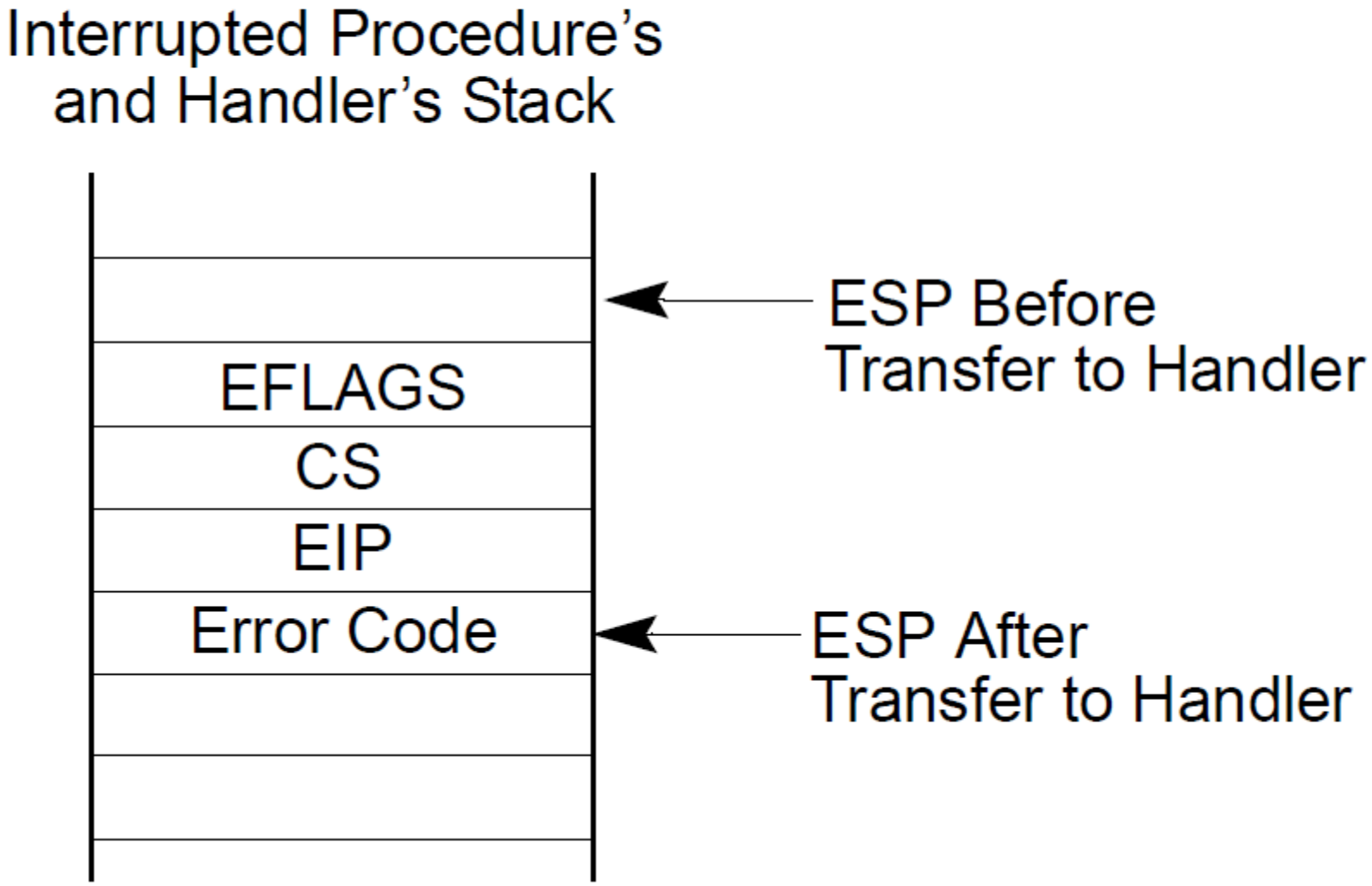
- Another magic control block
  - Pointed to by special task register (TR)
- Lots of fields for rarely-used features
- A feature we care about in a modern OS:
  - Location of kernel stack (fields SS/ESP)
    - Stack segment selector
    - Location of the stack in that segment

Processing of interrupt (cross PL)

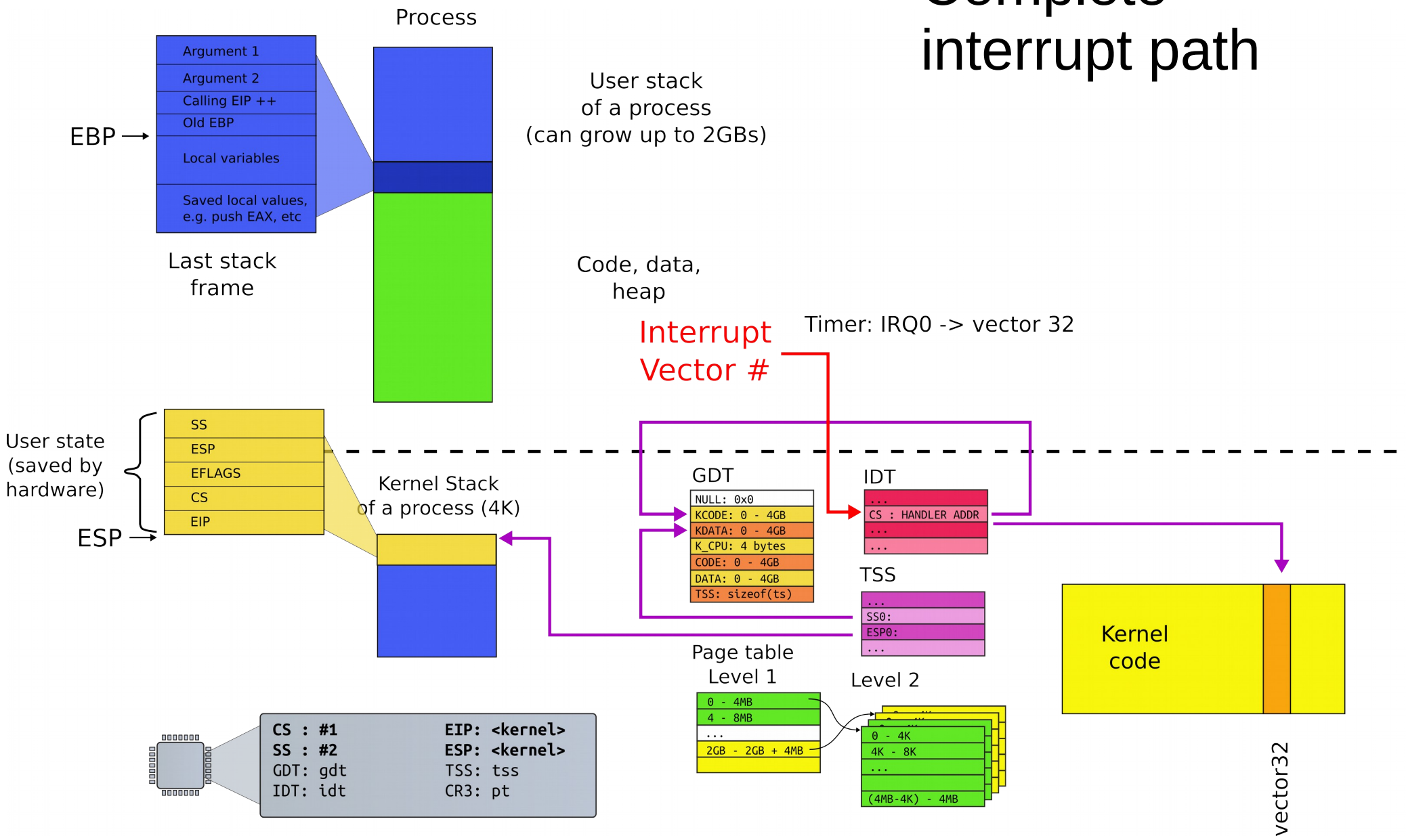
1. Save ESP and SS in a CPU-internal register
2. **Load SS and ESP from TSS**
3. Push user SS, user ESP, user EFLAGS, user CS, user EIP onto new stack (kernel stack)
4. Set CS and EIP from IDT descriptor's segment selector and offset
5. If the call is through an interrupt gate clear interrupts enabled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


Stack Usage with
Privilege-Level Change
Interrupted Procedure's
Stack
Handler's Stack
ESP Before
Transfer to Handler
SS
ESP
EFLAGS
CS
EIP
ESP After
Transfer to Handler
Error Code

Stack Usage with No Privilege-Level Change

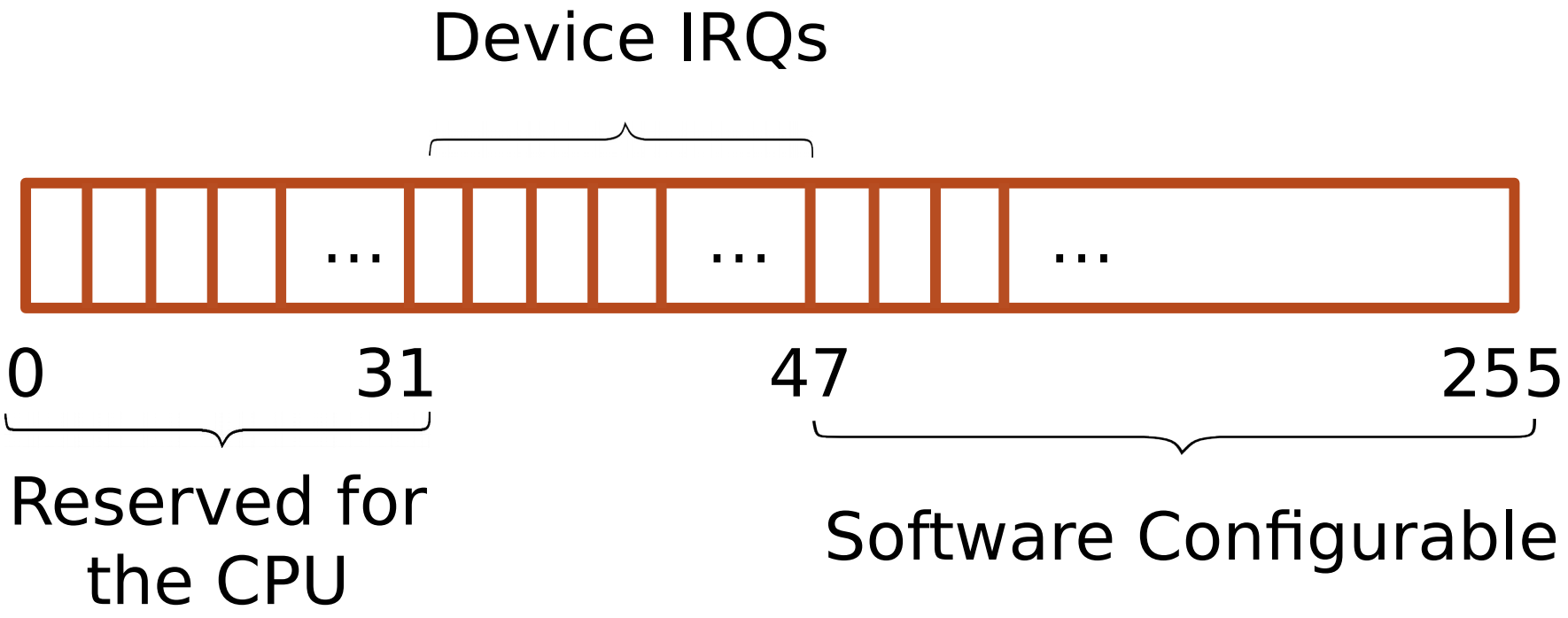


Complete interrupt path



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 *n* instruction.

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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.
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20-31		Reserved	
32-255		Maskable Interrupts	External interrupt from INTR pin or INT *n* instruction.

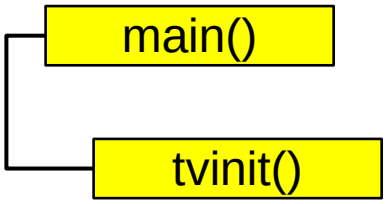
Nonmaskable interrupts (NMI)

- 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

Initialize IDT

- tvinit() is called from main()

```
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 }
```



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);
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                vectors[T_SYSCALL], DPL_USER);
3324
3325   initlock(&tickslock, "time");
3326 }
```
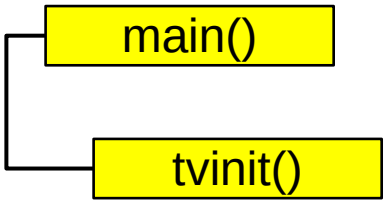
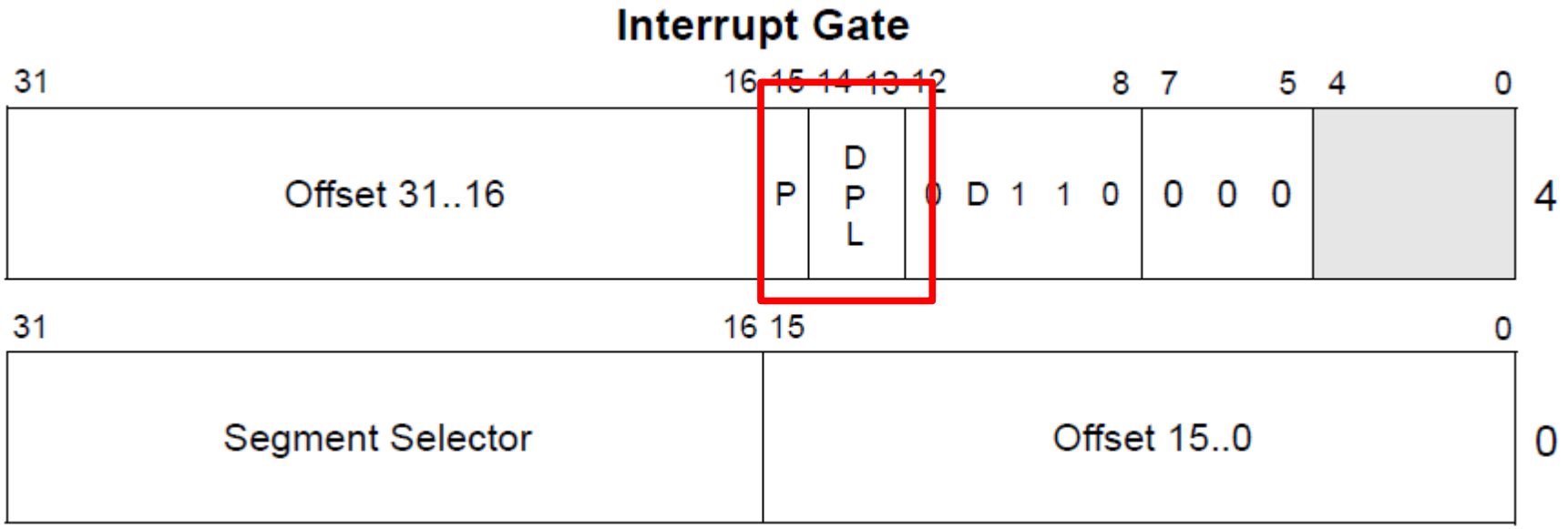



Protection

- 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,
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3324
3325   initlock(&tickslock, "time");
3326 }
```

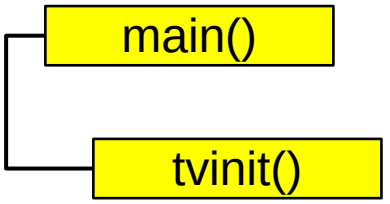

Initialize IDT

- 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);
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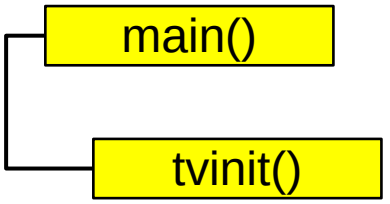

Initialize IDT

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

```
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);
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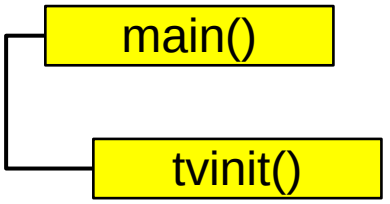
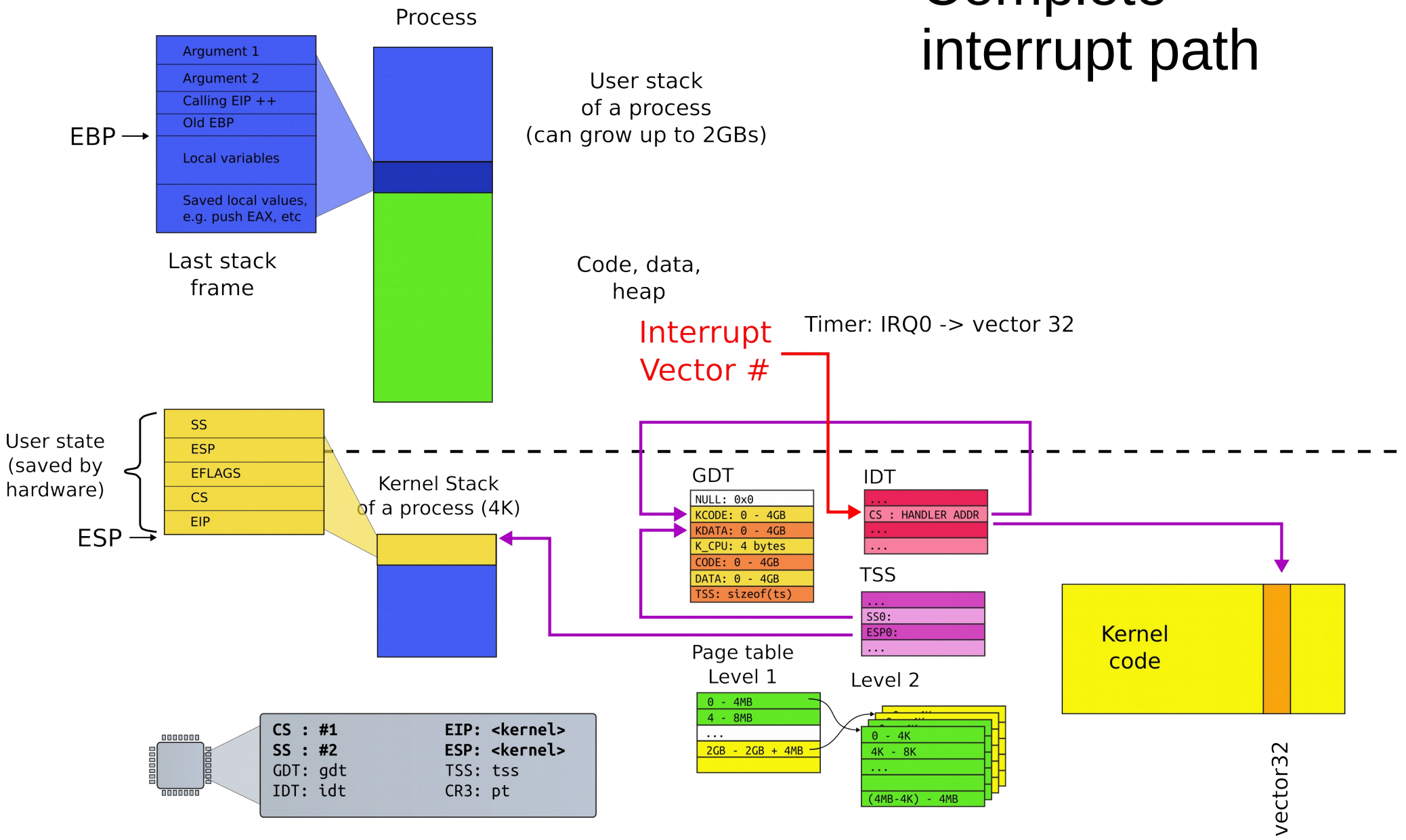
```



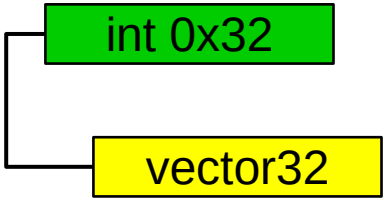
Interrupt path through the xv6 kernel

Complete interrupt path



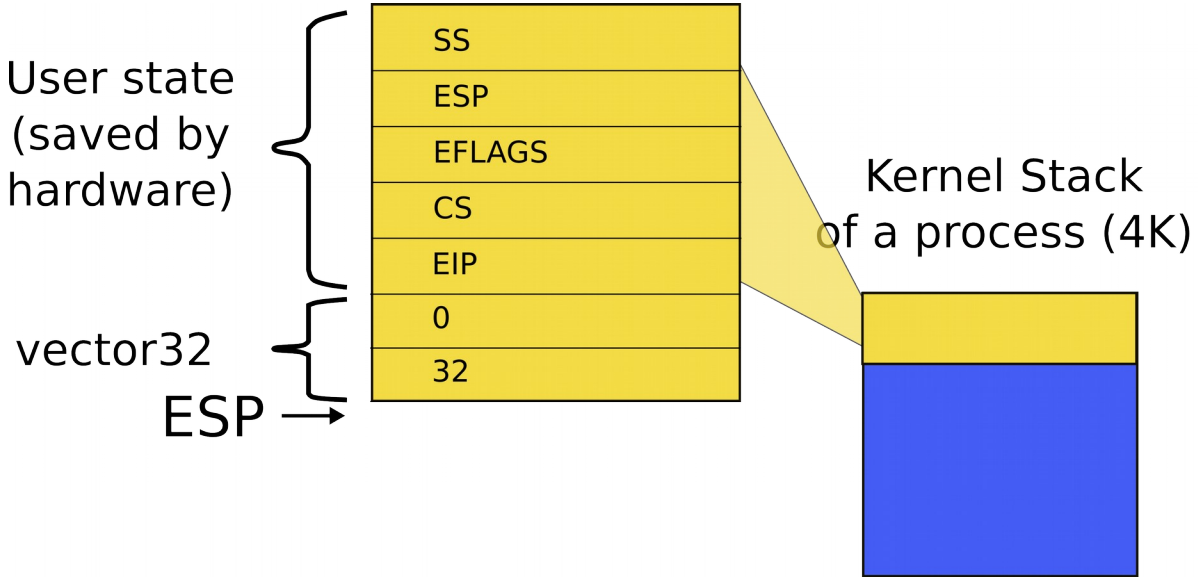
Timer Interrupt (int 0x32)

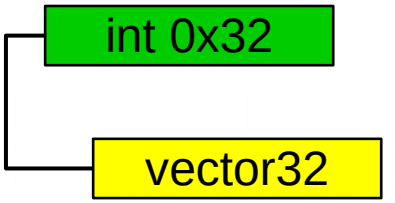
```
vector32:
  pushl $0    // error code
  pushl $32   // vector #
  jmp alltraps
```



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

Kernel stack after interrupt

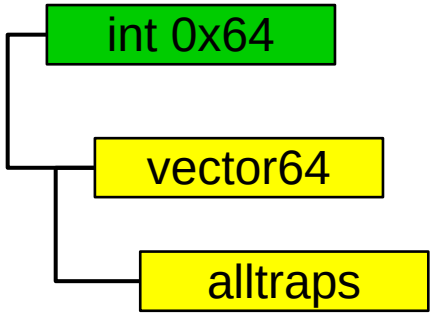




Call stack: vector32()

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
```

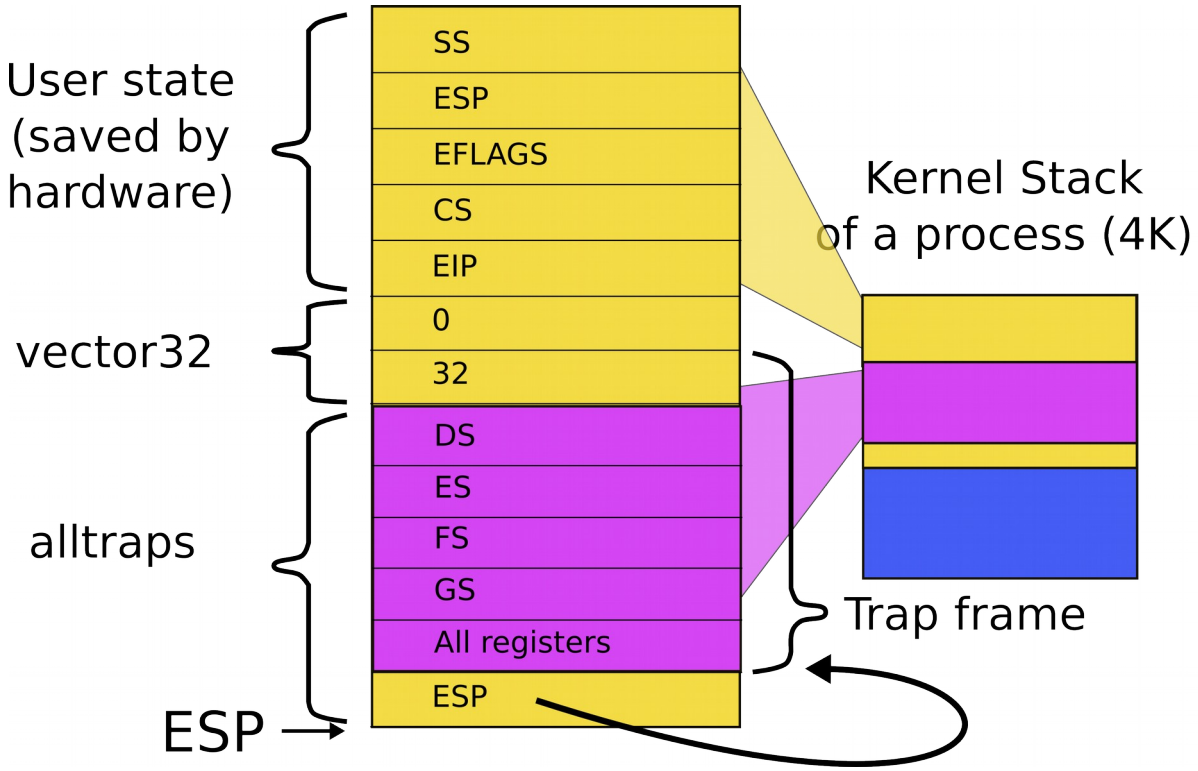


pusha

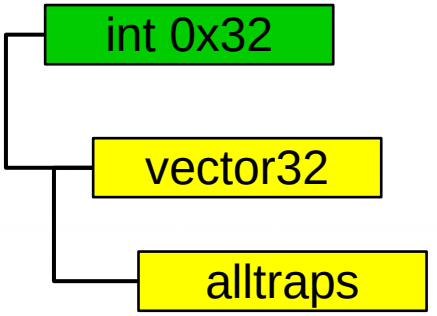
- An assembler instruction that saves all registers on the stack
  - https://c9x.me/x86/html/file_module_x86_id_270.html

```
Temporary = ESP;
Push(EAX);
Push(ECX);
Push(EDX);
Push(EBX);
Push(Temporary);
Push(EBP);
Push(ESI);
Push(EDI);
```

Kernel stack after interrupt

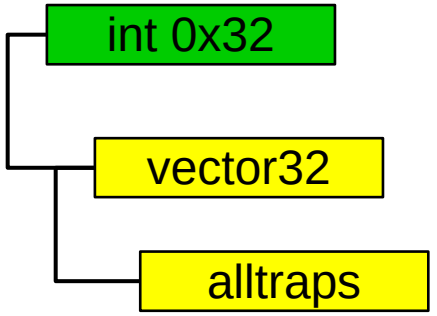


Call stack: vector32()
alltraps()



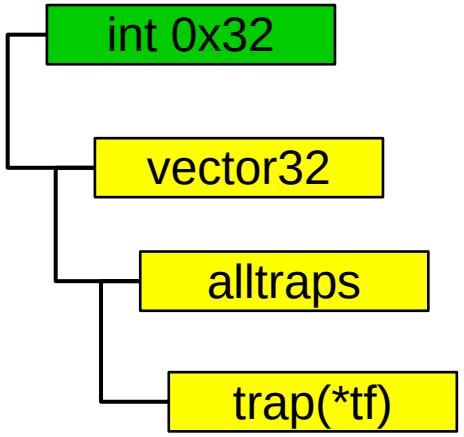
The end result: call trap()

```
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
```



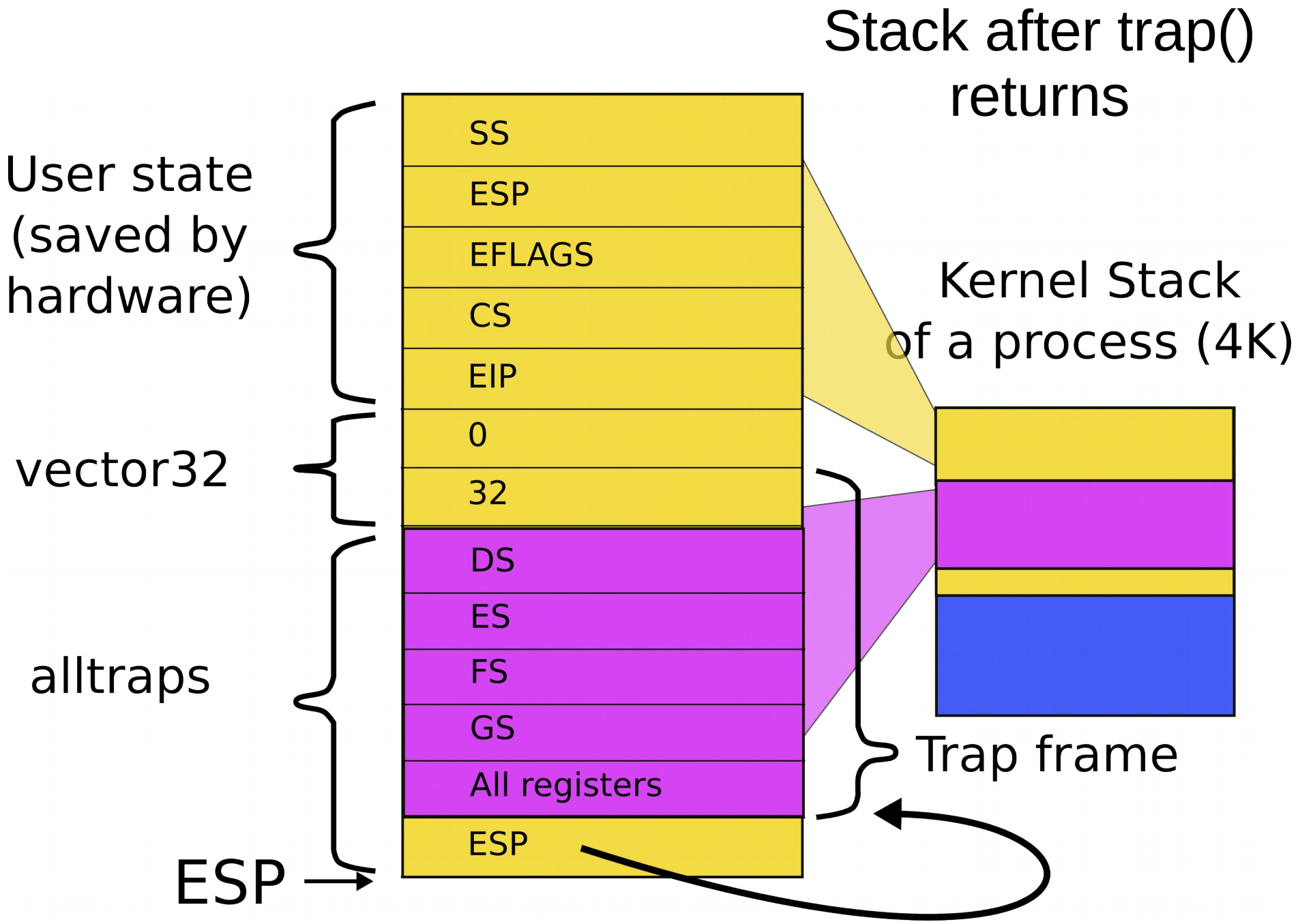
```
3351 trap(struct trapframe *tf)
3352 {
...
3363   switch(tf->trapno){
3364   case T_IRQ0 + IRQ_TIMER:
3365     if(cpu->id == 0){
3366     acquire(&tickslock);
3367     ticks++;
3368     wakeup(&ticks);
3369     release(&tickslock);
3370   }
3372   break;
...
3423   if(proc && proc->state == RUNNING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

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



alltraps(): exit from the interrupt

```
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
```


Stack after trap() returns
User state (saved by hardware)
vector32
alltraps
SS
ESP
EFLAGS
CS
EIP
0
32
DS
ES
FS
GS
All registers
ESP
ESP
Kernel Stack of a process (4K)
Trap frame

```
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
```

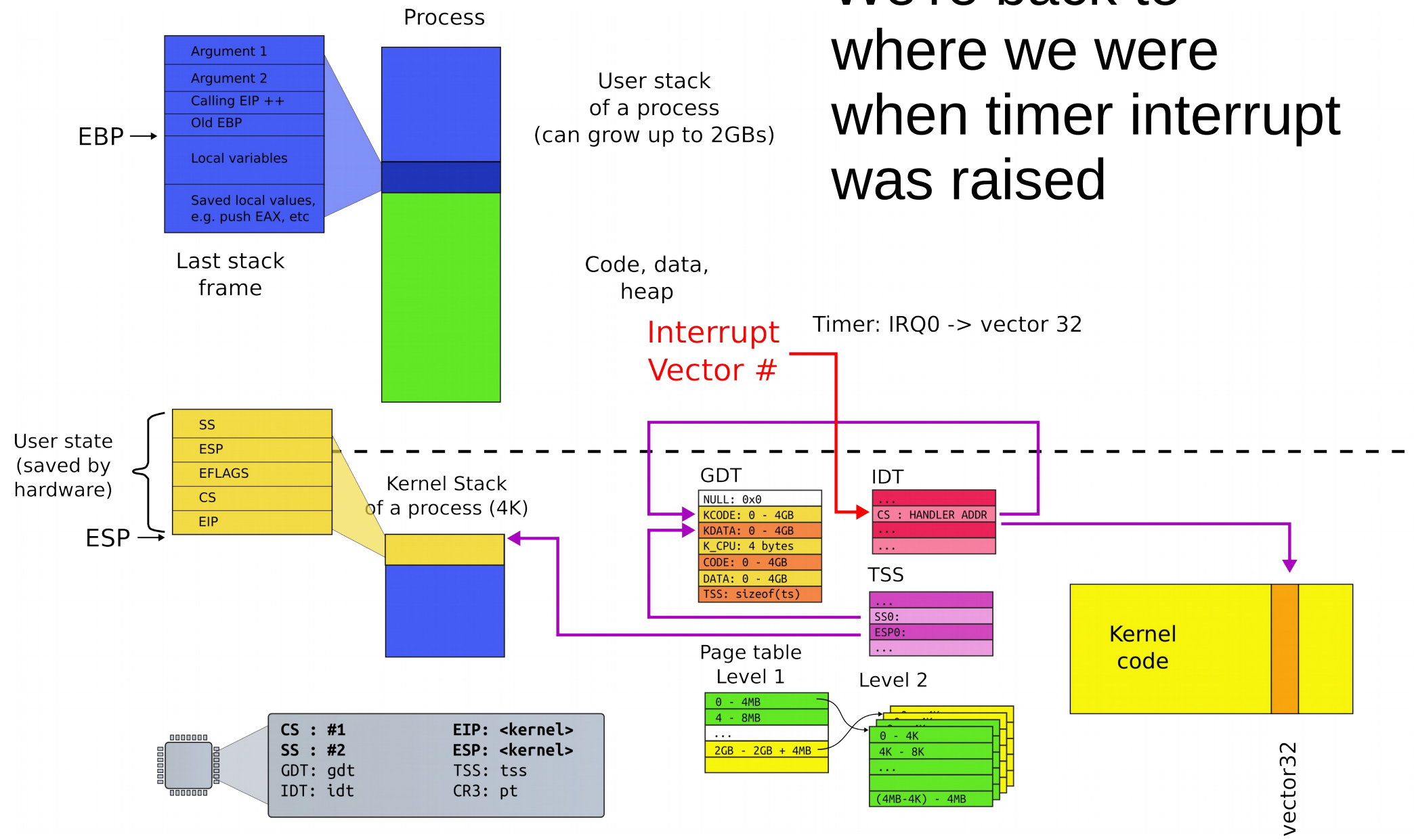
alltraps(): exiting

- 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

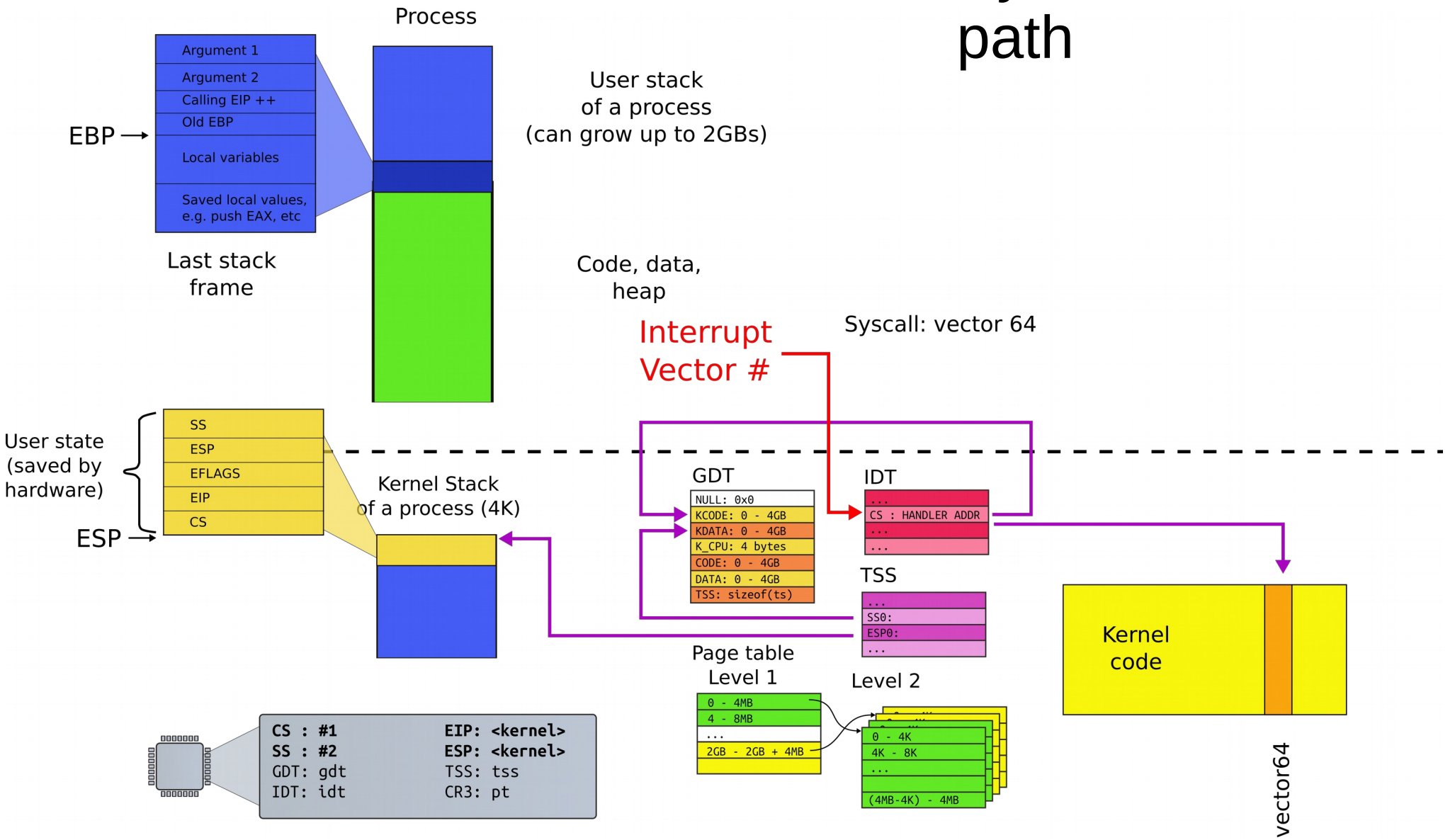


System Calls
(int 0x40)

Software interrupts can be used to implement system calls

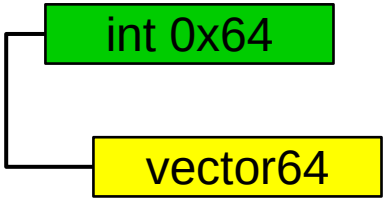
- The int N instruction provides a secure mechanism for kernel invocation
  - i.e., user can enter the kernel
  - But through a well-defined entry point
    - System call handler
- Xv6 uses vector 0x40 (or 64)
  - You can choose any other unused vector
  - Linux uses 0x80
    - Well now it uses sysenter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

System call path



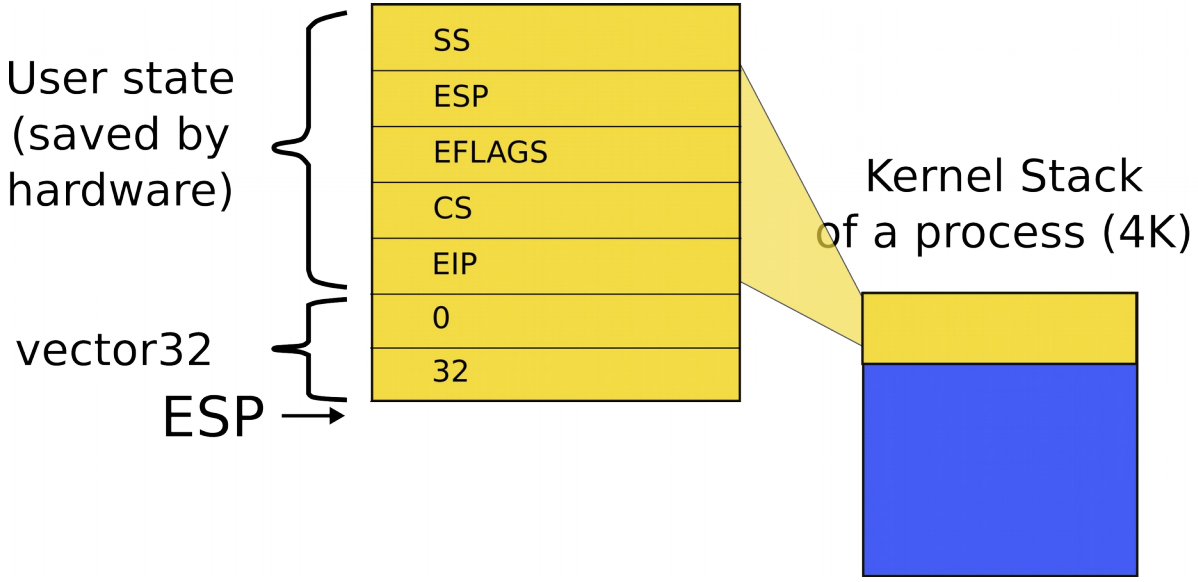
Where does IDT (entry 64) point to?

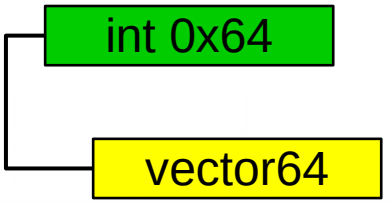
```
vector64:
  pushl $0     // error code
  pushl $64    // vector #
  jmp alltraps
```



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

Kernel stack inside system call

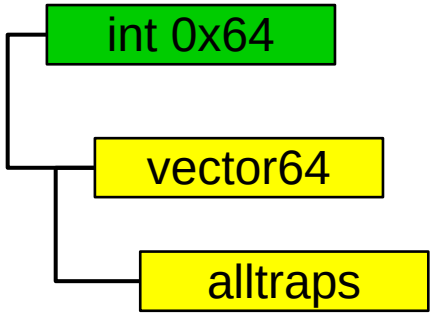




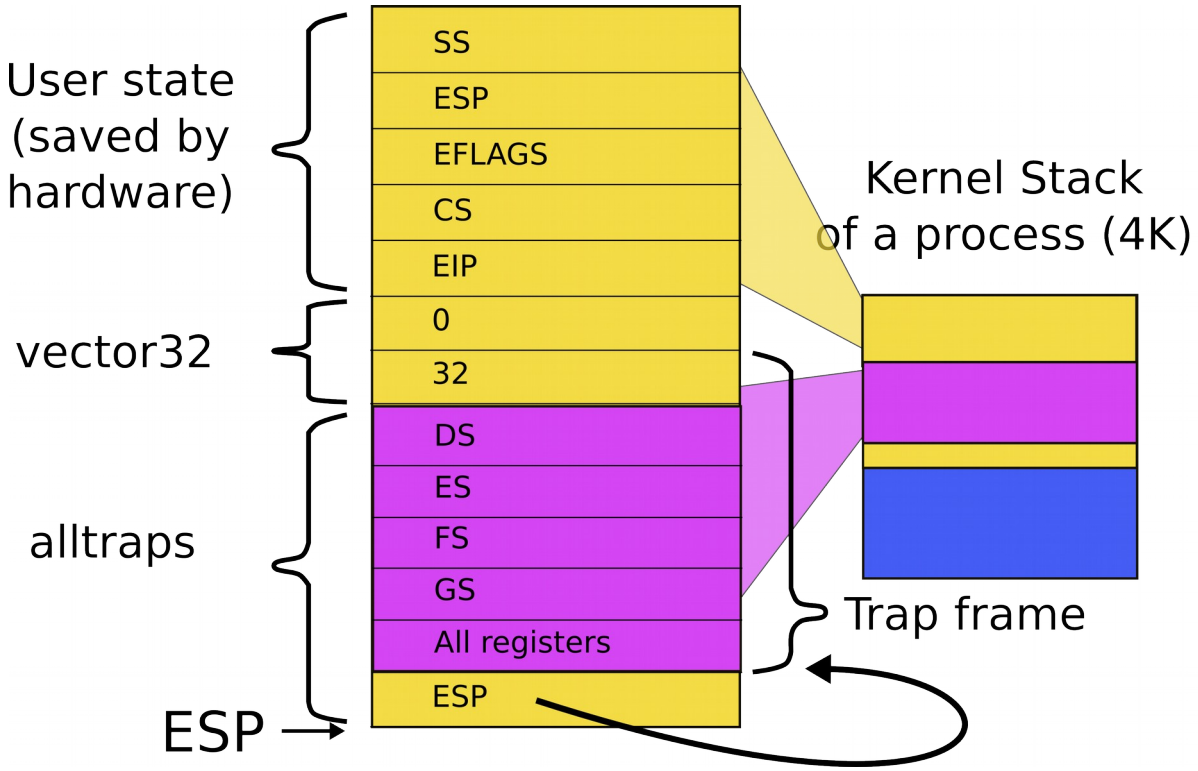
Call stack: vector32()

alltraps()

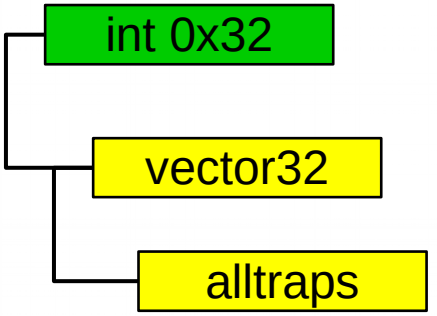
```
3254 alltraps:
3255 # Build trap frame.
3256 pushl %ds
3257 pushl %es
3258 pushl %fs
3259 pushl %gs
3260 pushal
3261
3262 # Set up data and per-cpu segments.
3263 movw $(SEG_KDATA<<3), %ax
3264 movw %ax, %ds
3265 movw %ax, %es
3266 movw $(SEG_KCPU<<3), %ax
3267 movw %ax, %fs
3268 movw %ax, %gs
3269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



Kernel stack inside system call

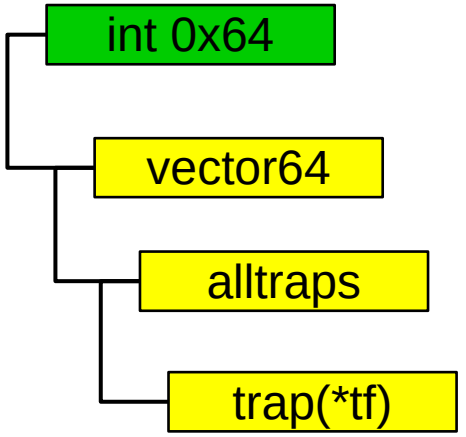


Call stack: vector32()
alltraps()



```
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()

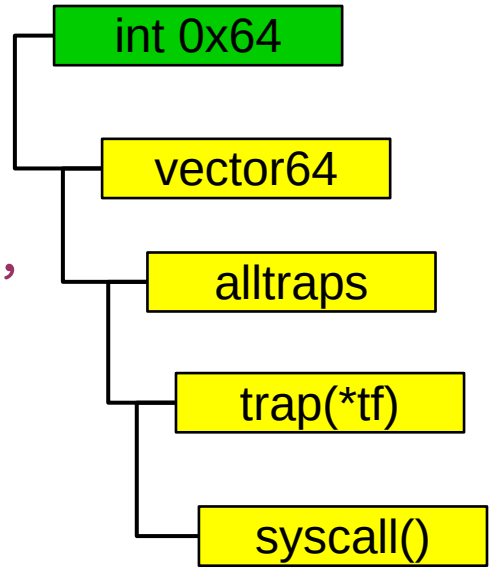


Syscall number

- 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     proc->tf->eax = syscalls[num]();
3632   } else {
3633     cprintf("%d %s: unknown sys call %d\n",
3634     proc->pid, proc->name, num);
3635     proc->tf->eax = -1;
3636   }
3637 }
```



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     proc->tf->eax = syscalls[num]();
3632   } else {
3633     cprintf("%d %s: unknown sys call %d\n",
3634     proc->pid, proc->name, num);
3635     proc->tf->eax = -1;
3636   }
3637 }
```

```
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 };
```

System call table

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

user.h

```
// 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 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 {
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```

```
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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 }
```

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

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 }
```

- Skip return eip

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 }
```

- Fetch n'th argument

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 }
```

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)

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

Thank you