

Processes

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Agenda

- Vocabulary (OSTEP Ch. 4)
 - What is a process? System calls? Scheduler? Address space?
- Memory management (OSTEP Ch. 13-17)
 - How to manage and isolate memory? What are memory APIs? How are they implemented?
- Processes in action (xv6 Ch. 3: system calls, x86 protection, trap handlers)
 - Process control block, user stack<>kernel stack, sys call handling
- Scheduling (xv6 Ch5: context switching, OSTEP Ch. 6-9)
 - Response time, throughput, fairness

Process is a running program

- Load program from disk to memory
 - Exactly how we loaded OS
- Give control to the process. Jump cs, eip

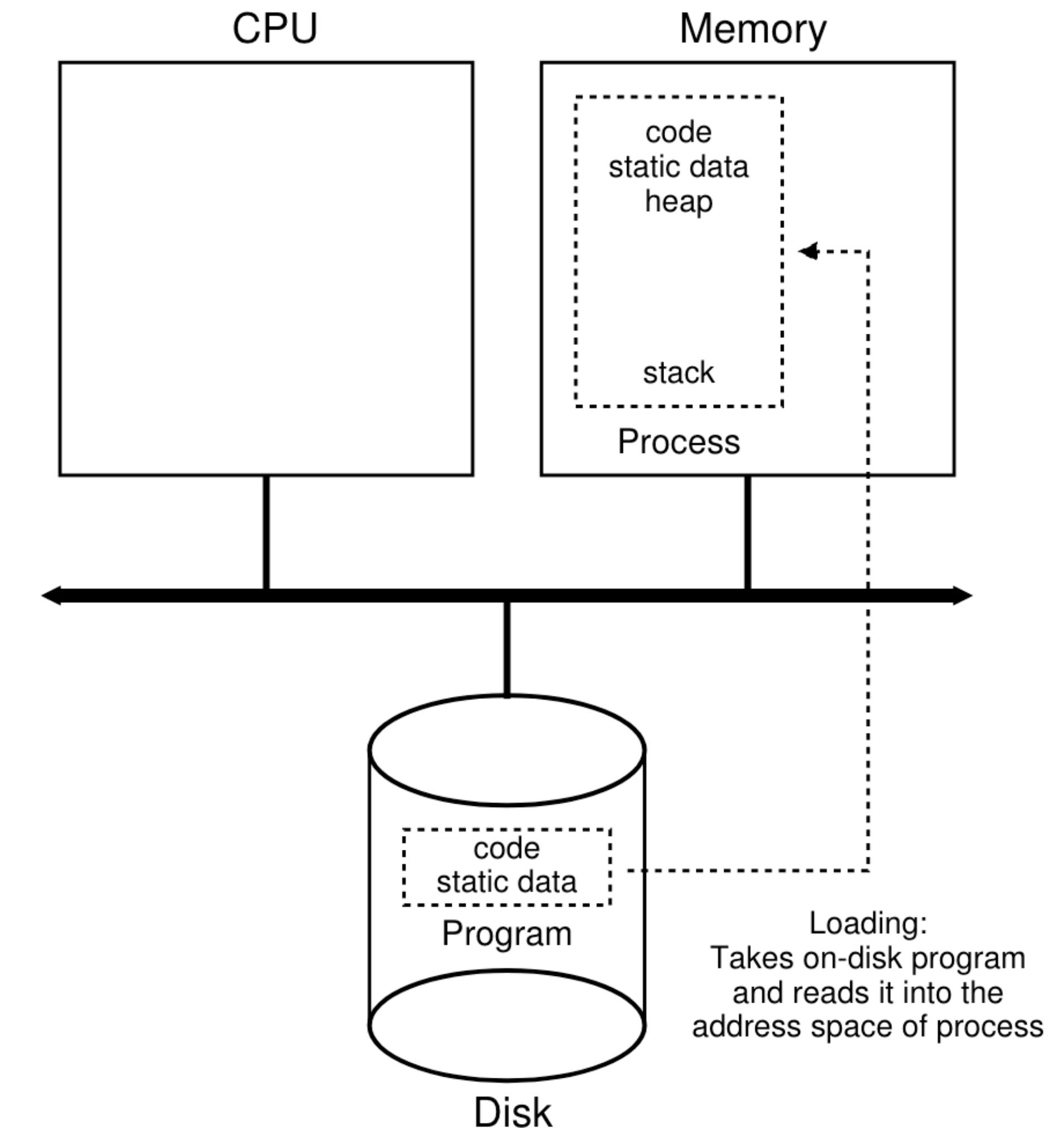


Figure 4.1: Loading: From Program To Process

Processes can ask OS to do work for them

System calls

```
$ strace cat /tmp/foo
...
openat(AT_FDCWD, "/tmp/foo", 0_RDONLY) = 3
read(3, "hi\n", 131072)                = 3
write(1, "hi\n", 3)                    = 3
...
```

OS maintains process states

Scheduler switches between processes

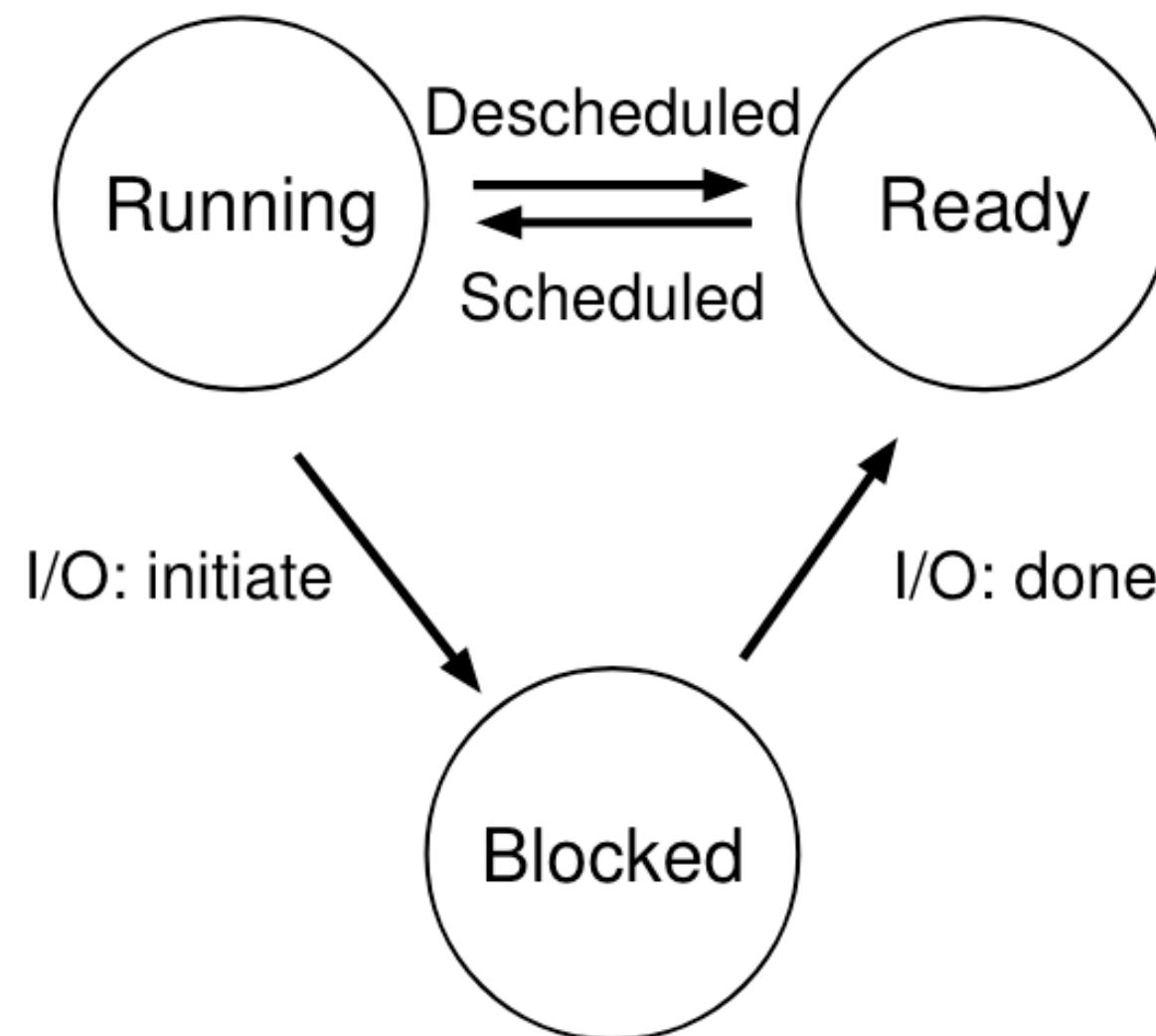


Figure 4.2: Process: State Transitions

Time	Process ₀	Process ₁	Notes
1	Running	Ready	
2	Running	Ready	
3	Running	Ready	
4	Blocked	Running	Process ₀ initiates I/O
5	Blocked	Running	Process ₀ is blocked, so Process ₁ runs
6	Blocked	Running	
7	Ready	Running	I/O done
8	Ready	Running	Process ₁ now done
9	Running	—	
10	Running	—	Process ₀ now done

Figure 4.4: Tracing Process State: CPU and I/O

Calculator analogy: Computing long sum



20
10
30
50
30
10
20
10

- $2 \ 0 =$ (move pointer to 10)
- $+ 1 \ 0 =$ (move pointer to 30)
- $+ 3 \ 0 =$ (move pointer to 50)
- $+ 5 \ 0 =$ (move pointer to 30)
- $+ 3 \ 0 =$ (move pointer to 10)
- $+ 1 \ 0 =$ (move pointer to 20)
- $+ 2 \ 0 =$ (move pointer to 10)

Sharing the calculator

20	10
10	70
30	20
50	40
30	20
10	10
20	50
10	10

- Steps to share the calculator:
 - $20 + 10 = 30 + 30 = 60$
 - Write 60 in notebook, remember that we were done till 30, give calculator
 - $10 + 70 = 80$
 - Write 80 in notebook, remember that we were done till 70, give the calculator back

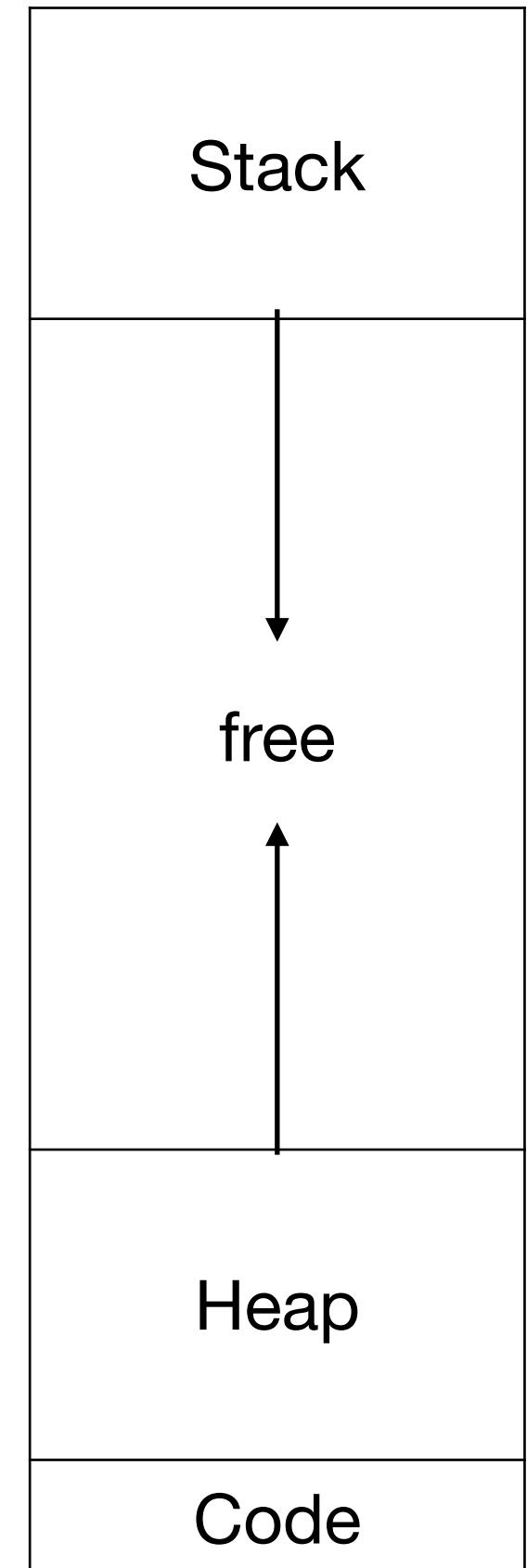
Memory isolation and management

OSTEP Ch. 13-17

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Process Address Space

Code, Heap, Stack



Process address space

Function calling in action

Stack

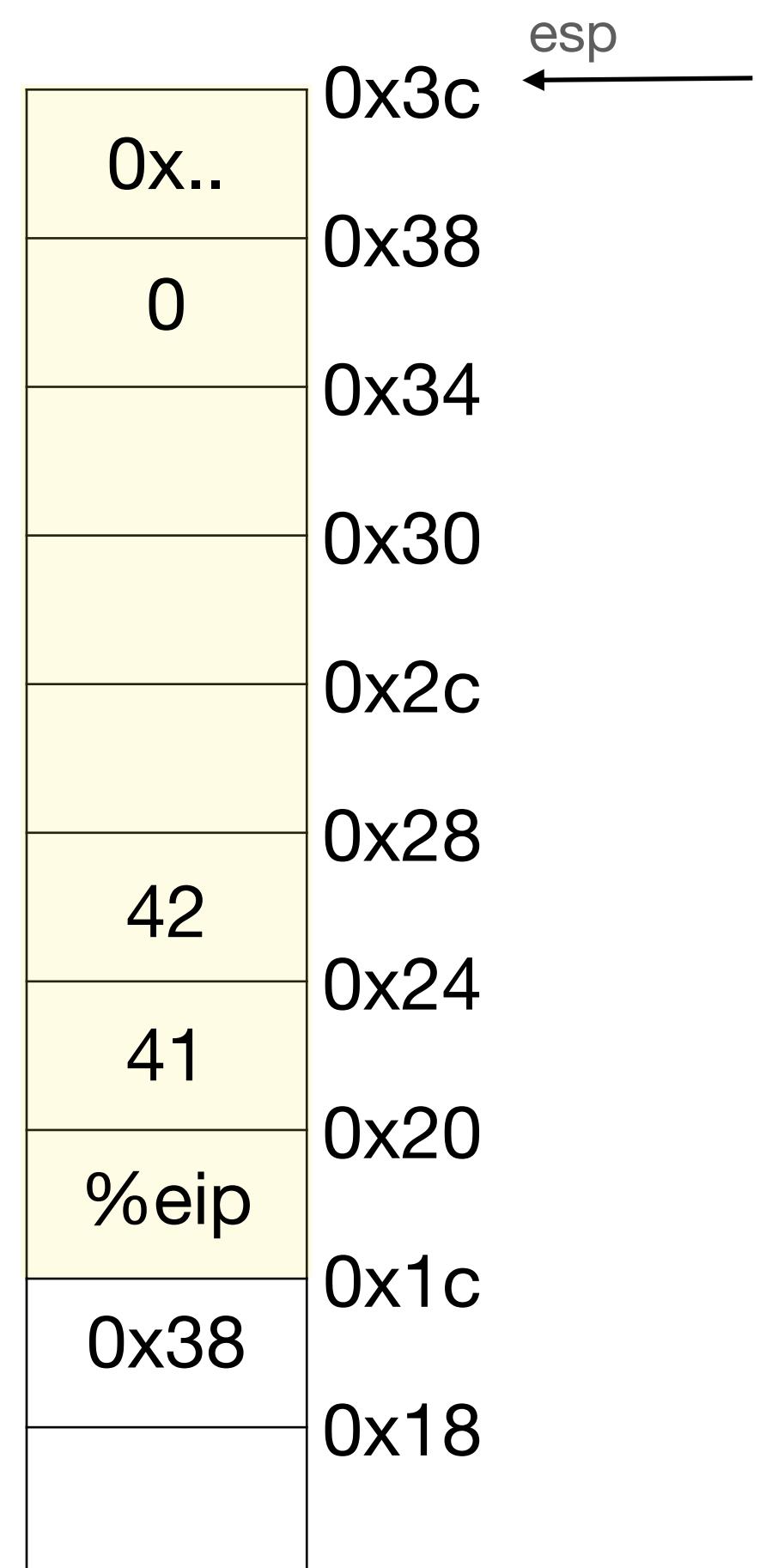
```
02.s

_foo:
    pushl %ebp
    movl %esp, %ebp
    movl 8(%ebp), %eax
    addl 12(%ebp), %eax
    popl %ebp
    retl

    .globl _main
    .p2align 4, 0x90
_main:
    pushl %ebp
    movl %esp, %ebp
    subl $24, %esp
    movl $0, -4(%ebp)
    movl $41, (%esp)
    movl $42, 4(%esp)
    calll _foo
    addl $24, %esp
    popl %ebp
    retl

## -- Begin function main
```

ebp →



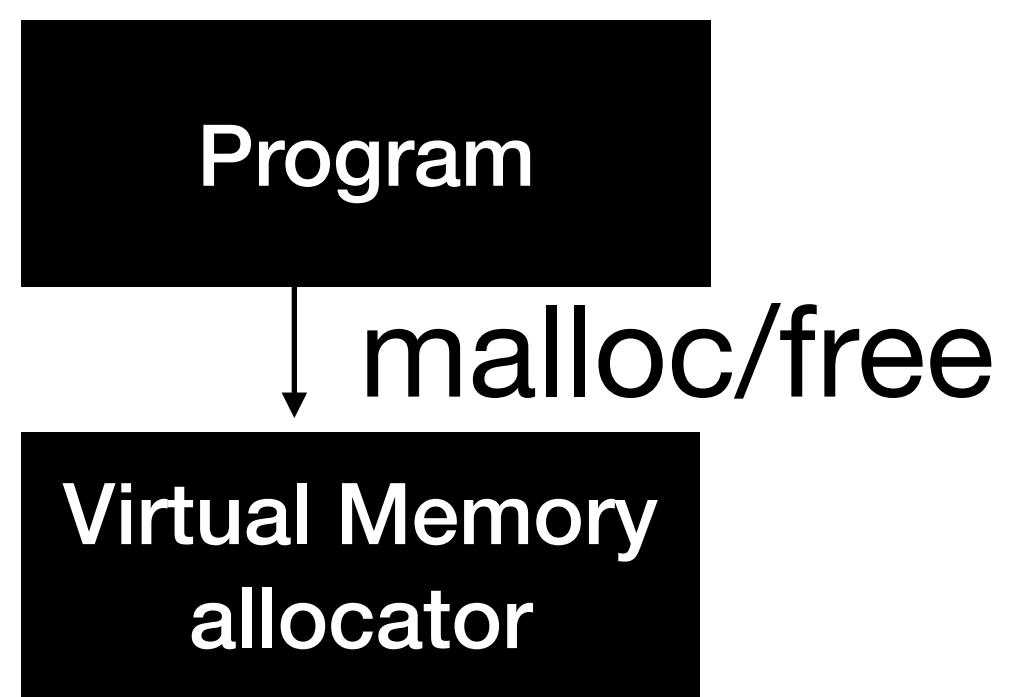
eip →

Memory APIs and bugs

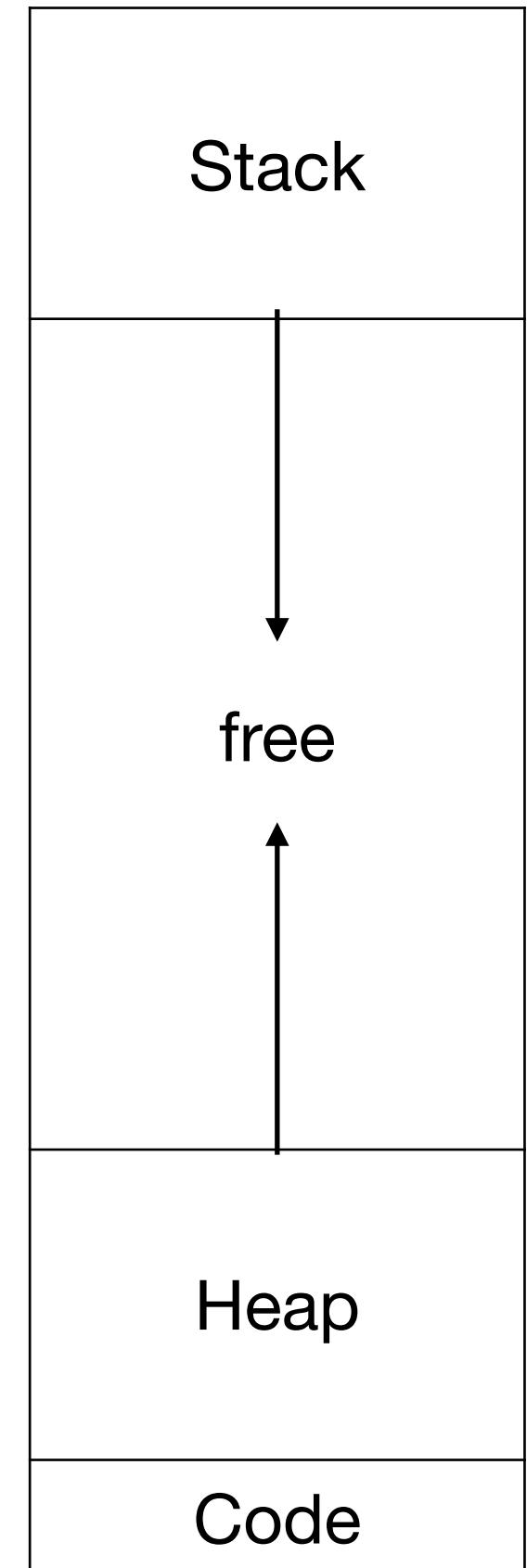
- malloc, free, va.c.
 - malloc is for dynamic allocation. Size is not known at compile time. Slower than stack allocations. Need to find free space.
- Null pointer dereference. null.c
- Memory leak. leak.c
- Buffer overflow. overflow.c
- Use after free. useafterfree.c
- Invalid free. invalidfree.c
- Double free. doublefree.c
- Uninitialised read. uninitread.c

Memory allocator

Works with virtual memory



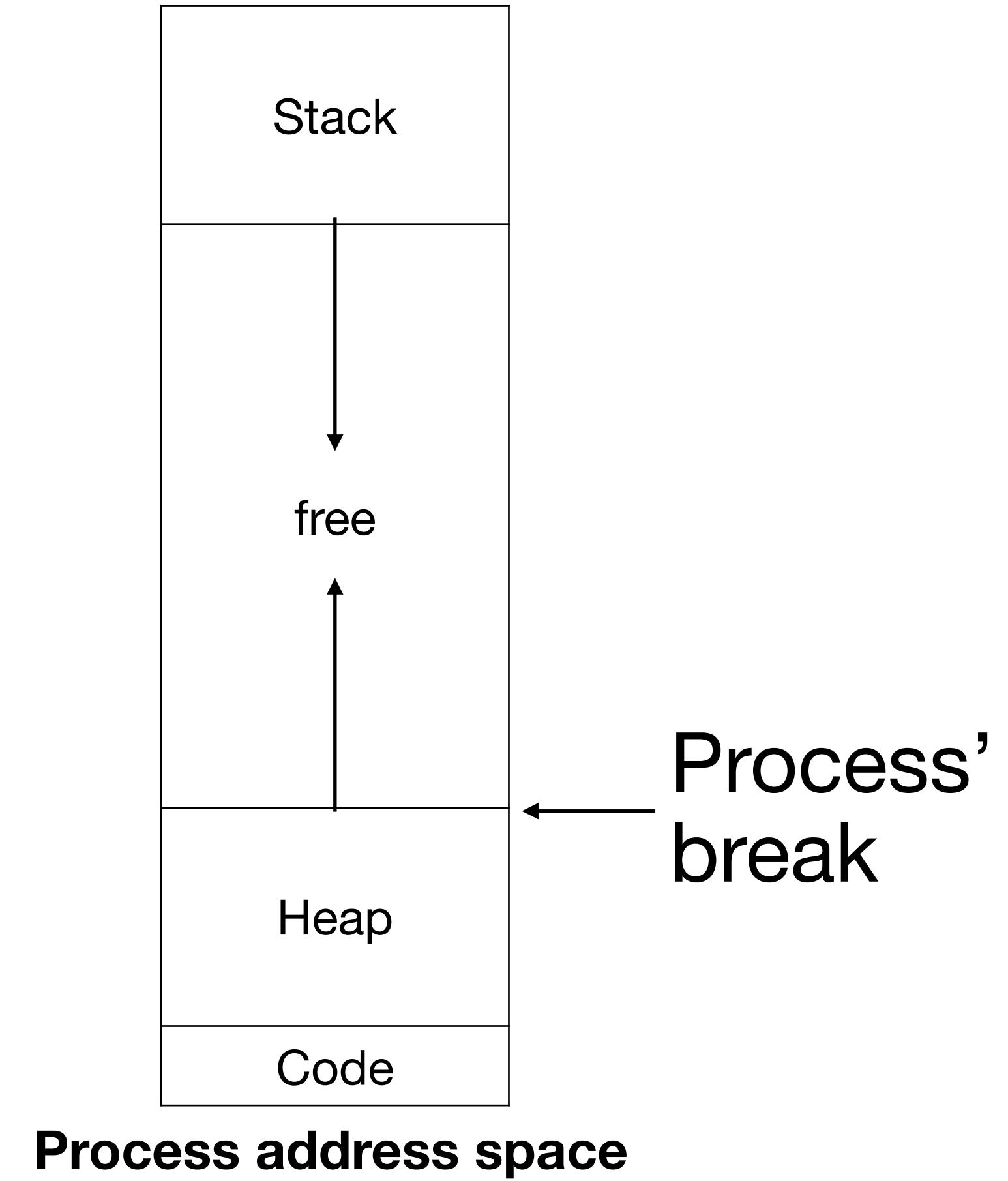
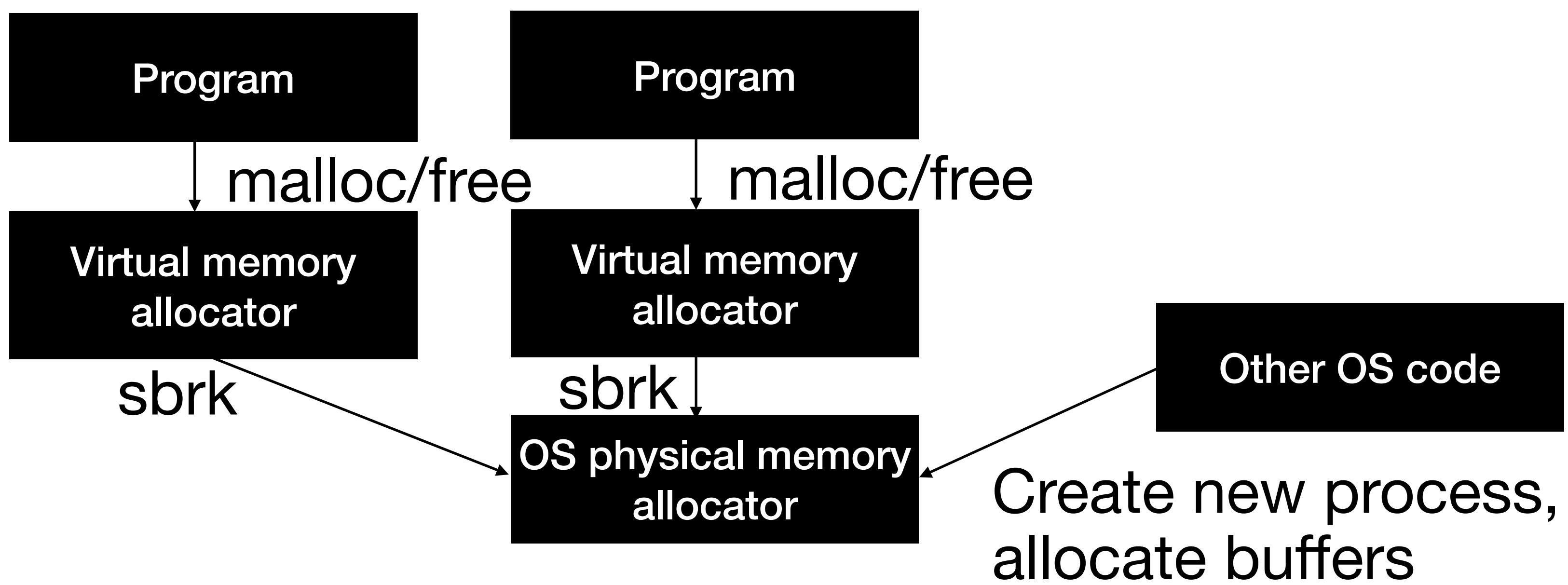
Manages heap memory



Process address space

OS memory allocator

- `sbrk(int increment)` increments process' break. *increment* can be negative.



Memory allocation

```
ptr=malloc(size_t size);  
  
free(ptr);
```

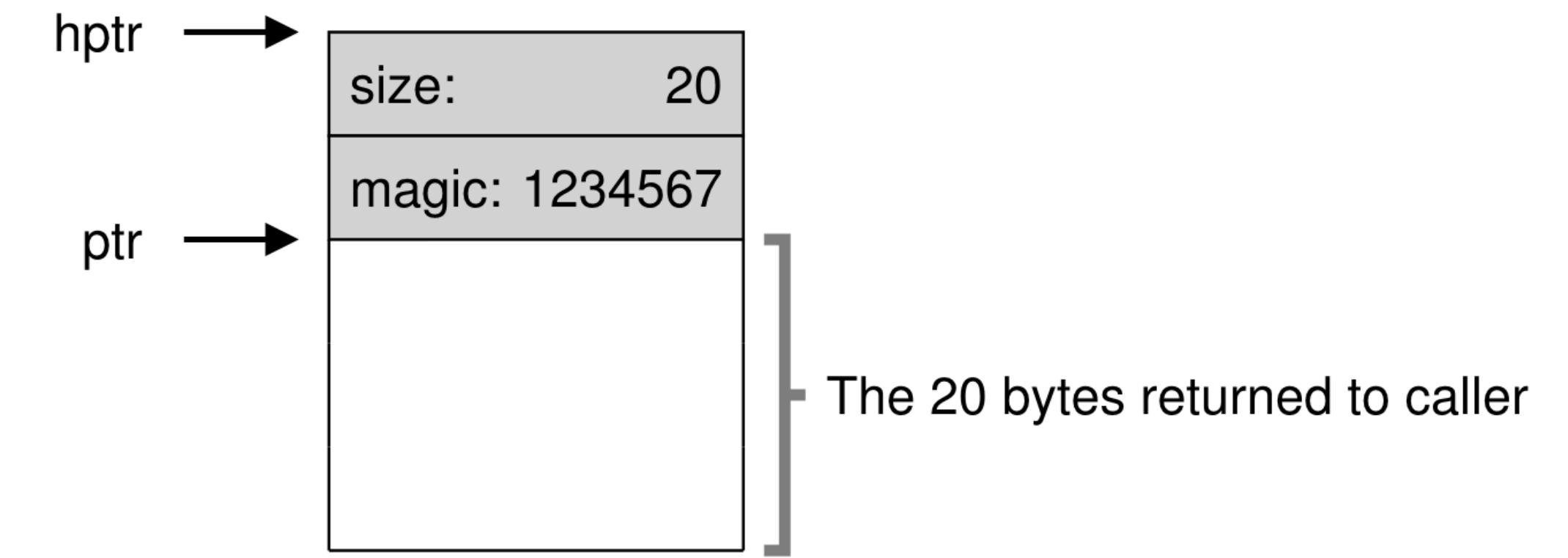
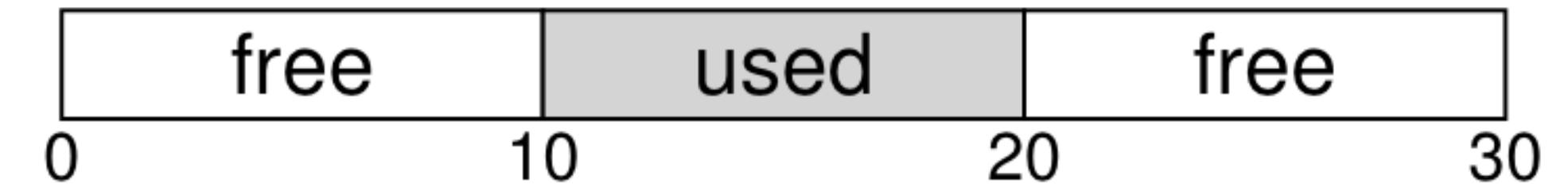


Figure 17.2: Specific Contents Of The Header

Stack allocations are faster than heap allocations. No need to find space.

Memory allocator



Fragmented heap over time

- Assumptions
 - Do not apriori know allocation size and order
 - Cannot move memory once it is allocated. Program might have the pointer to it.
- Goals
 - Quickly satisfy variable-sized memory allocation requests. How to track free memory?
 - Minimize fragmentation

Memory (de)allocation patterns

- Small mallocs can be frequent. Large mallocs are usually infrequent.
 - After malloc, program will initialise the memory area.
- “Clustered deaths”: Objects allocated together die together.

Free list splitting and coalescing

```
ptr = malloc(100)
```

```
sptr = malloc(100)
```

```
optr = malloc(100)
```

```
free(sptr)
```

```
free(ptr)
```

```
free(optr)
```

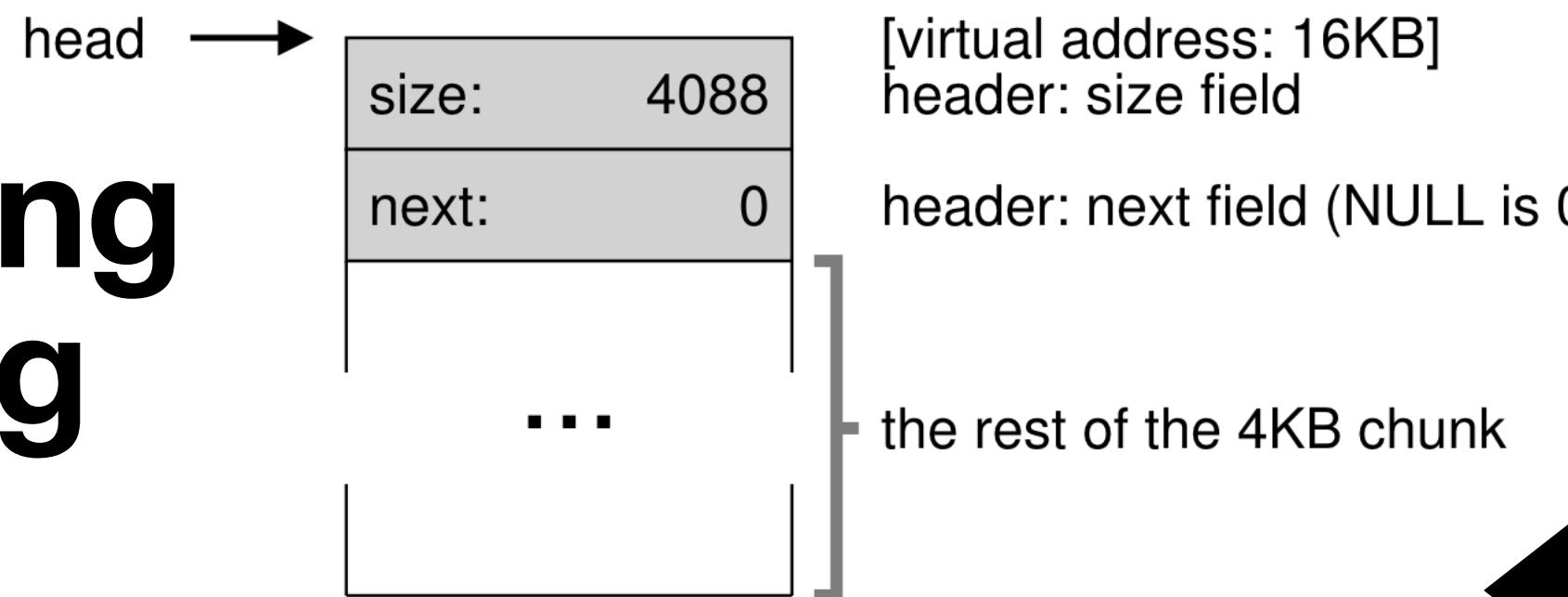


Figure 17.3: A Heap With One Free Chunk

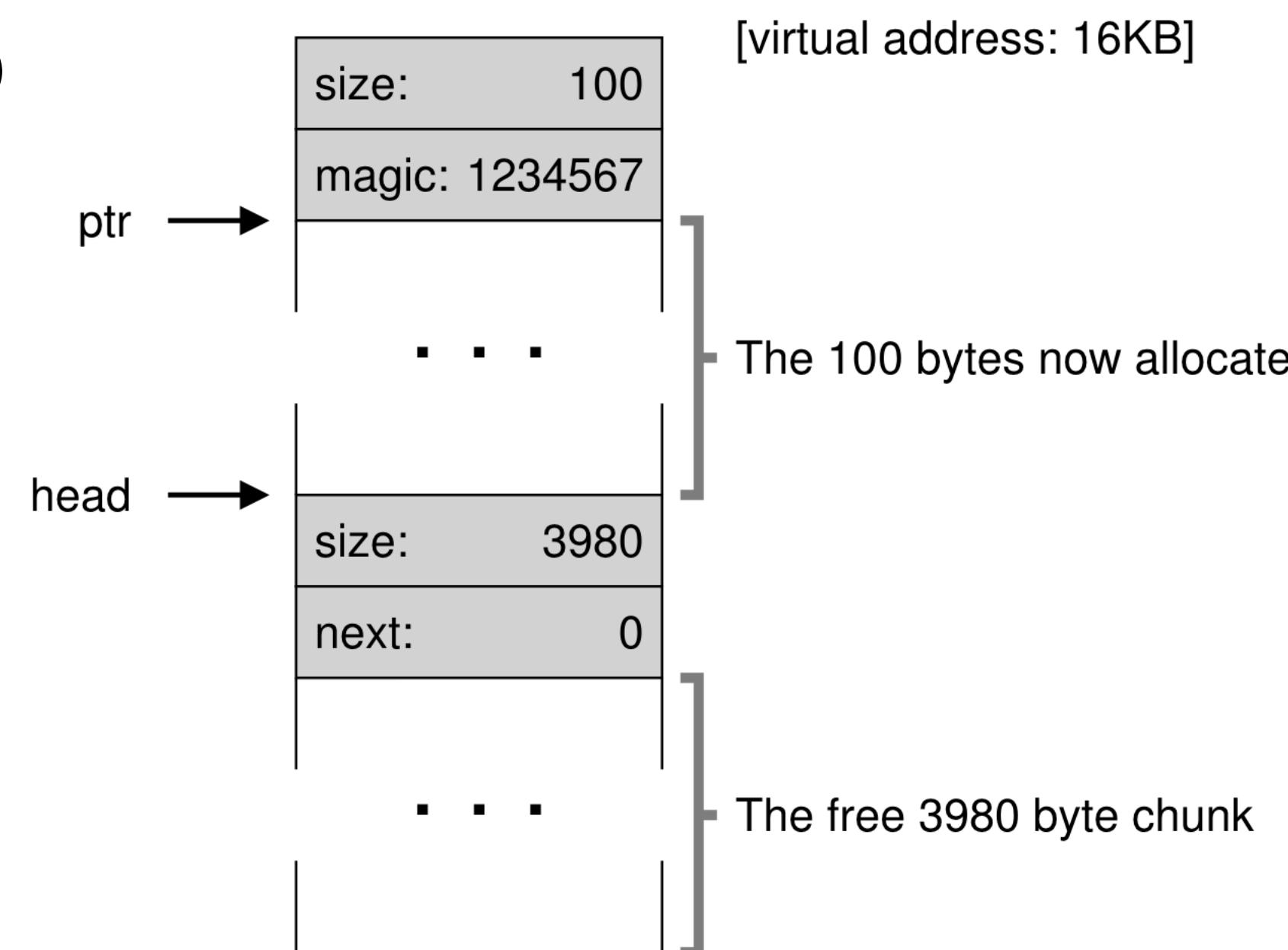


Figure 17.4: A Heap: After One Allocation

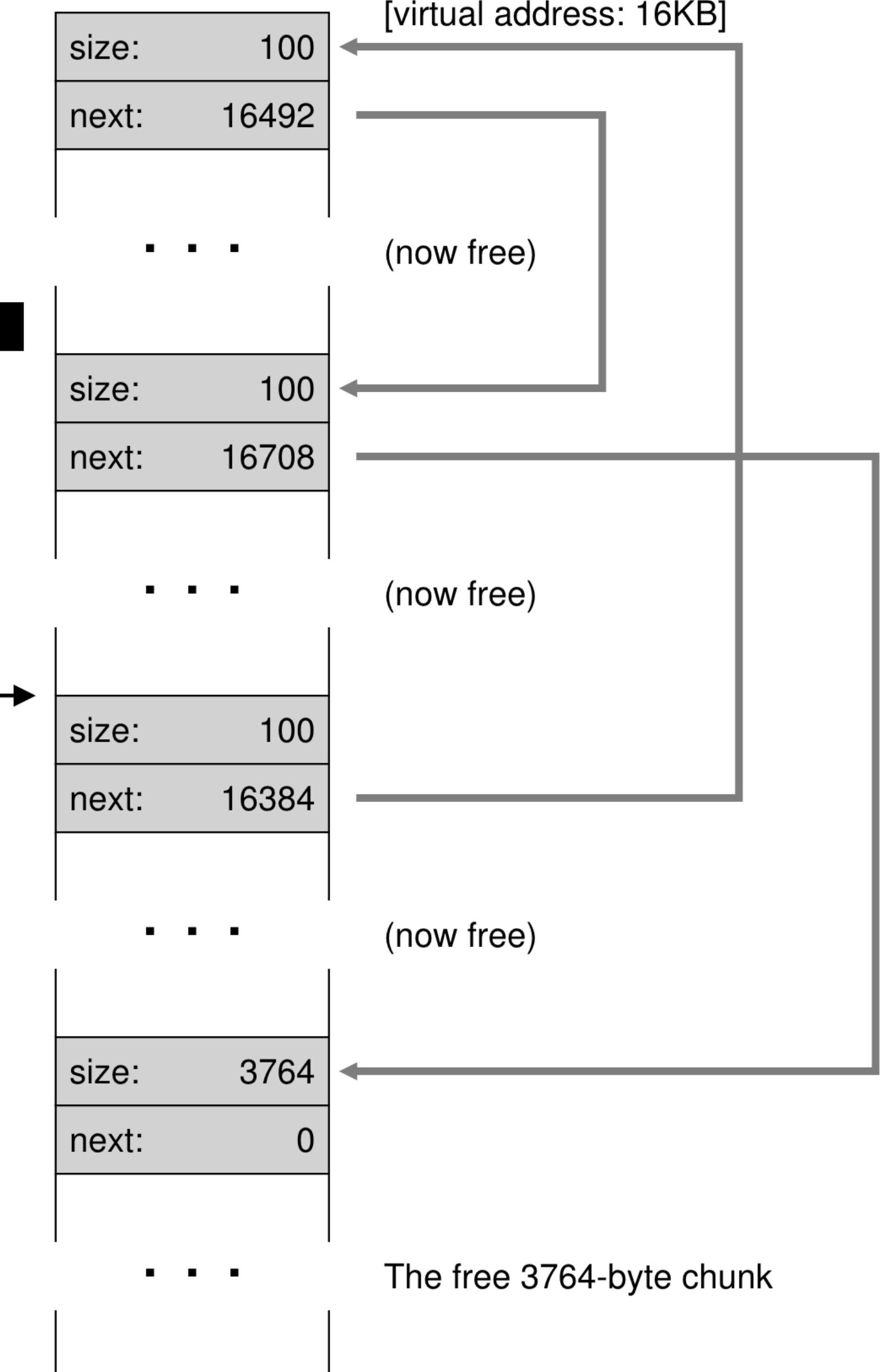


Figure 17.7: A Non-Coalesced Free List

Which block to allocate?

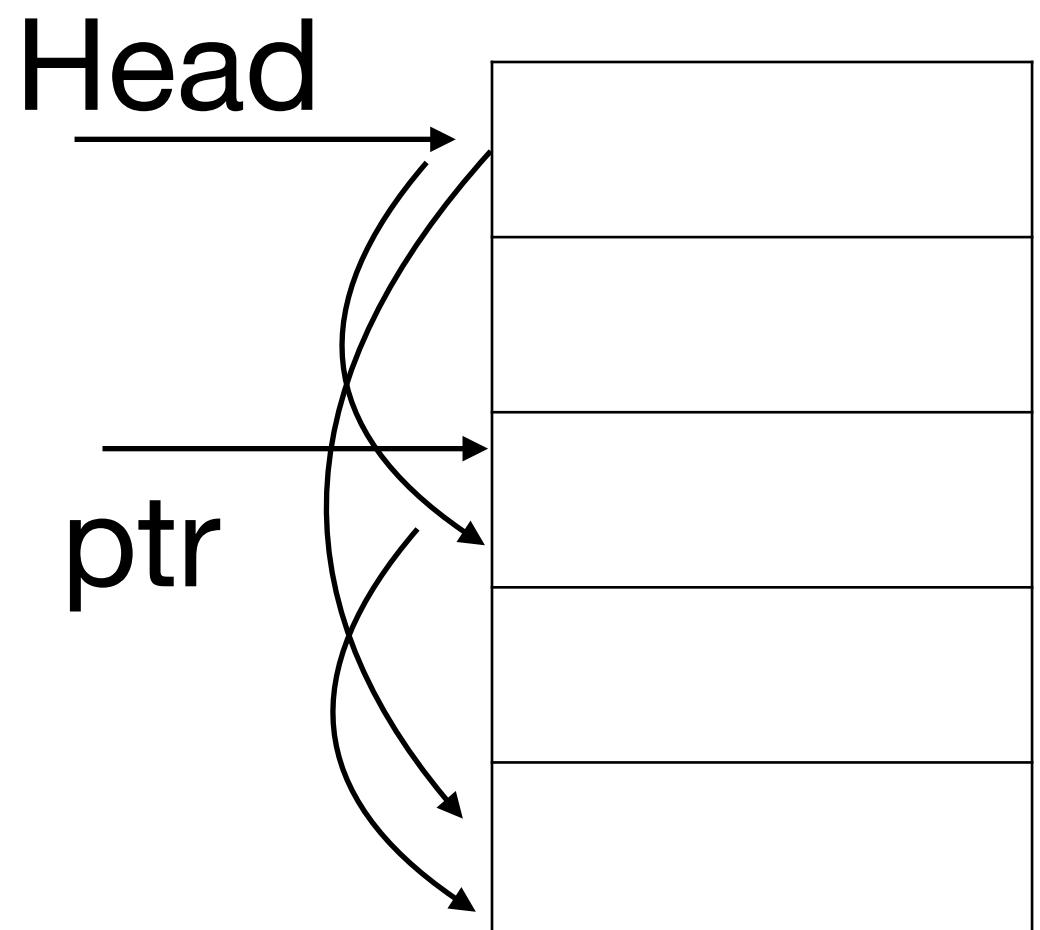
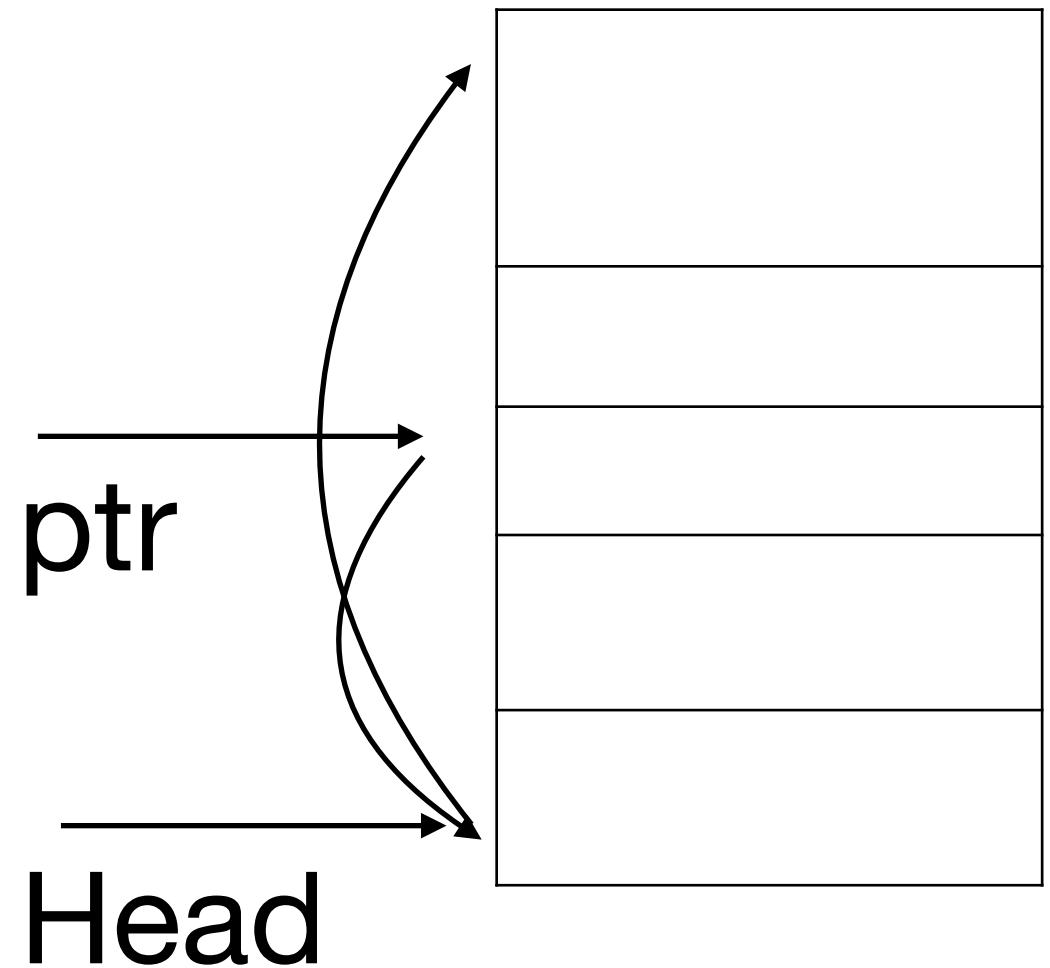
Example: malloc(15)

- Best fit
 - Slow. need to search the whole list
- First fit
 - Faster. (xv6: umalloc.c)
- Fragmentation
 - Example: malloc(25)



In which order to maintain lists?

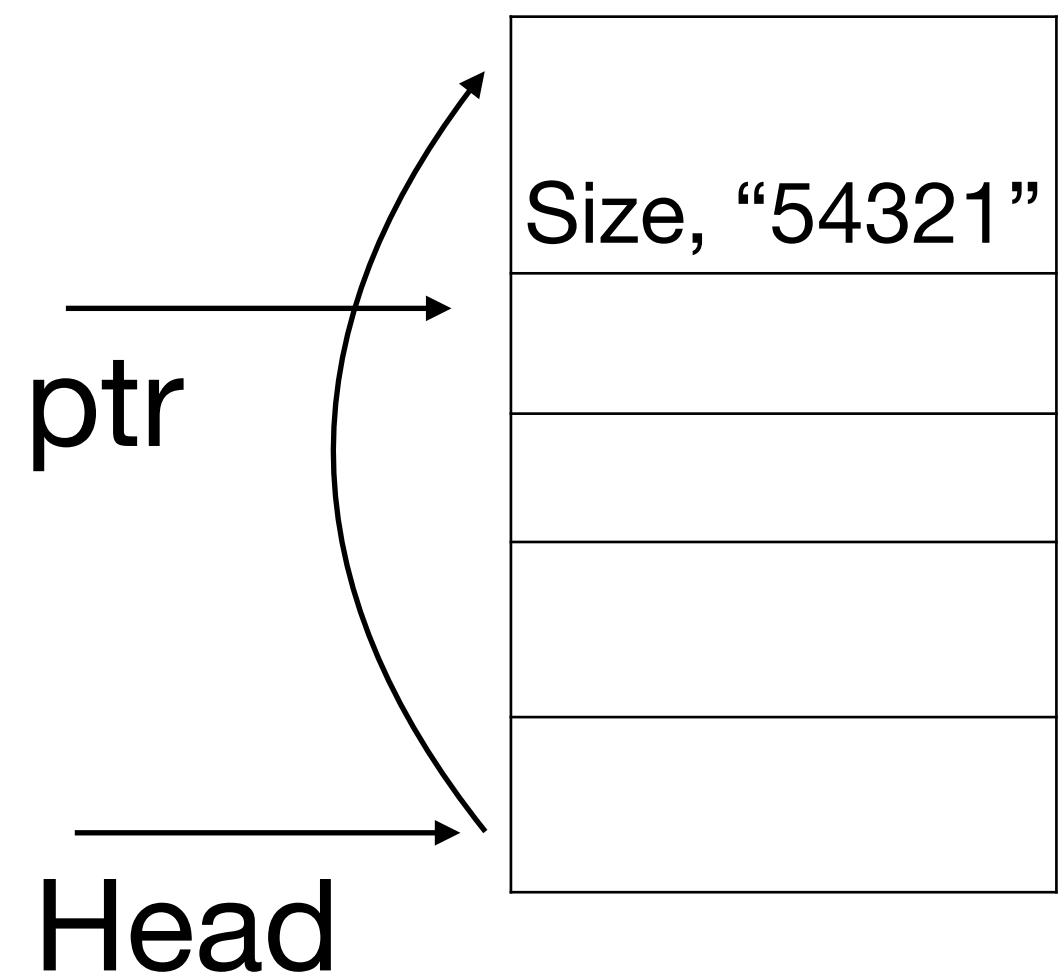
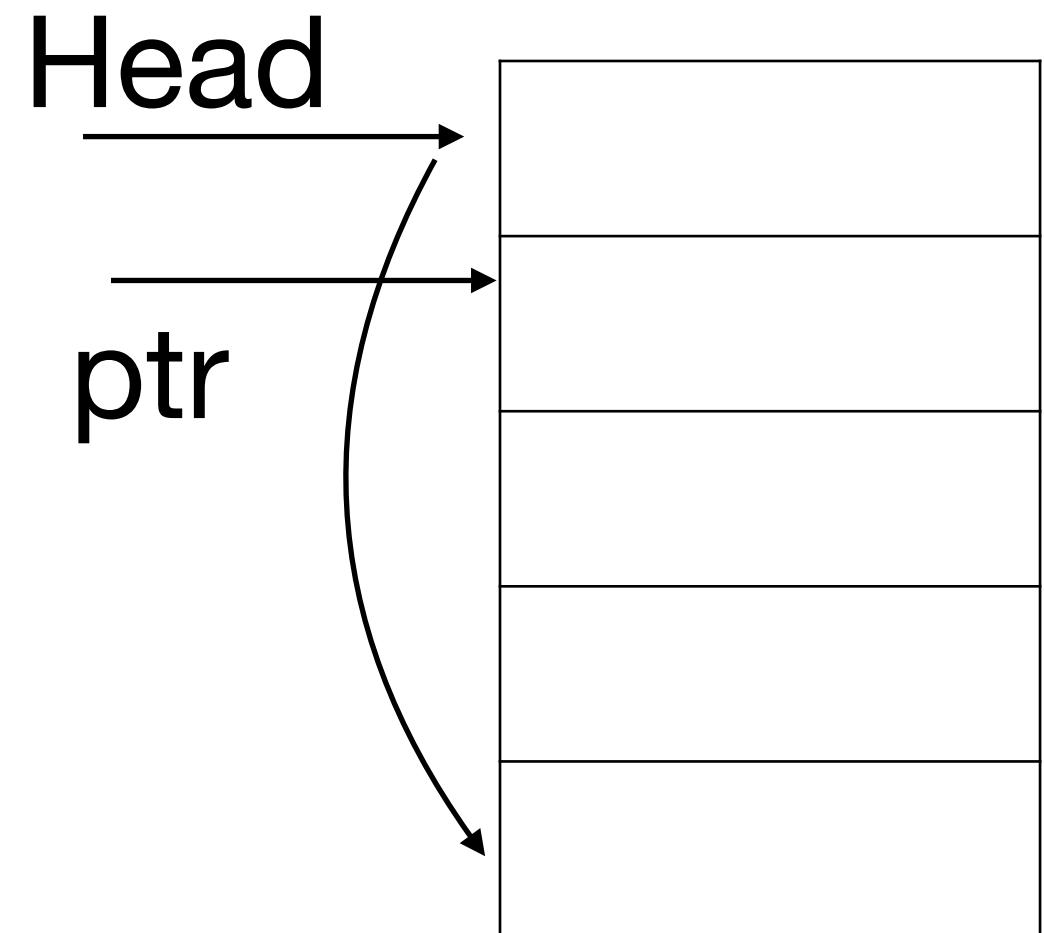
- (De)allocation order
- Address order
 - Slow frees: need to traverse the free list
 - (xv6: umalloc.c)
 - Address order, first fit will allocate back-to-back allocations contiguously.
 - Due to “clustered deaths”, we may get better chances of coalescing



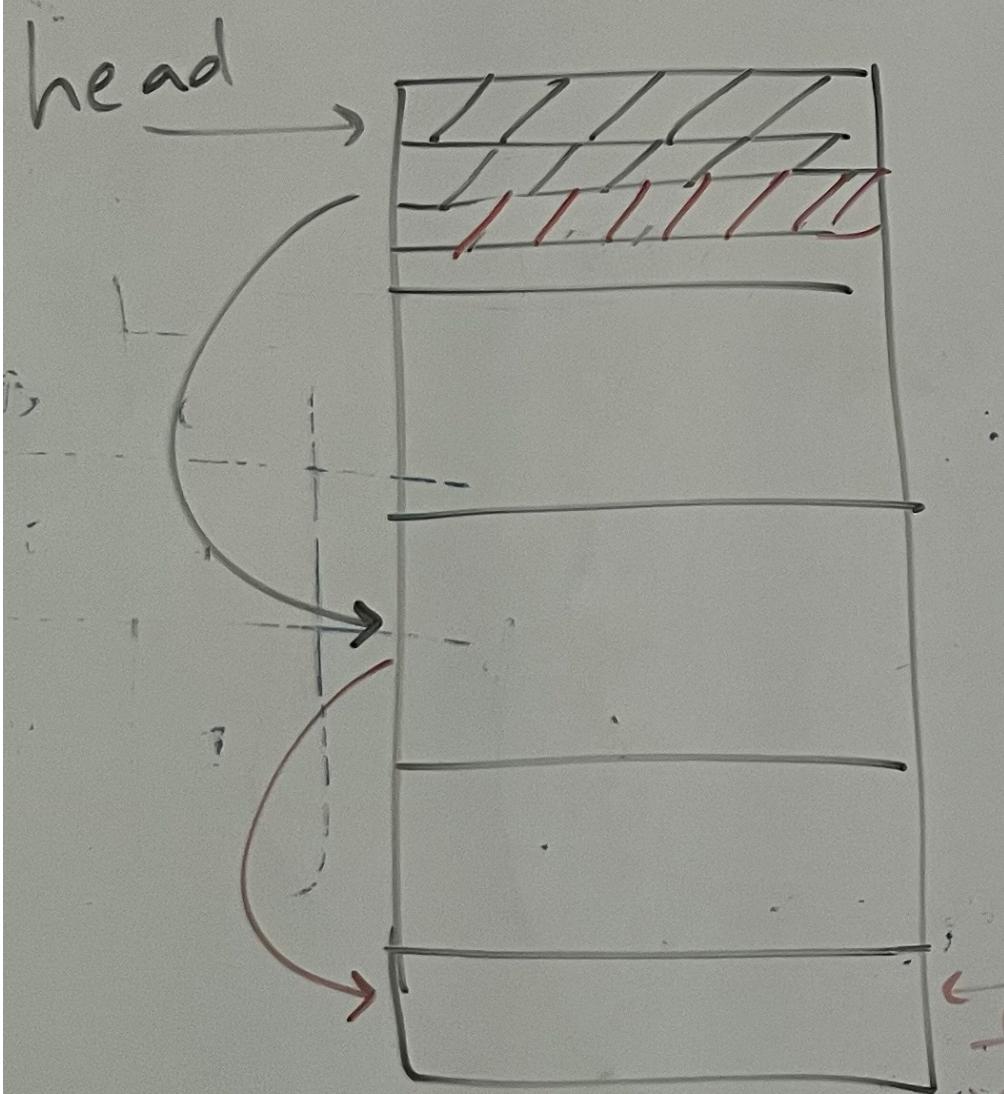
How to do coalescing?

Example: free(ptr)

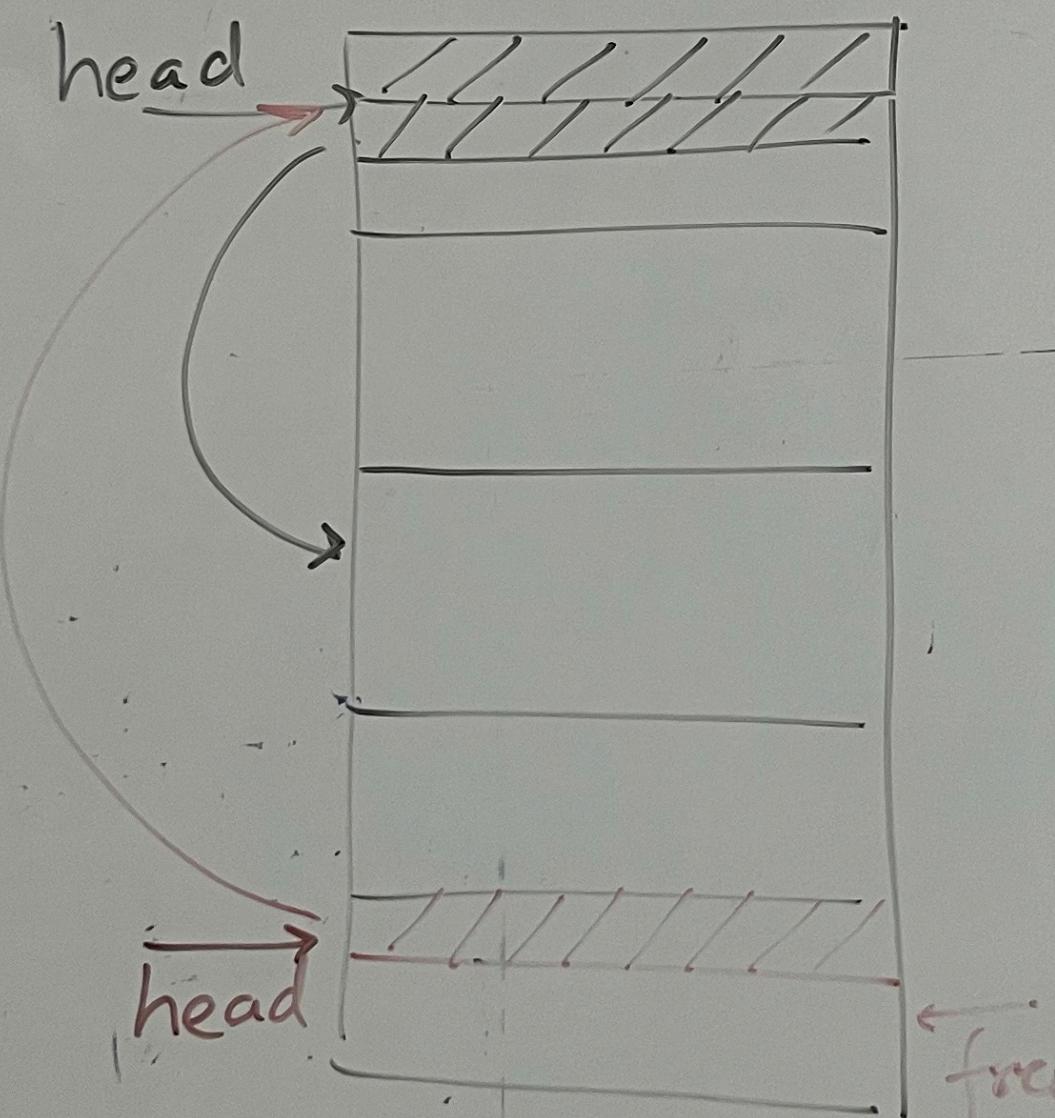
- Straightforward in address order since we are traversing the free list in address order
- In deallocation order: when an area is freed, check if the “boundary tag” is present in the footer above
- First fit and address order
 - Better chances of coalescing for clustered deaths, simpler coalescing (no boundary tag)
 - First fit causes fragmentation
 - Address order slows frees due to traversing free list



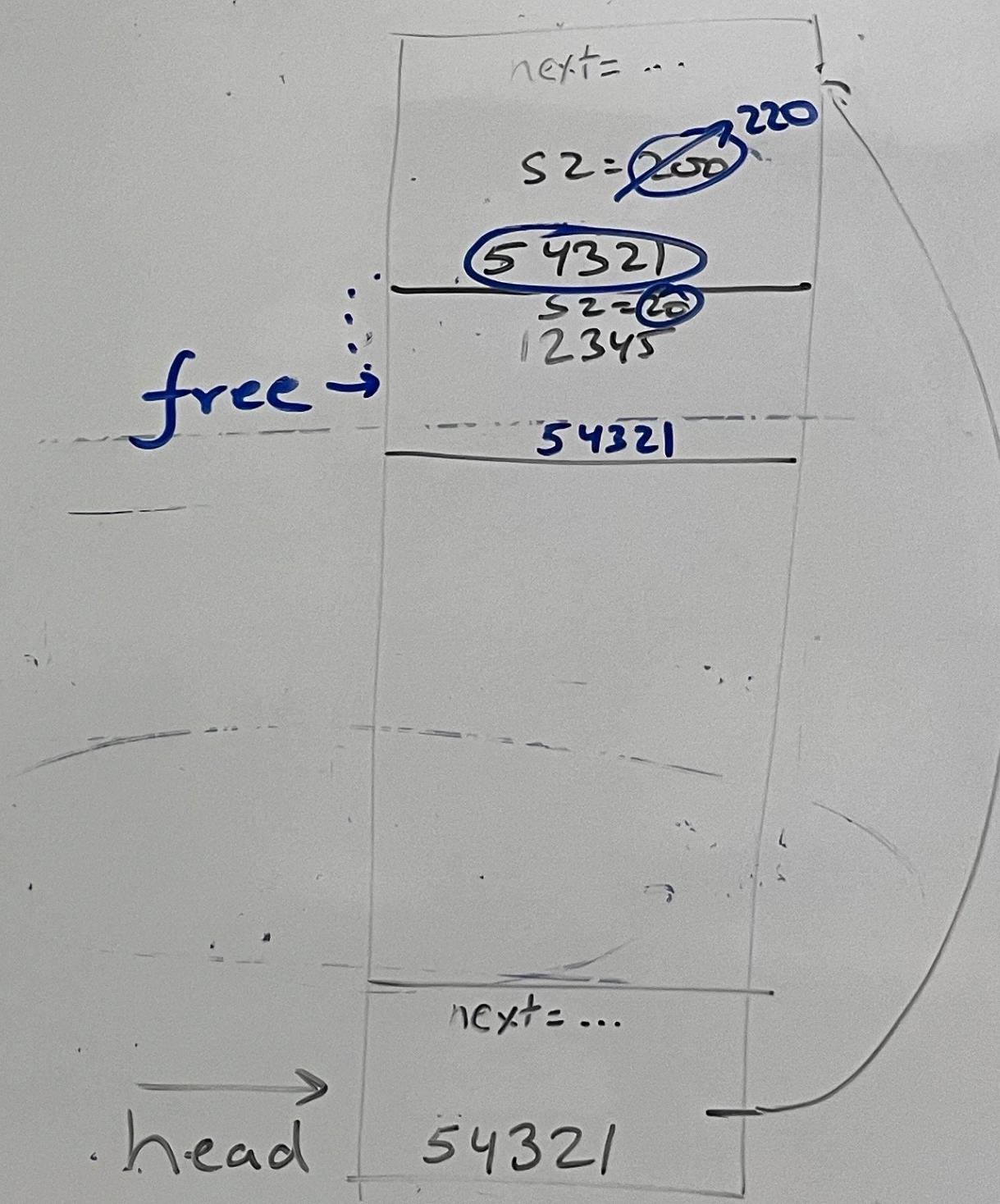
First fit
address order



First fit
(de) allocation order

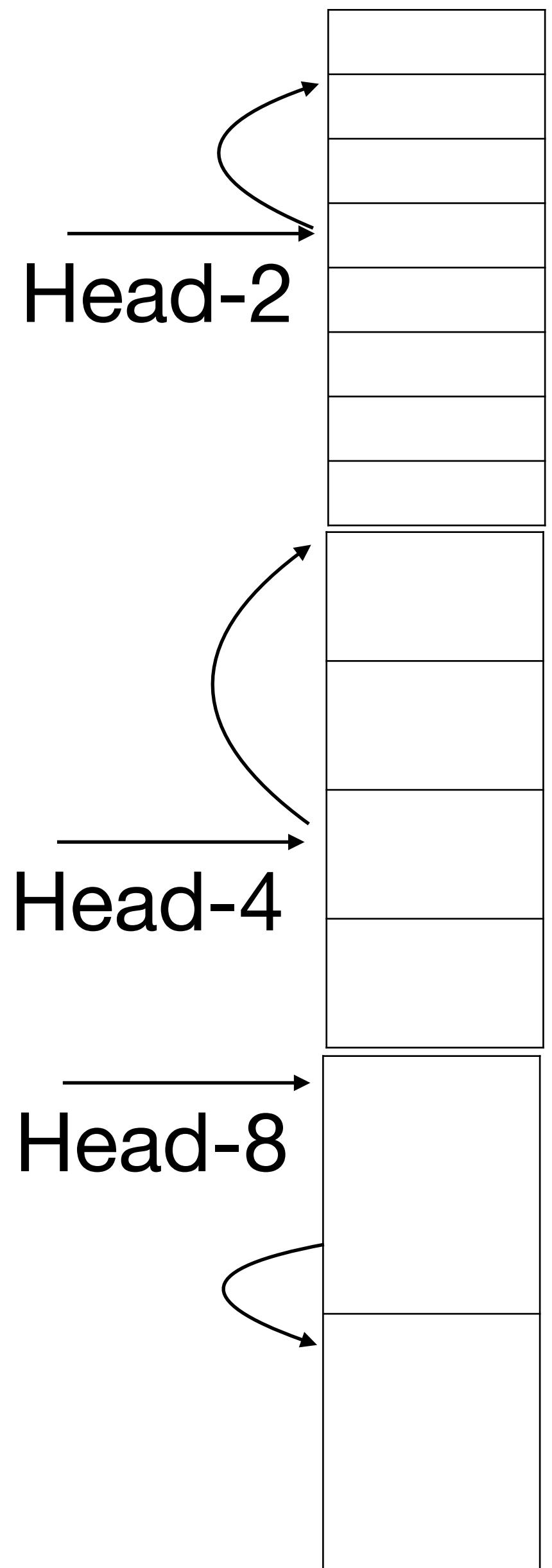


Boundary tag



Segregated lists

- Separate lists for each size.
- “Segregated fit”: First fit in the smallest object list that can fit the object. Approximates best fit.
 - No splitting, coalescing
- Internal fragmentation: allocates more than asked
- Wastes memory: If no allocation from object size, have unnecessary reserved space for it



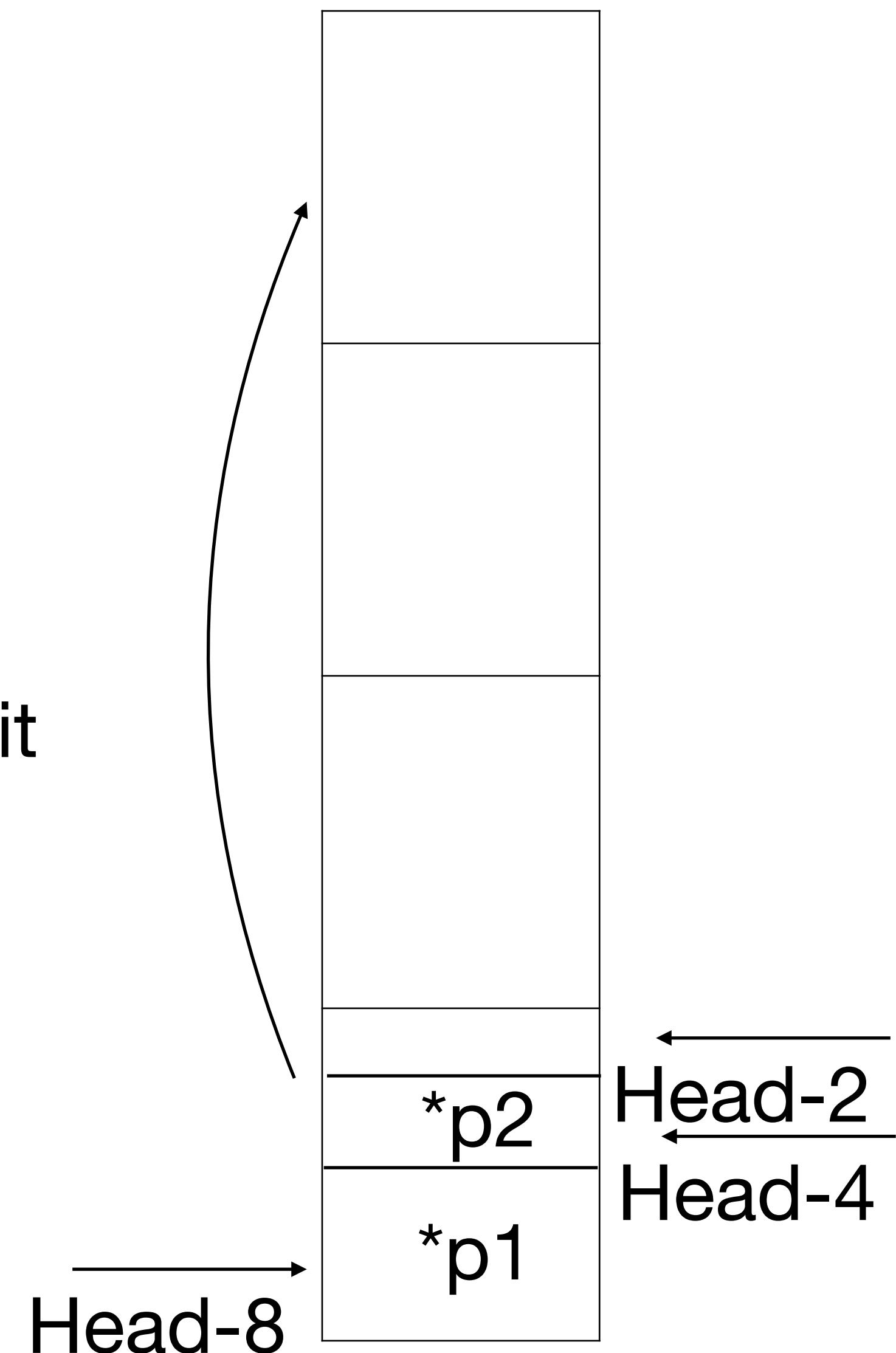
Slab allocator

Used in Linux Kernel

- Knows the size of allocations made by the Linux kernel. Keep segregated lists for each such struct.
 - No internal fragmentation: Exactly the size of the struct
 - Hierarchical allocator: Return unused lists back to global allocator

Buddy allocator

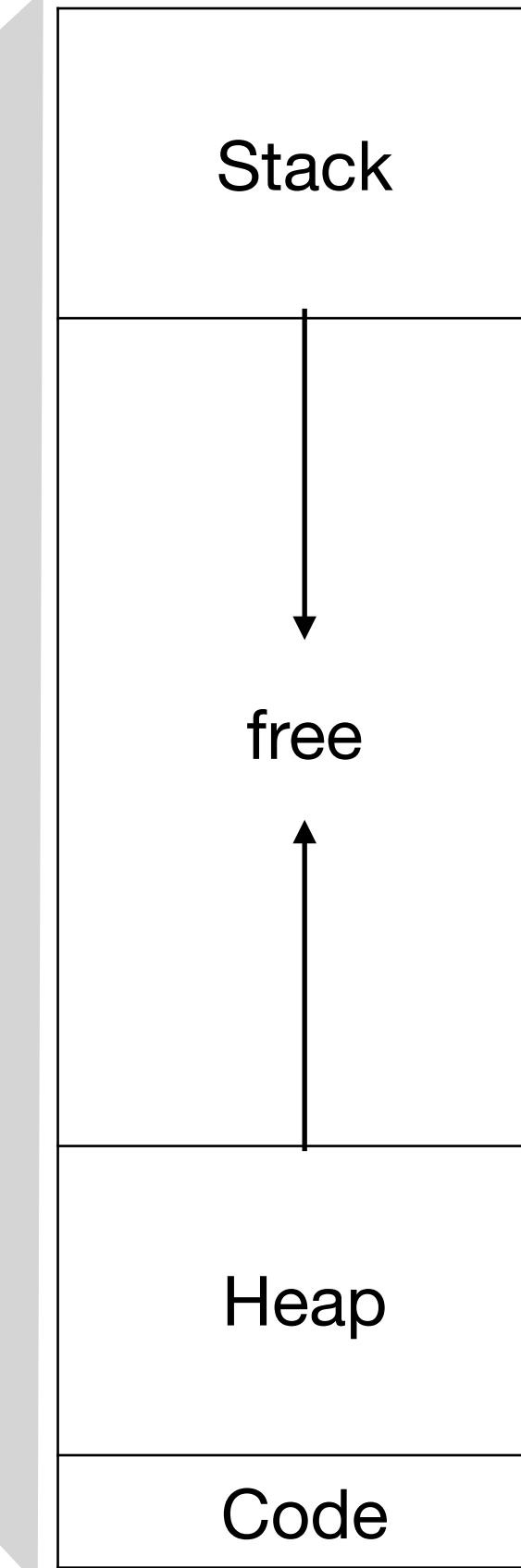
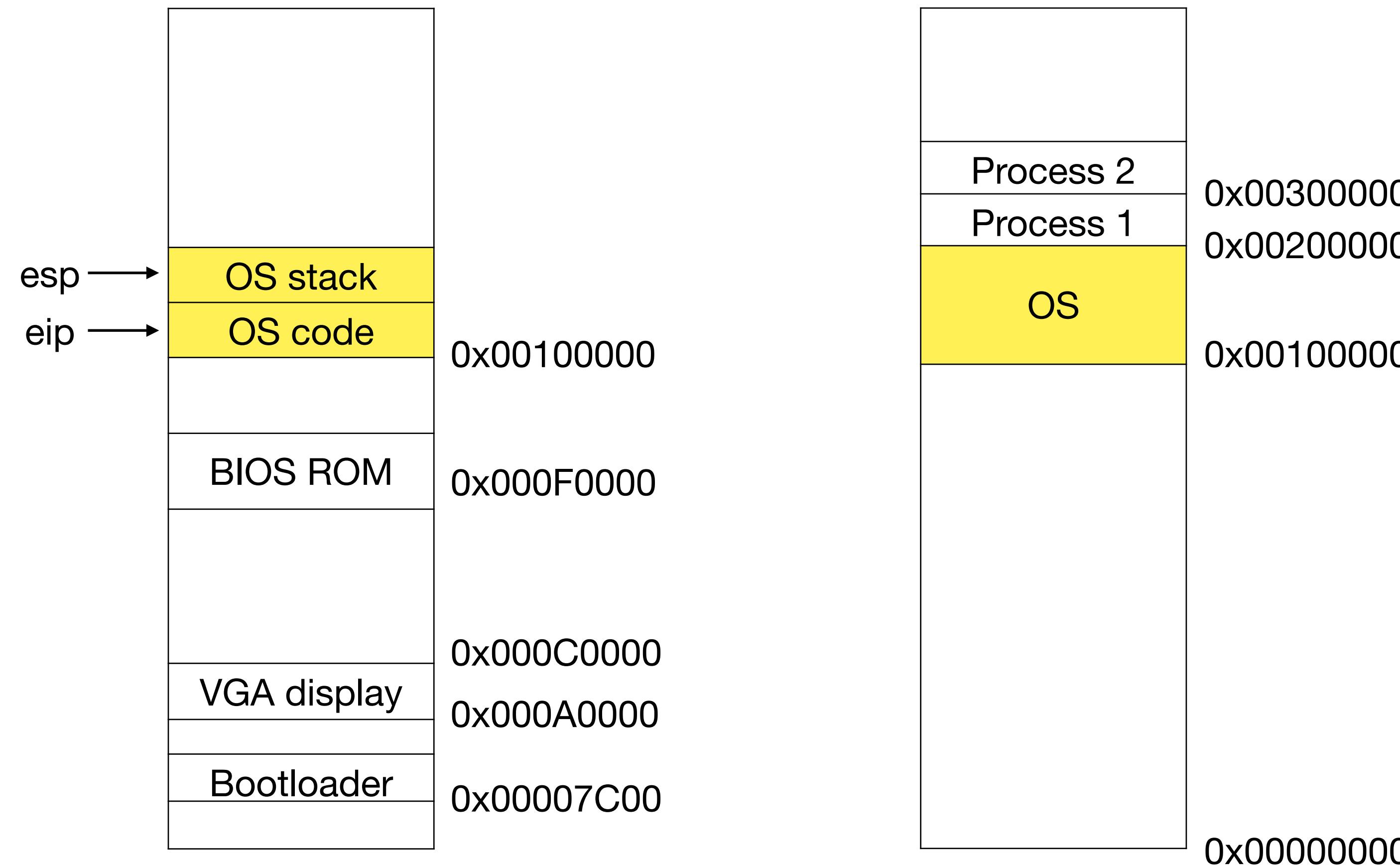
- Example:
 - $p1 = \text{malloc}(3)$
 - $p2 = \text{malloc}(2)$
- First fit with segregated lists approximates best fit
- Straightforward splitting and coalescing
- Deallocation order: fast frees
- Used in Linux kernel



Aside: automatic memory management

- “Higher level” languages do not expose raw pointers to programmers.
Example: Java, Python, Go
 - The language runtime manages memory. Programmer need not call free.
 - Largely prevents memory leaks, dangling references, double free, null pointer dereference
 - Mark and sweep garbage collector, reference counting based garbage collector
 - Copying GC can do compaction to defragment heap. Will rewrite pointers.
 - Can incur heavy performance penalty

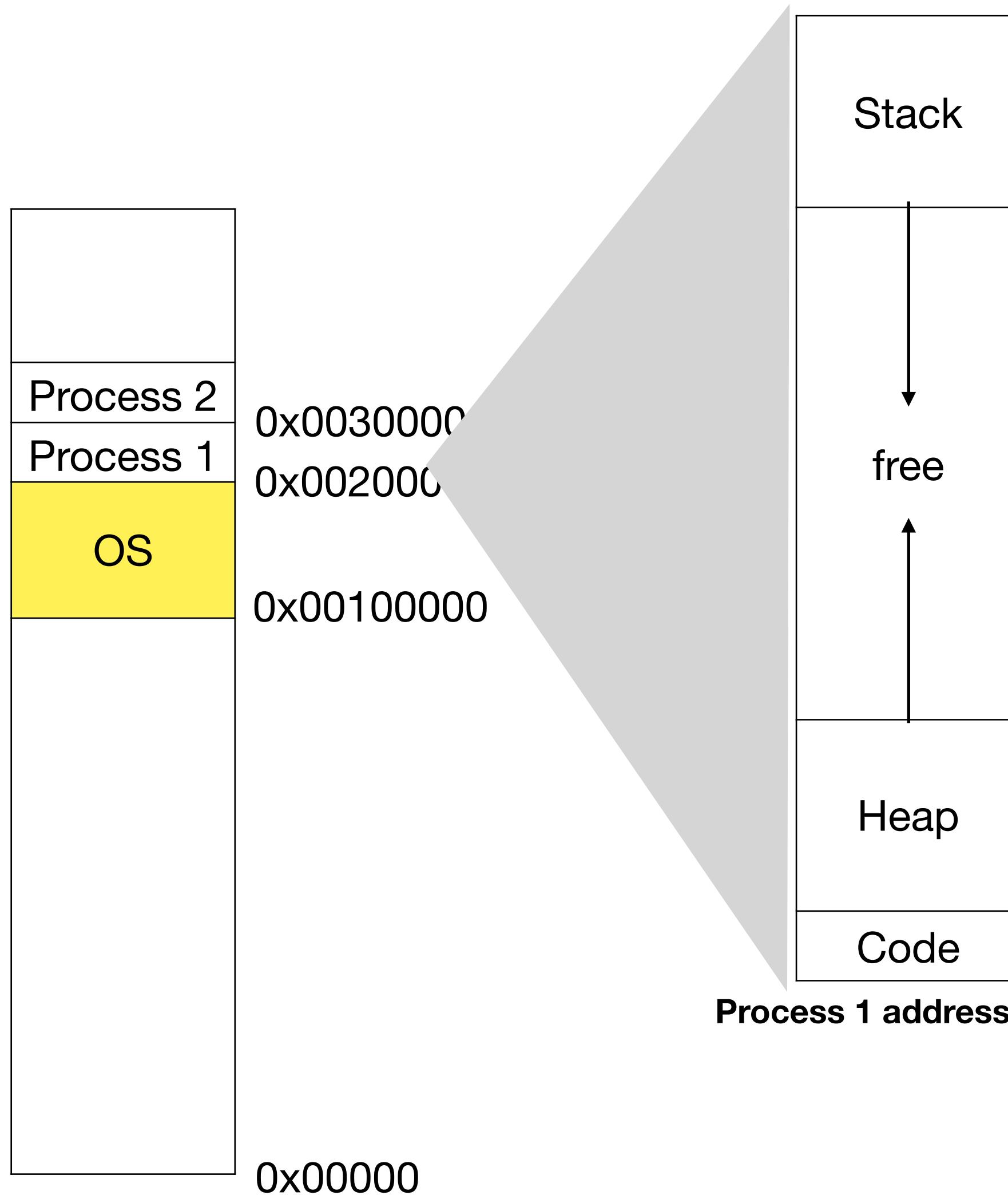
Memory isolation and address space



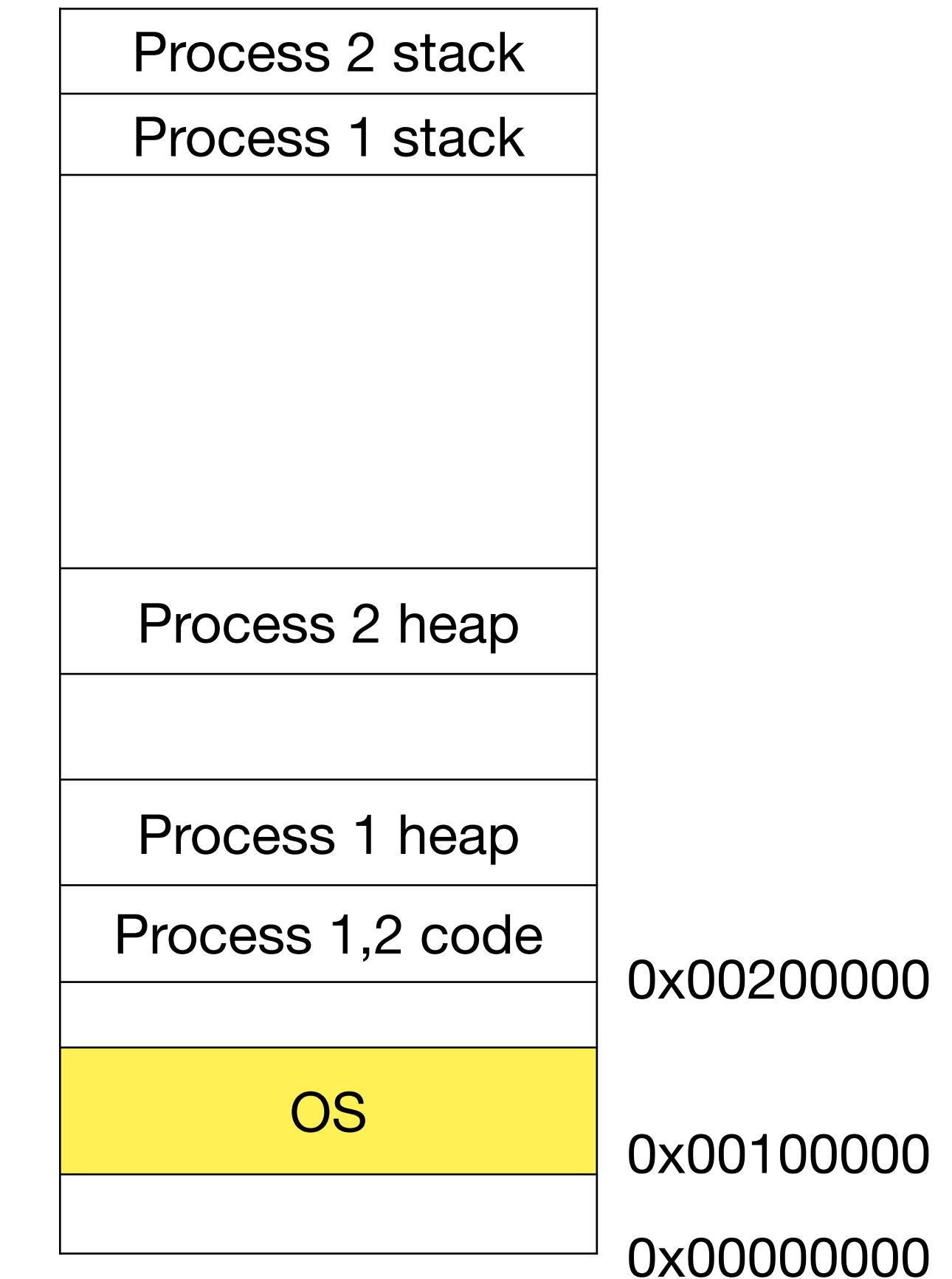
Process 1 address space

Due to address translation, compiler need not worry where the program will be loaded!

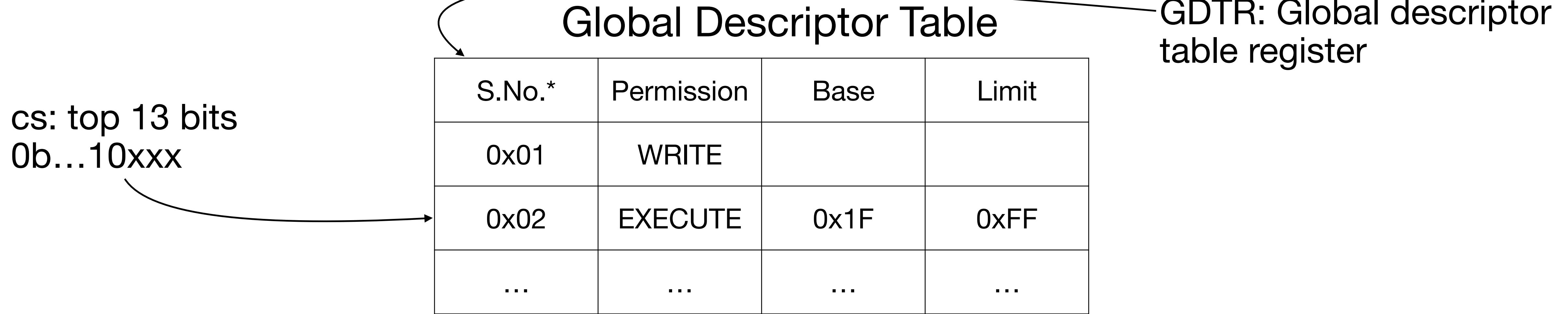
Segmentation



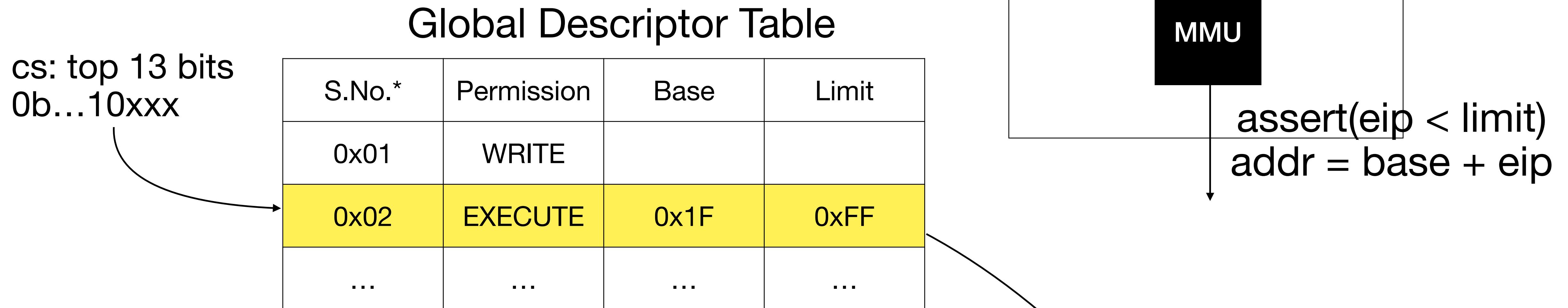
- Place each segment independently to not map free space
- Share code segments to save space
 - Mark non-writeable



Many segments can be initialised in GDT



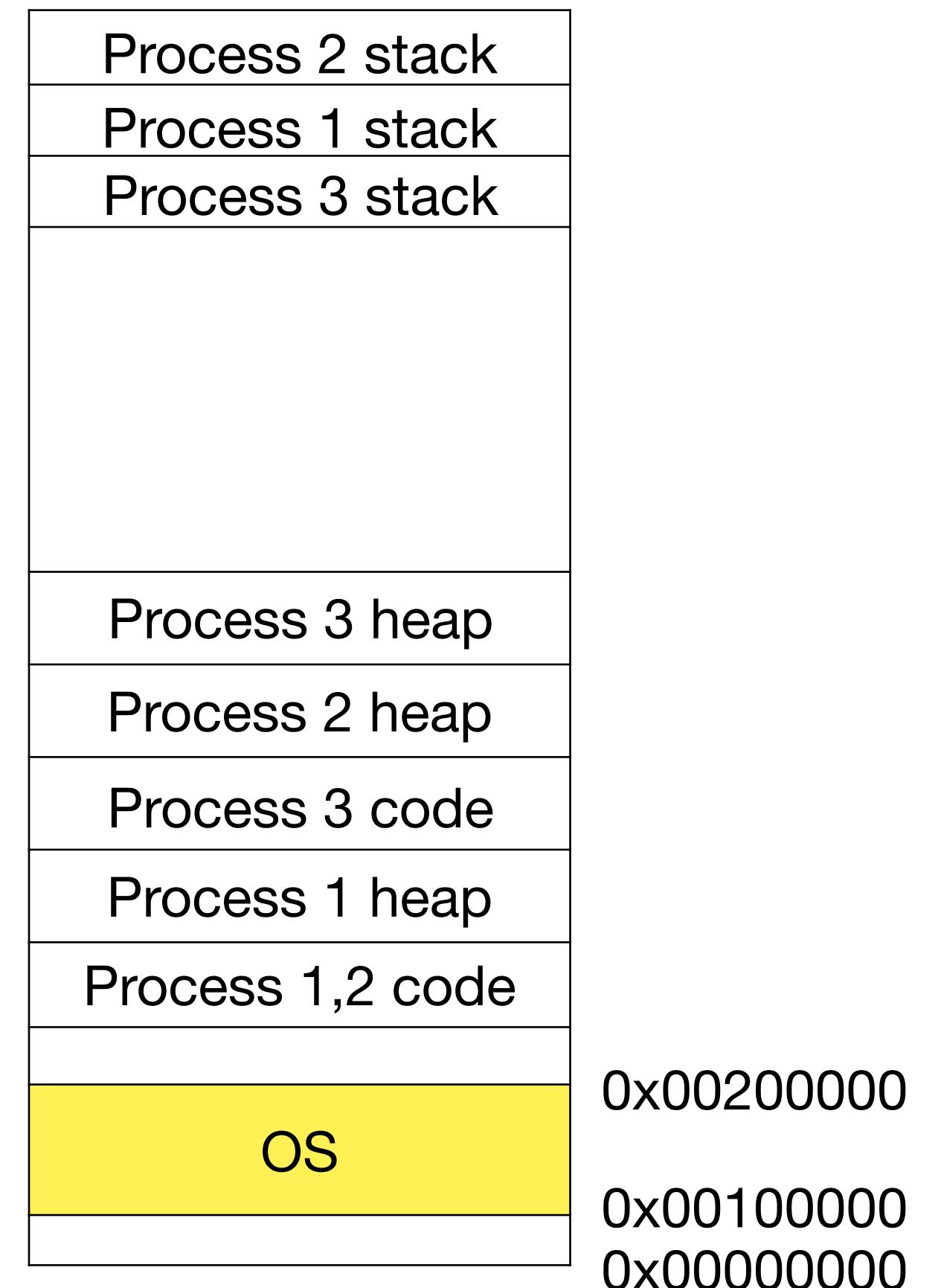
Address translation



- Can “protect” different segments from each other

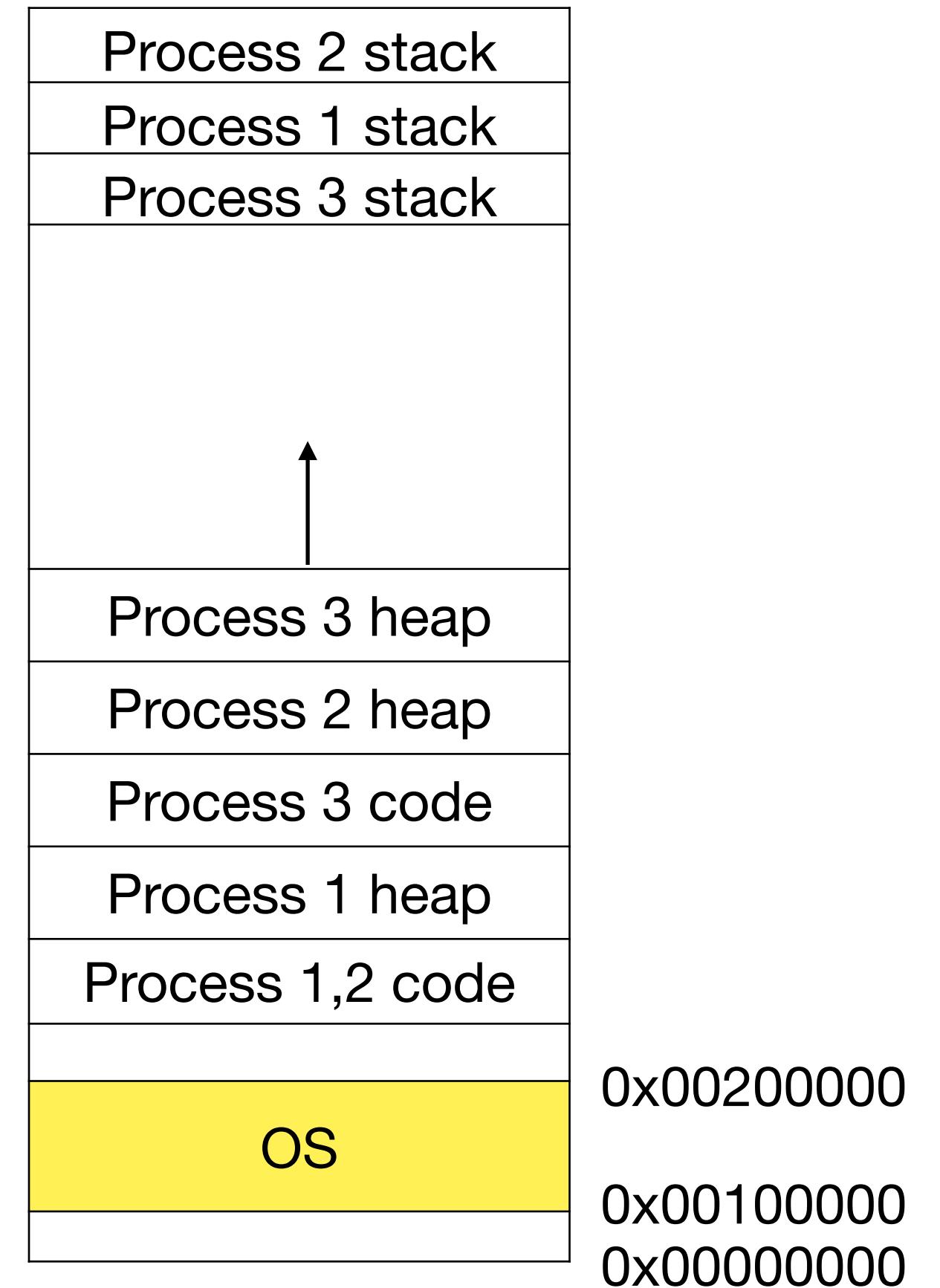
Allocating memory to a new process

- Find free spaces in physical memory.
- Create new entries in GDT for the new process.



Growing heap

- sbrk can grow heap segment



External fragmentation

- After many processes start and exit, memory might become “fragmented” (similar to disk)
 - Example: cannot allocate 20 KB segment
 - Compaction: copy all allocated regions contiguously, update segment base and bound registers
 - Copying is expensive
 - Growing heap becomes not possible

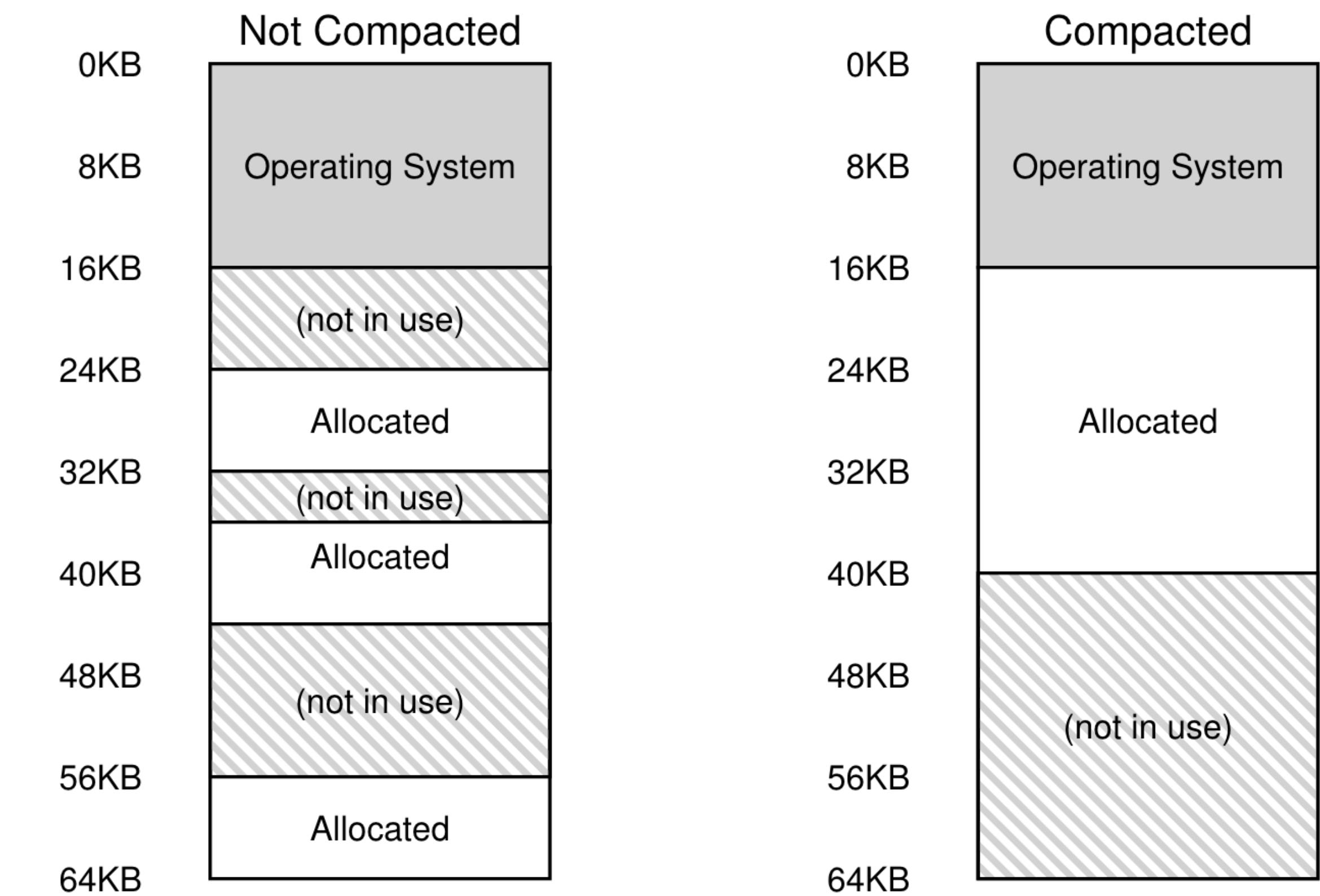
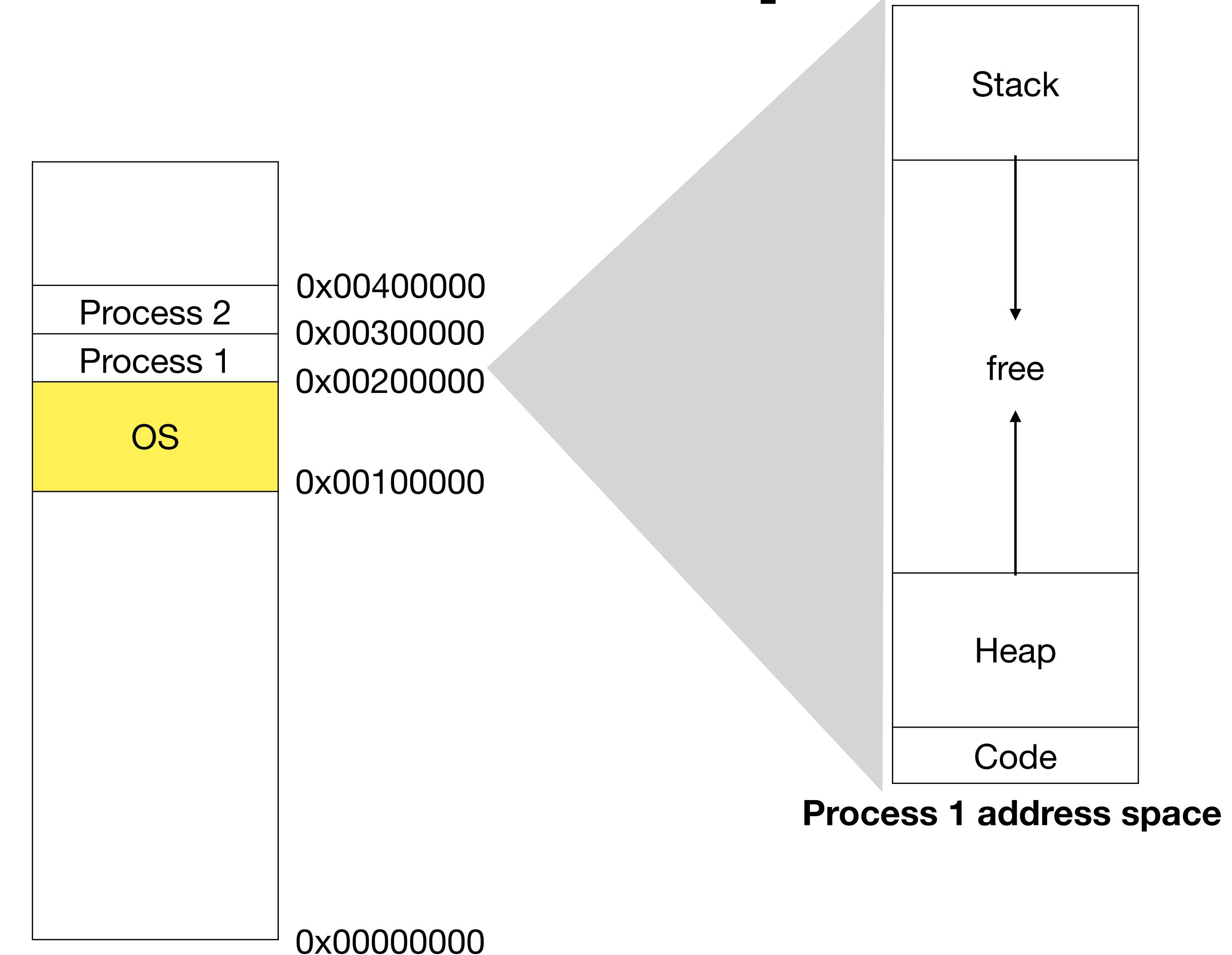


Figure 16.6: Non-compacted and Compacted Memory

Processes in action

xv6 Ch. 3: system calls, x86 protection, trap handlers

Memory isolation and address space



Protection

- Process cannot modify OS code since it is not in process' *address space*
- Process cannot modify GDT and IDT entries since GDT, IDT are not in its address space
- What stops process from calling lgdt and lidt instructions?
 - Ring 0: kernel mode. Ring 3: user mode
 - lgdt and lidt are *privileged instructions* only callable from “ring 0”

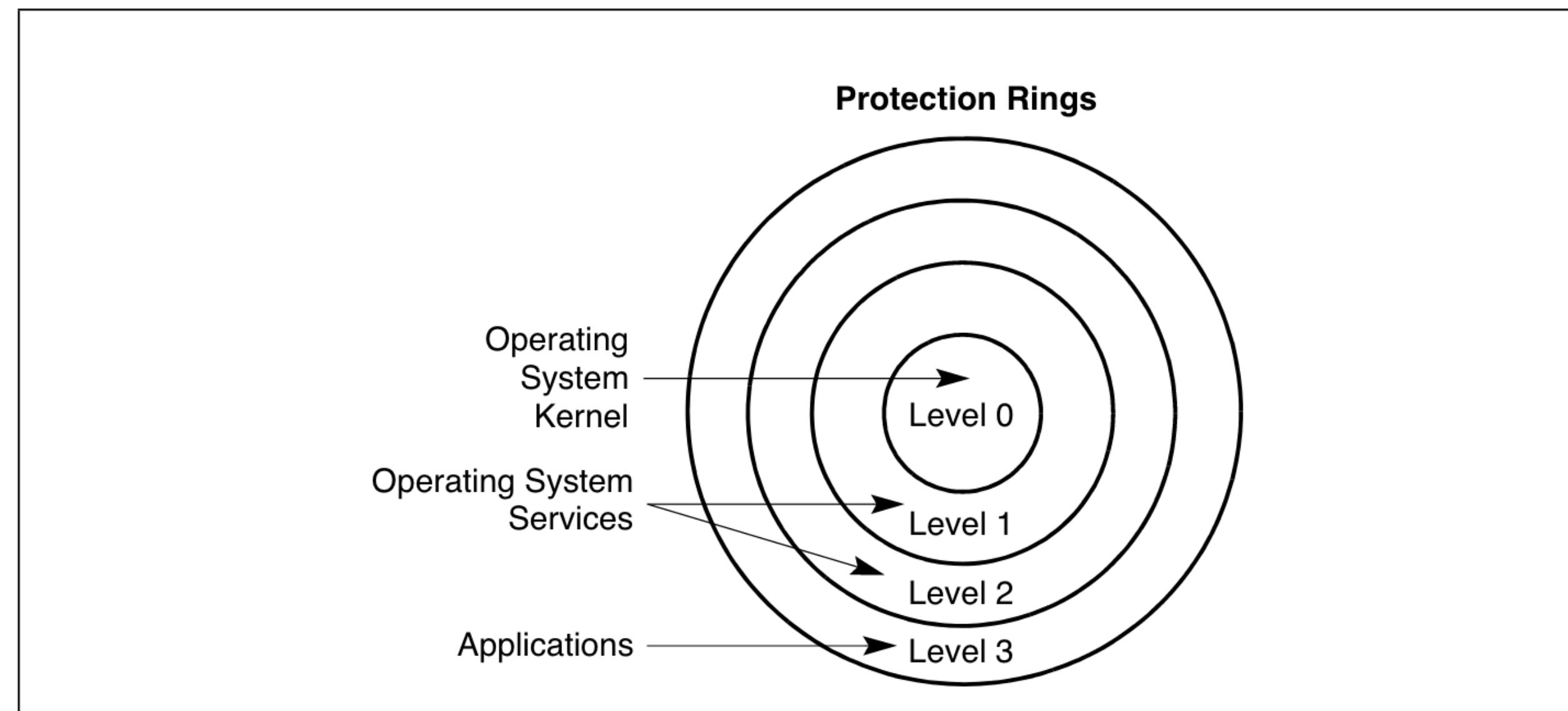
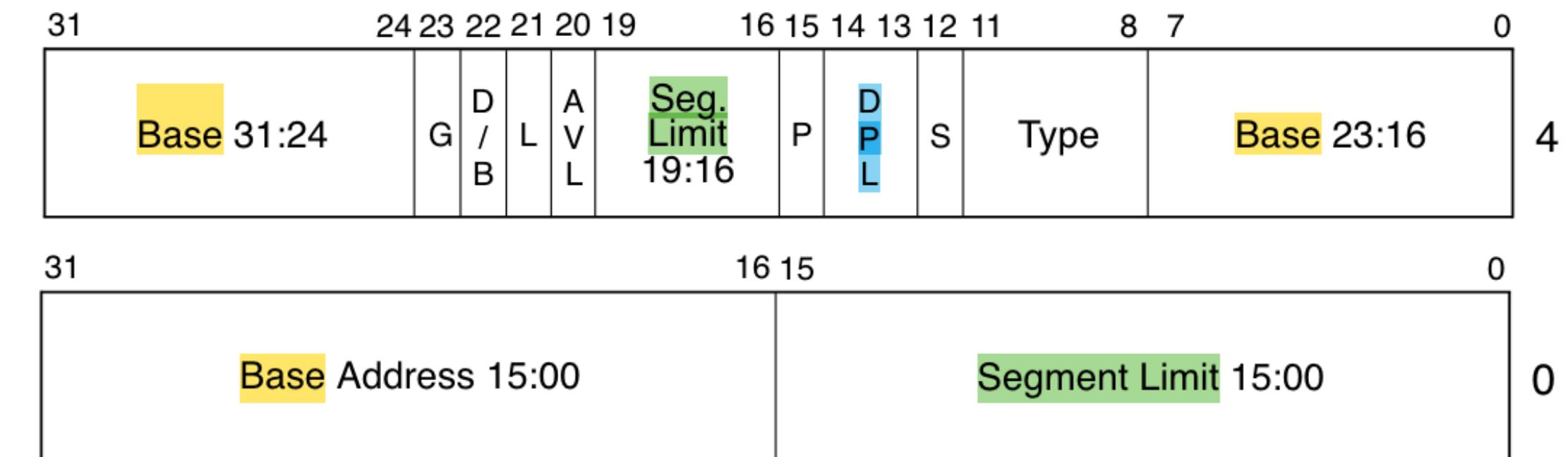


Figure 5-3. Protection Rings

How does hardware know the current privilege level?

- Two LSBs of %cs determine “current privilege level” (CPL)
- Two LSBs of other segment selectors specify “required privilege level” (RPL)
- Segment descriptor specifies “descriptor privilege level” (DPL)



Legend:

- 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

Figure 3-8. Segment Descriptor

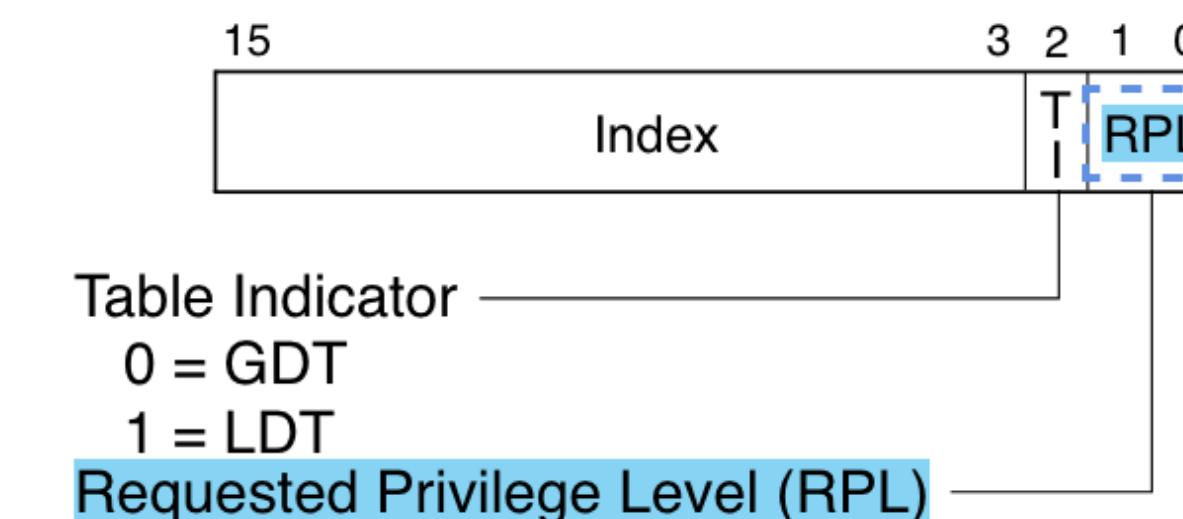


Figure 3-6. Segment Selector

How does hardware enforce the current privilege level?

- Privileged instructions can only be called when CPL=0
- Programs can change their segment selectors
 - Programs cannot lower their CPL directly
 - INT instruction causes a software interrupt to set ring = 0
 - CPL <= DPL and RPL <= DPL

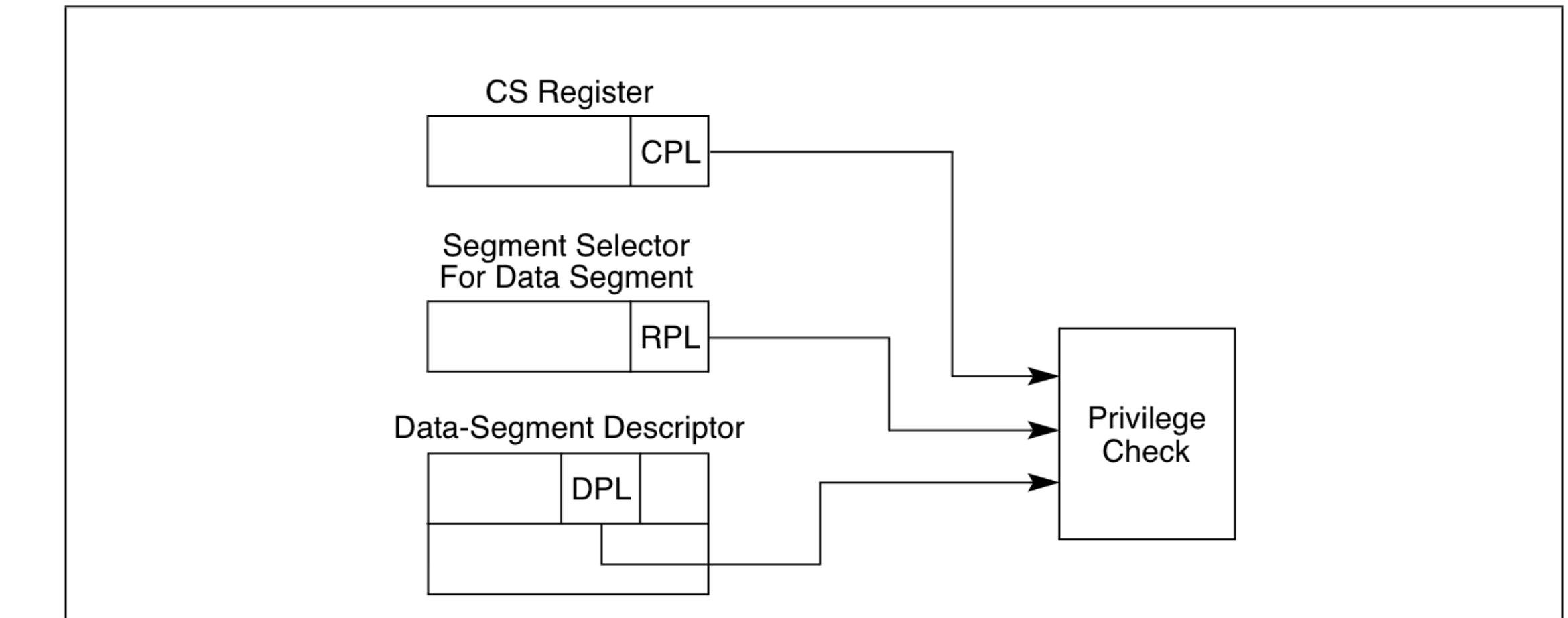


Figure 5-4. Privilege Check for Data Access

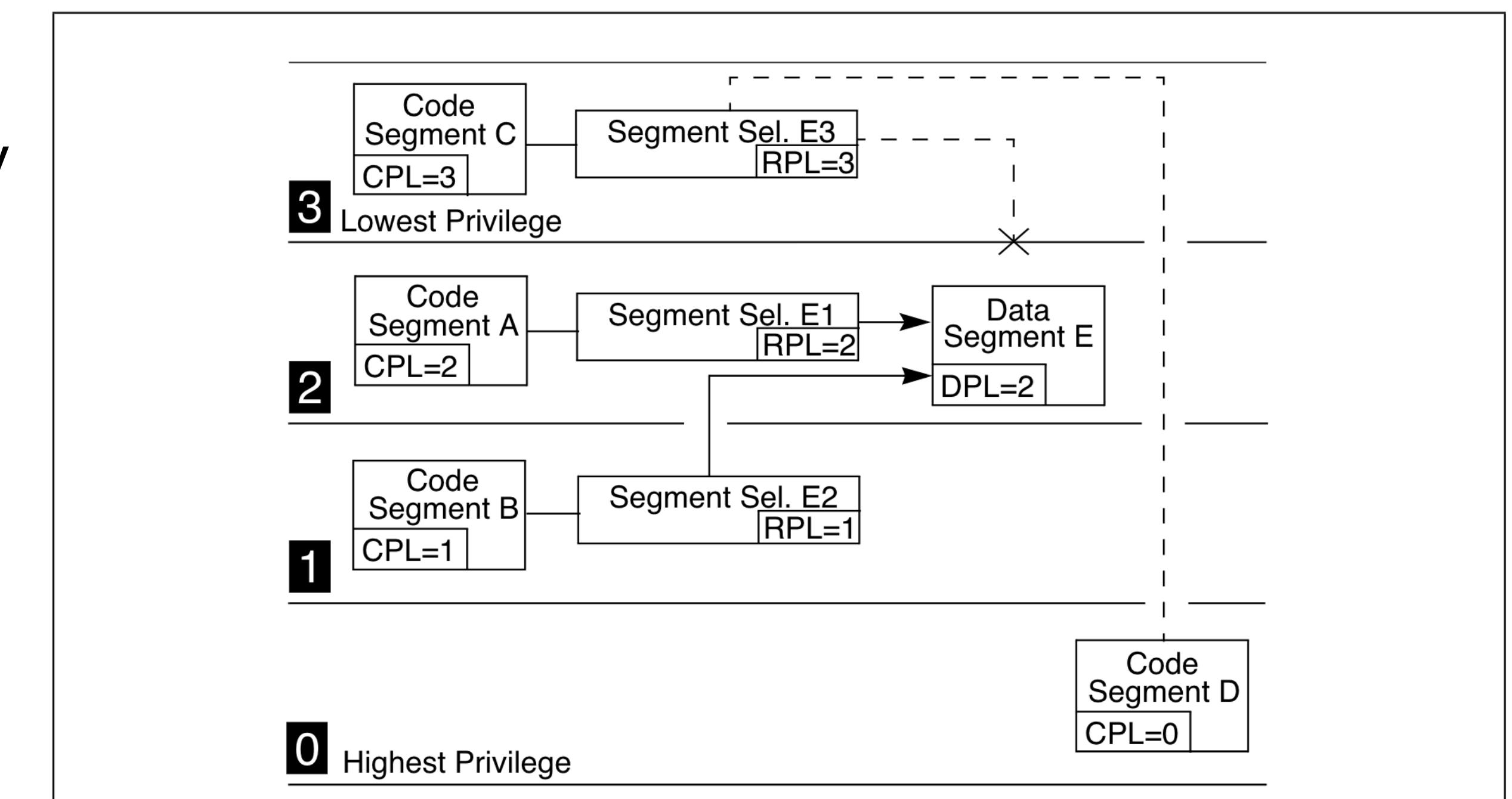
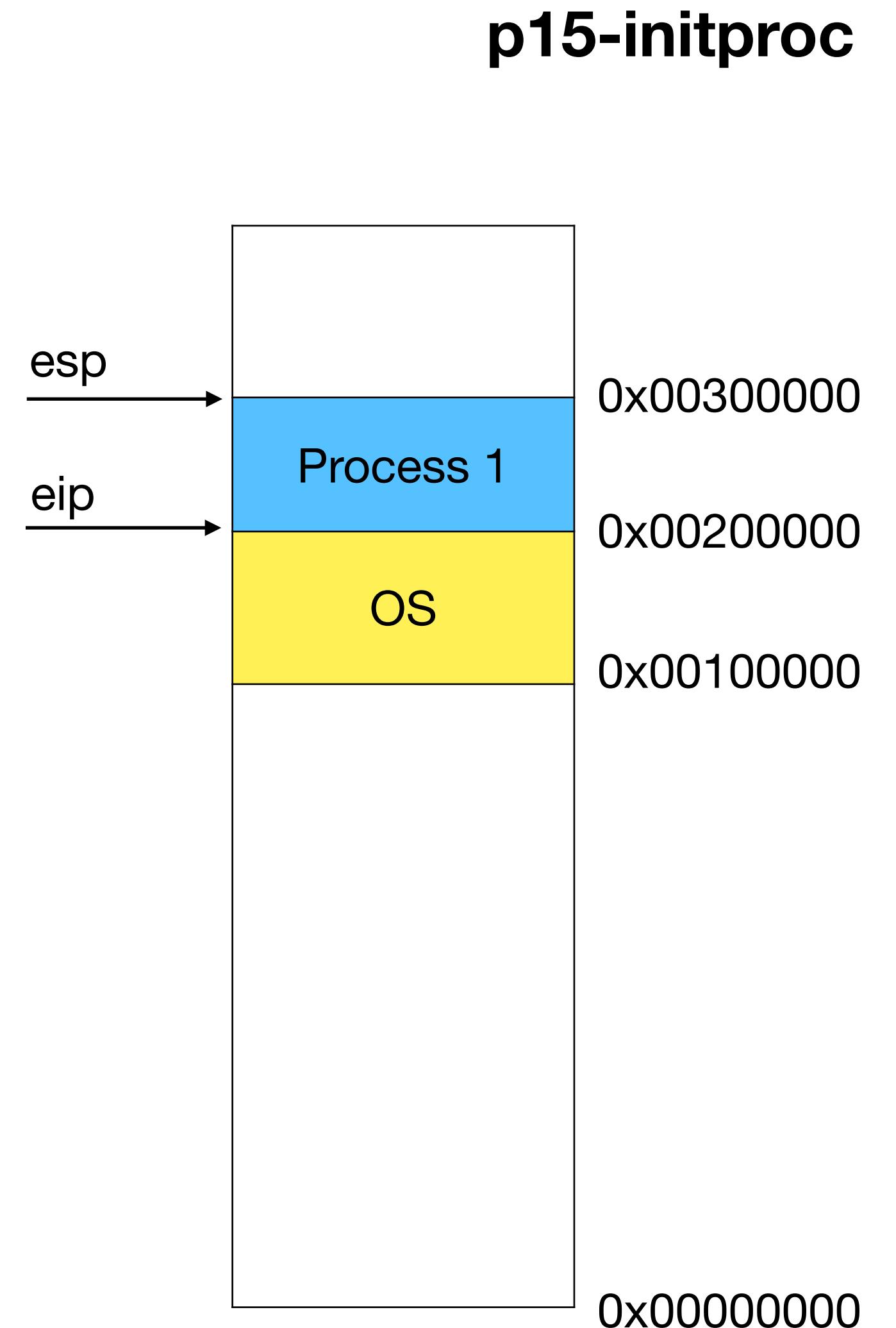


Figure 5-5. Examples of Accessing Data Segments From Various Privilege Levels

Setting up our first process in xv6!

- main.c calls seginit, then pinit, then scheduler.
- seginit in vm.c creates code (UCODE) and data segments (UDATA) from STARTPROC (2MB) to 3MB. Flat memory model!
- pinit in proc.c copies program binary to STARTPROC and sets cs,ds,ss,es to the program's segments. Last two bits are set to DPL_USER. Sets eip=0, esp=1MB. Enables interrupt flag in eflags. proc.c maintains list of processes in ptable. We are just starting one process for now.
- scheduler in proc.c selects RUNNABLE process and switches to it.
- Process cannot change GDT entries, IDT entries since they are not in address space of the process! Process cannot call lgdt, lidt since it will run in ring 3.



Understanding swtch

```
pinit(){  
    p = allocproc();  
  
    memmove(p->offset, _binary_initcode_start,);  
  
    p->tf->ds,es,ss = (SEG_UDATA<<3) | DPL_USR;  
    p->tf->cs = (SEG_UCODE<<3) | DPL_USR;  
    p->tf->eflags = FL_IF;  
    p->tf->eip = 0;  
}  
}
```

```
eip  
allocproc() {  
    sp = (char*)(STARTPROC + (PROCSIZE>>12));  
  
    sp -= sizeof *p->tf;  
  
    p->tf = (struct trapframe*)sp;  
  
    sp -= sizeof *p->context;  
  
    p->context = (struct context*)sp;  
  
    p->context->eip = (uint)trapret;  
  
    return p;  
}  
}
```

```
scheduler()
```

```
...
```

```
    swtch(p->context);  
}  
}
```

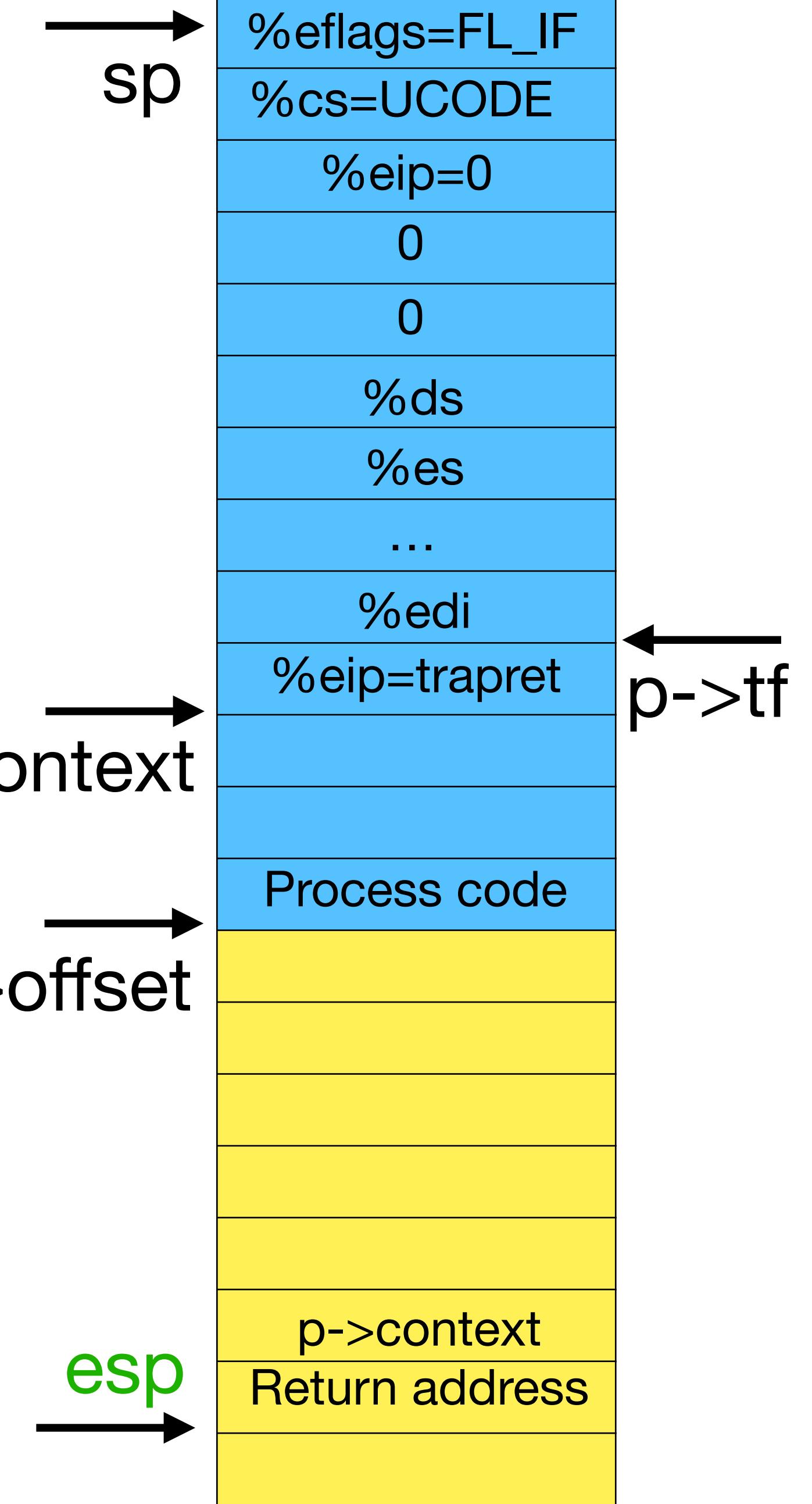
```
swtch:
```

```
    movl 4(%esp), %eax  
    movl %eax, %esp  
    movl $0, %eax  
    ret
```

```
.globl trapret
```

```
trapret:
```

```
    popal  
    popl %gs  
    popl %fs  
    popl %es  
    popl %ds  
    addl $0x8, %esp  
    iret
```



Interrupt handling revisited

```
eip → for(;;)
;
trap.c
void
trap(struct trapframe *tf)
{
    switch(tf->trapno){
    case T_IRQ0 + IRQ_TIMER:
        ticks++;
        cprintf("Tick! %d\n", ticks);
        lapiceoi();
    ...
return
```

vectors.S

```
.globl vector0
vector0:
    pushl $0
    pushl $0
    jmp alltraps
```

trapasm.S

```
alltraps:
    pushal
    pushl %esp
    call trap
    addl $4, %esp
    popal
    addl $0x8, %esp
    iret
```

IDT

GDT

ebp

trap frame

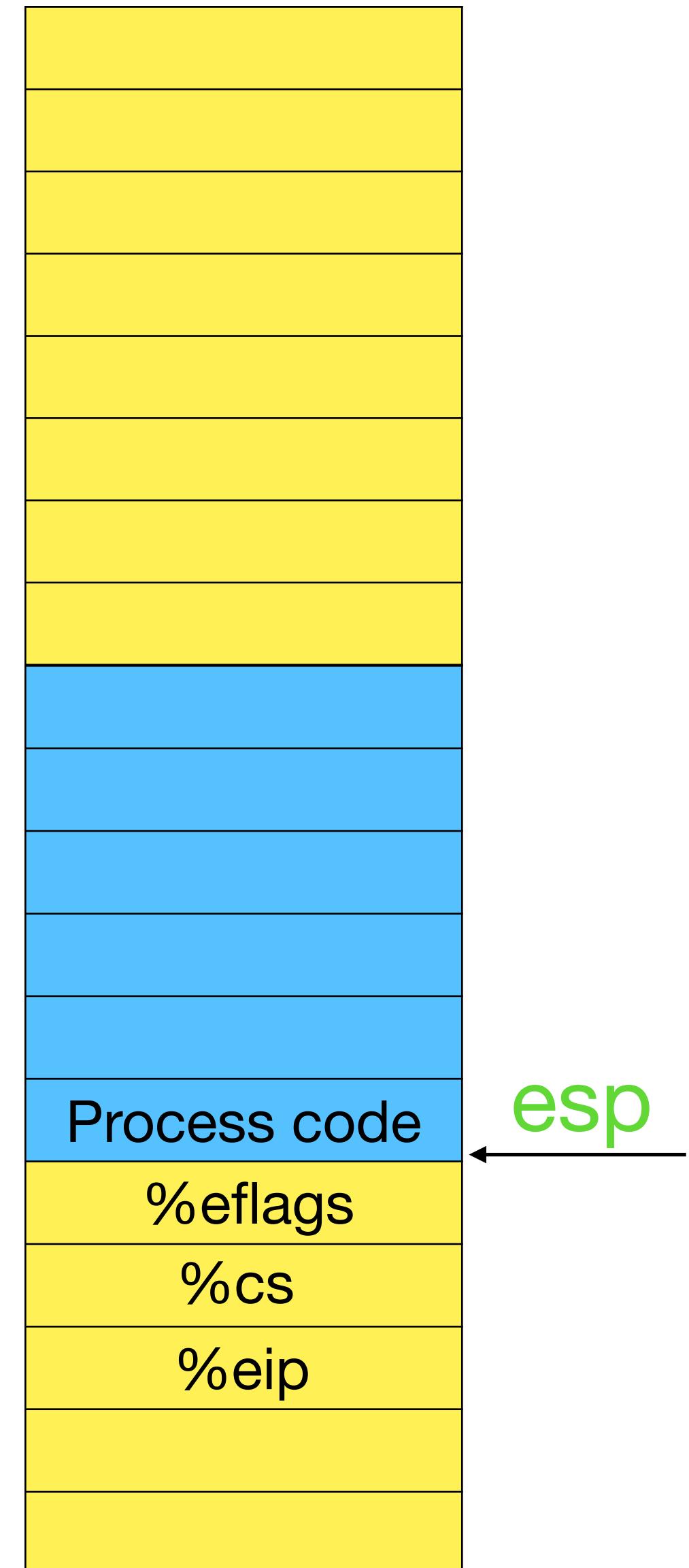
esp

Stack

...
param 1
%eip
%ebp_old
local var 1
local var 2
%eflags
%cs
%eip
0
0
%eax
%ecx
...
%edi
tf
%eip

Interrupt handling problem

- We cannot trust `%esp` of the process. Hardware might write (`%eflags`, `%cs`, `%eip`) into another process' address space or into OS memory.
- Use a separate stack set up by the OS!



OS tells hardware where the kernel stack is

- In task-state segment (TSS), OS sets up
 - Stack segment for transition to ring 0 in SS0 and
 - Stack pointer for transition to ring 0 in ESP0

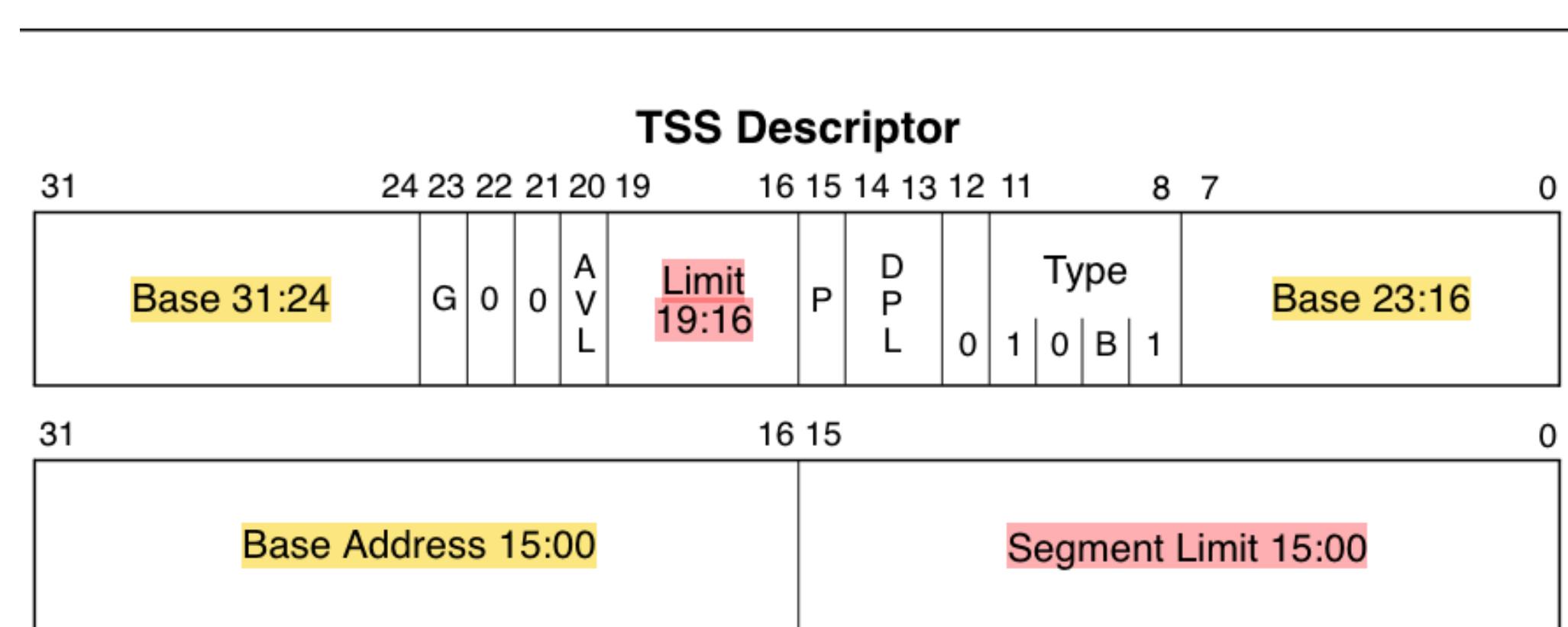
31	15	0
I/O Map Base Address	Reserved	T 100
Reserved	LDT Segment Selector	96
Reserved	GS	92
Reserved	FS	88
Reserved	DS	84
Reserved	SS	80
Reserved	CS	76
Reserved	ES	72
	EDI	68
	ESI	64
	EBP	60
	ESP	56
	EBX	52
	EDX	48
	ECX	44
	EAX	40
	EFLAGS	36
	EIP	32
	CR3 (PDBR)	28
Reserved	SS2	24
	ESP2	20
Reserved	SS1	16
	ESP1	12
Reserved	SS0	8
	ESP0	4
Reserved	Previous Task Link	0

 Reserved bits. Set to 0.

Figure 7-2. 32-Bit Task-State Segment (TSS)

OS tells hardware where the kernel stack is (2)

- OS sets up an entry in GDT that contains location of TSS
 - LTR instruction changes task register



AVL	Available for use by system software
B	Busy flag
BASE	Segment Base Address
DPL	Descriptor Privilege Level
G	Granularity
LIMIT	Segment Limit
P	Segment Present
TYPE	Segment Type

Figure 7-3. TSS Descriptor

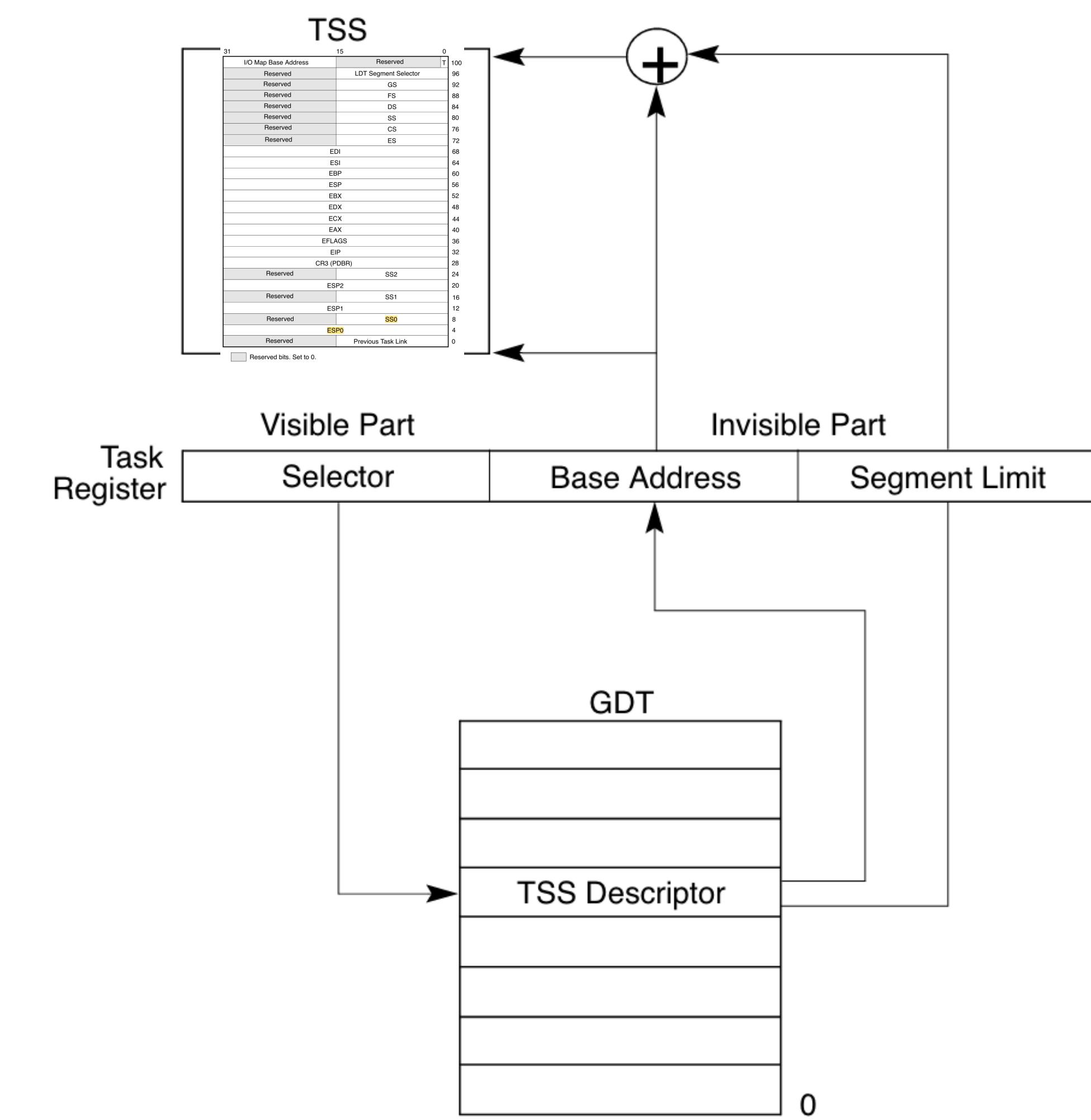
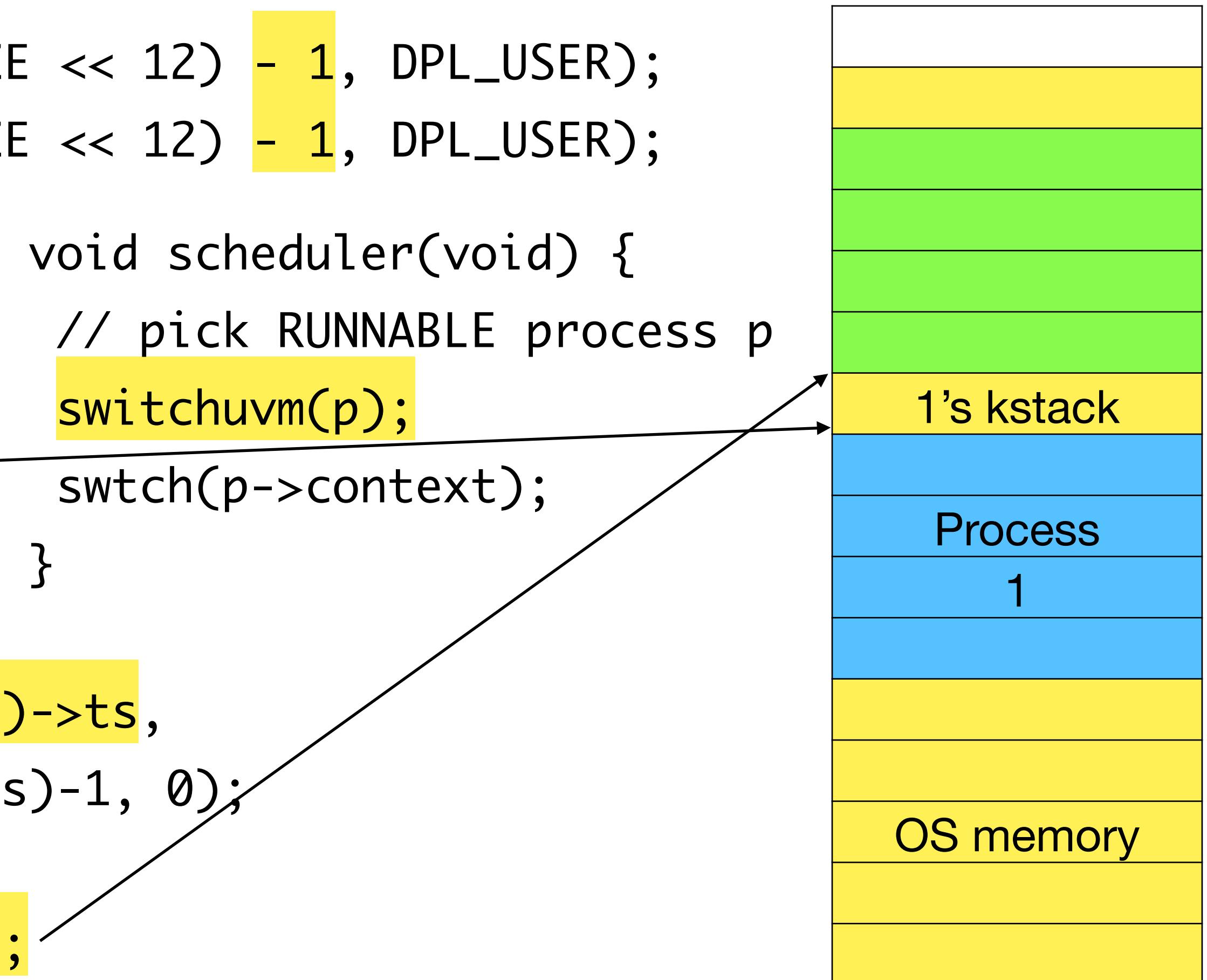


Figure 7-5. Task Register

Code walkthrough: setting up kernel stack p16-tss

```
void seginit(void) {  
    c->gdt[SEG_UCODE] = SEG(.., STARTPROC, (PROCSIZE << 12) - 1, DPL_USER);  
    c->gdt[SEG_UDATA] = SEG(.., STARTPROC, (PROCSIZE << 12) - 1, DPL_USER);  
}  
  
static struct proc* allocproc(void) {  
    sp = (char*)(STARTPROC + (PROCSIZE>>12));  
    p->kstack = sp - KSTACKSIZE;  
}  
  
void switchuvm(struct proc *p) {  
    mycpu()->gdt[SEG_TSS] = SEG16(STS_T32A, &mycpu()->ts,  
                                    sizeof(mycpu()->ts)-1, 0);  
    mycpu()->ts.ss0 = SEG_KDATA << 3;  
    mycpu()->ts.esp0 = (uint)p->kstack + KSTACKSIZE;  
    ltr(SEG_TSS << 3);  
}
```



Interrupt handling

- Each IDT entry is 64-bits. Contains code segment and eip
- When interrupt appears,
 - Hardware changes SS and ESP according to the TSS
 - Hardware changes CS and EIP to the one pointed by IDT entry.

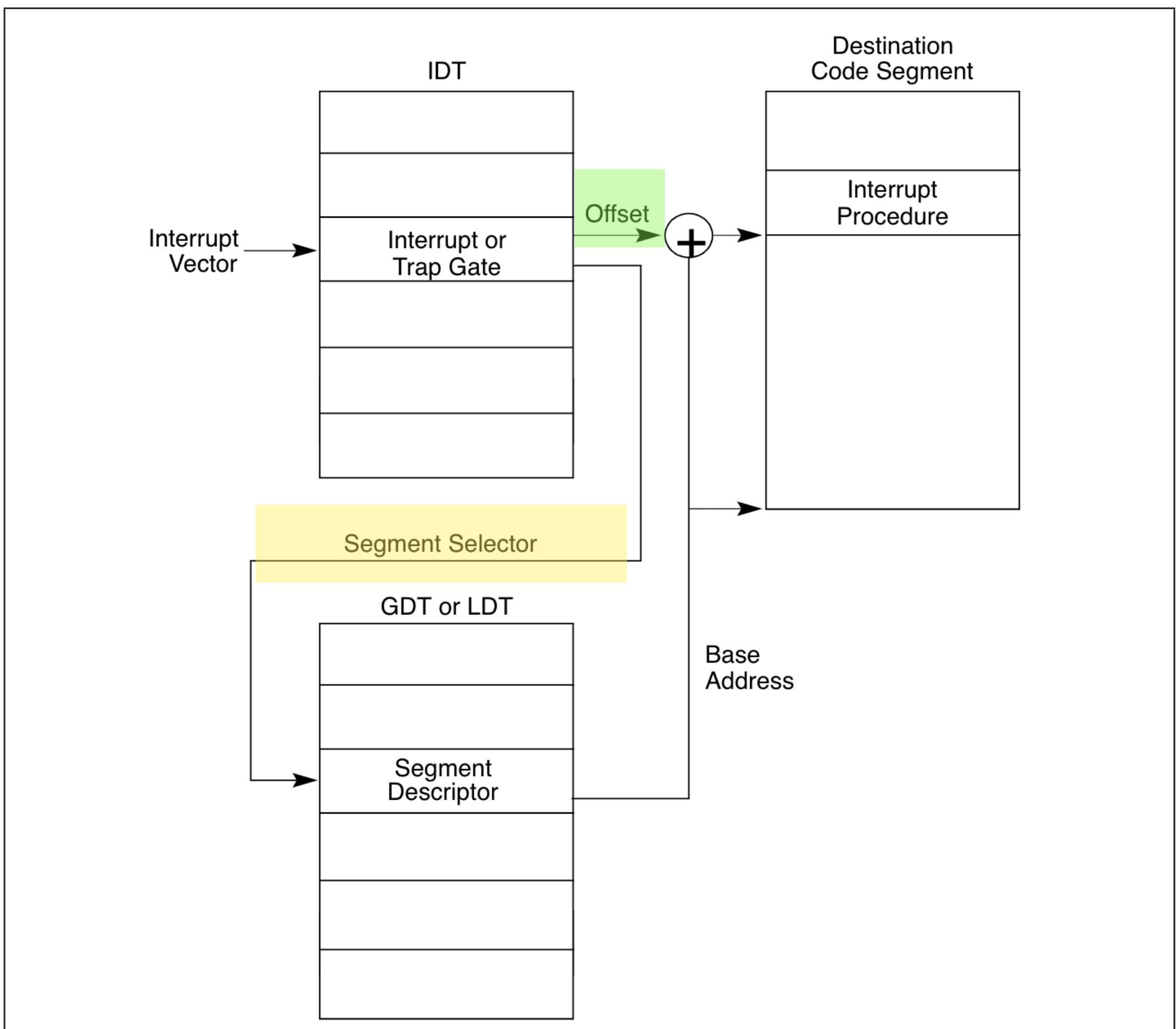
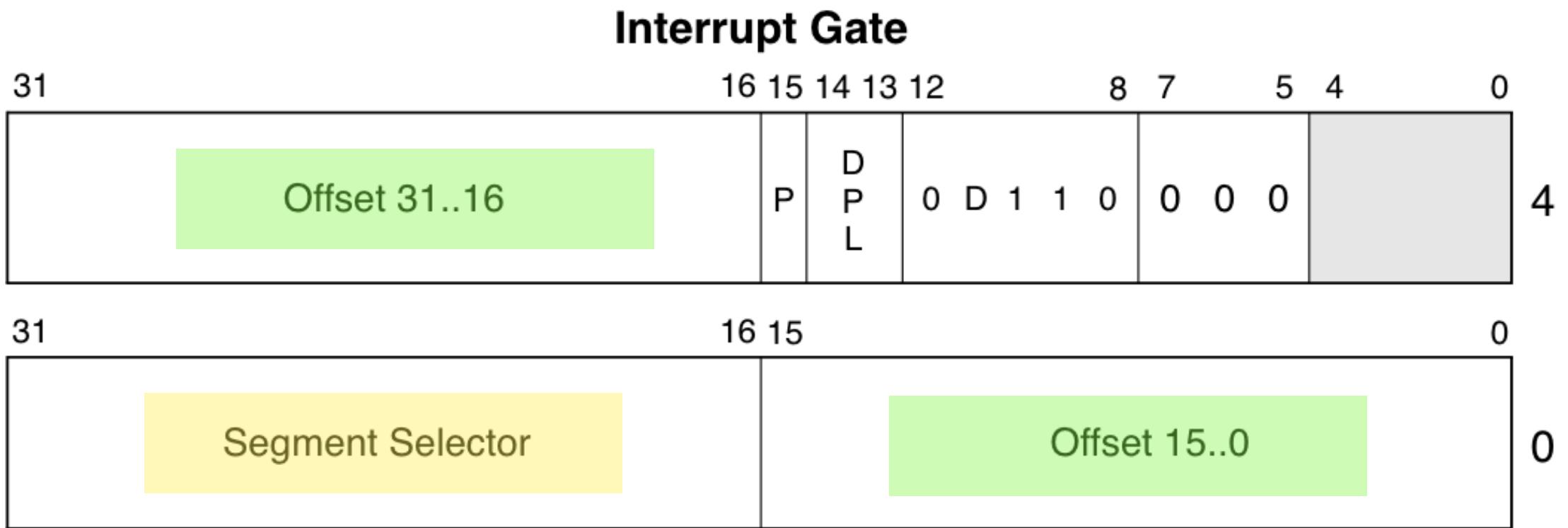


Figure 6-3. Interrupt Procedure Call

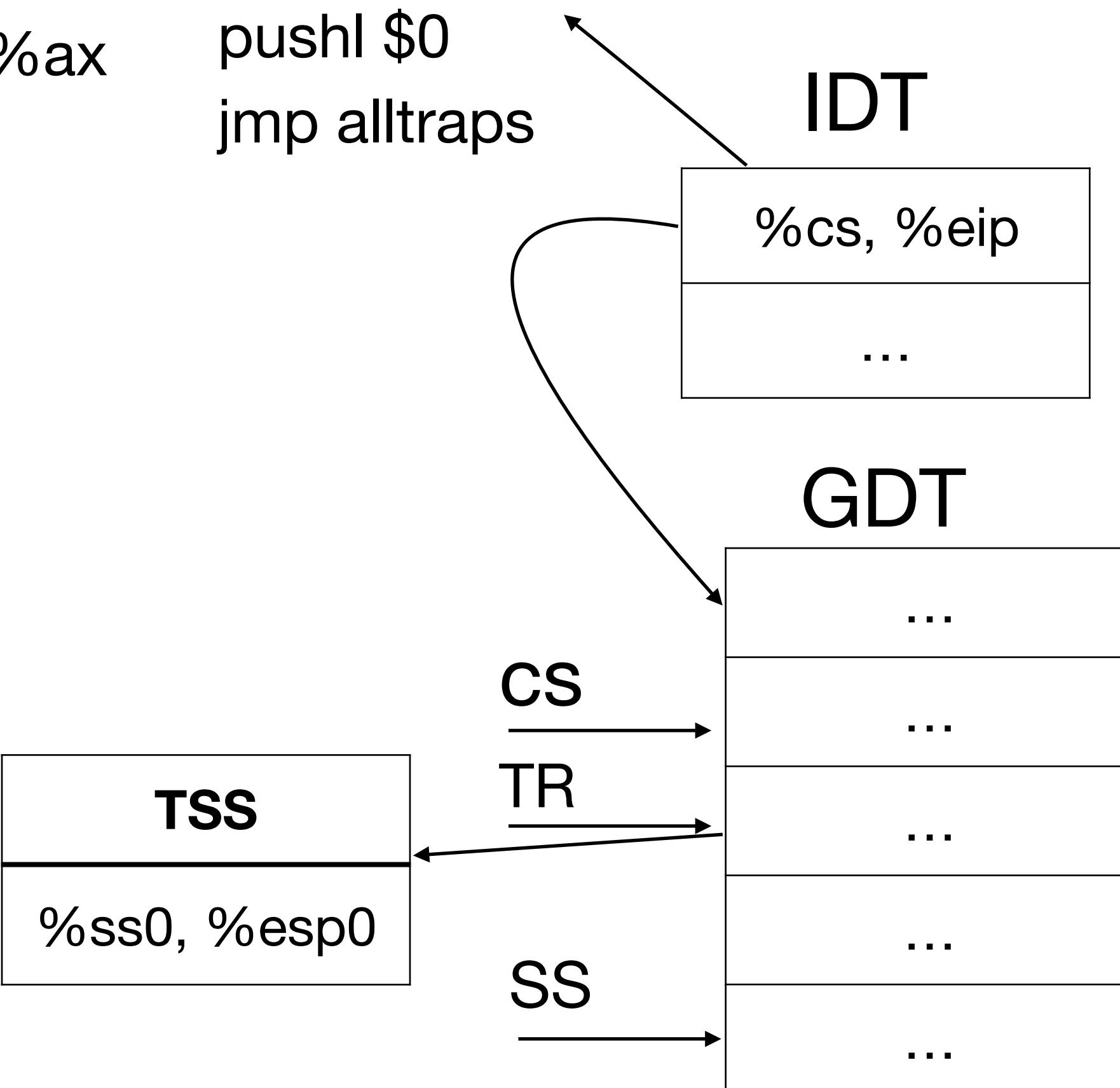
Interrupt handling with user process running

eip → for(;;)
;

trapasm.S
alltraps:
pushl %ds..
pushal
movw \$(SEG_KDATA<<3), %ax
movw %ax, %ds..
pushl %esp
call trap
addl \$4, %esp
popal
popl %ds..
addl \$0x8, %esp
iret

vectors.S

.globl vector0
vector0:
pushl \$0
pushl \$0
jmp alltraps

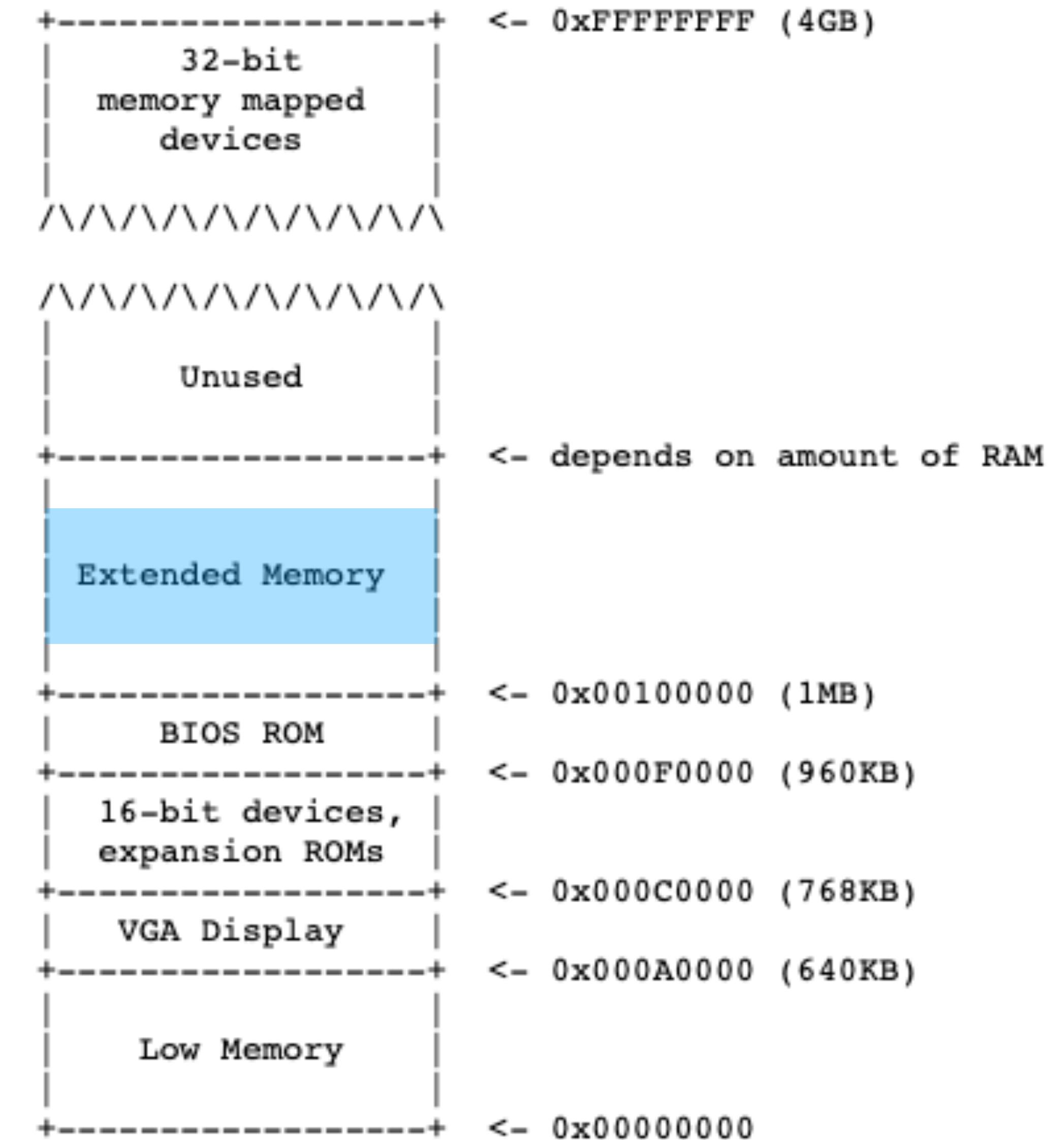


Protection so far

- Can processes read/write each other's memory?
 - No, since the other process' memory is not *addressable* by (not in the *address space* of) the process
- Can process take over IDT, GDT, TSS?
 - IDT, GDT, TSS are not in address space. Cannot run LIDT, LGDT, LTR instructions since they are *privileged instructions* (only runnable from ring 0)
- Can process change its privilege to ring 0?
 - Not directly. It can change only via trap handling mechanism. OS code runs upon a trap. Trap handling writes to kernel stack.
- Can process run away with the CPU?
 - CPU will be snatched at the time of timer interrupt

IO protection

- Memory mapped IO
 - Can directly read from / write to IO devices if OS keeps it in *process address space*



Port-mapped IO protection

inb(0x1F7), outb(0x1F2, 1), ...

- Option 1: Make in and out instruction privileged. Processes must do IO via kernel.
 - Expensive user mode-kernel mode transitions for IO intensive processes.
- Option 2: Set EFLAGS.IOPL = 3
 - Processes (CPL=3) cannot modify EFLAGS.IOPL
 - Gives permission to access all IO ports

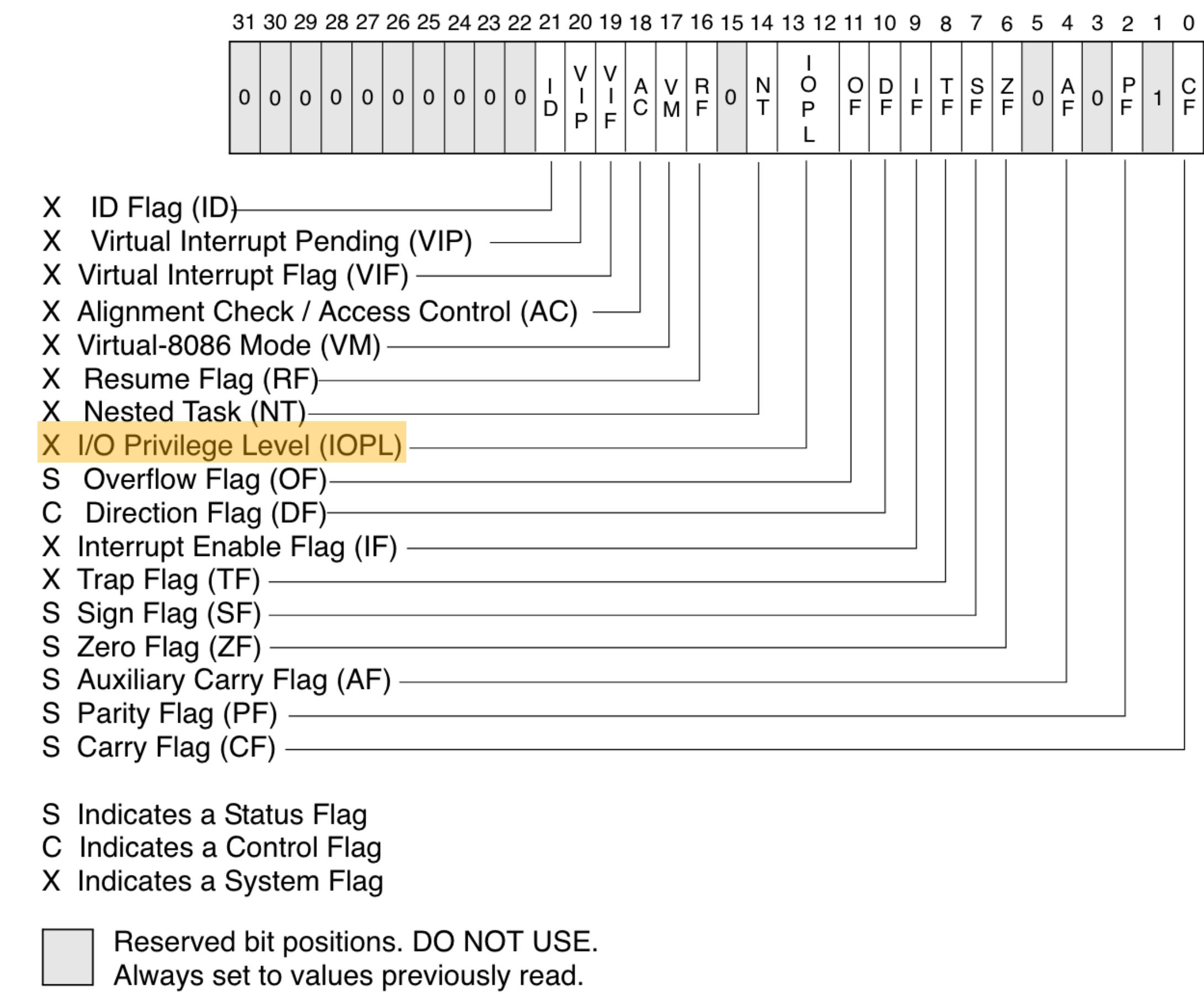


Figure 3-8. EFLAGS Register

Port-mapped IO protection (2)

- Option 3: Use a bitmap to decide which IO ports are directly accessible
 - If CPL > EFLAGS.IOPL, use bitmap to decide if in, out instruction should generate a trap
 - Example: `outb(41, 1)` is allowed if 41st bit is set to 0

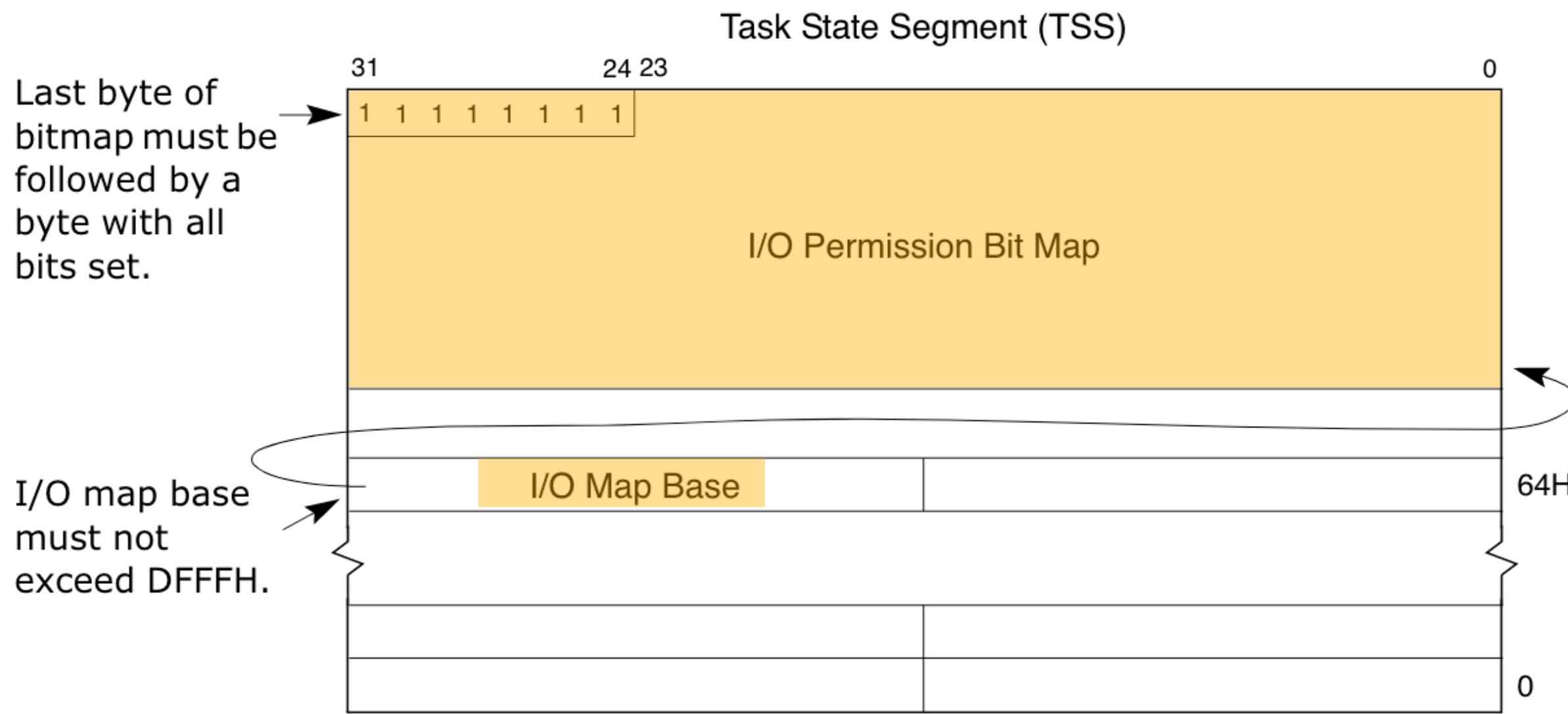


Figure 18-2. I/O Permission Bit Map

31	I/O Map Base Address	15	Reserved	0
	Reserved		LDT Segment Selector	100
	Reserved		GS	96
	Reserved		FS	92
	Reserved		DS	88
	Reserved		SS	84
	Reserved		CS	80
	Reserved		ES	76
			EDI	72
			ESI	68
			EBP	64
			ESP	60
			EBX	56
			EDX	52
			ECX	48
			EAX	44
			EFLAGS	40
			EIP	36
			CR3 (PDBR)	32
	Reserved		SS2	28
			ESP2	24
	Reserved		SS1	20
			ESP1	16
	Reserved		SS0	12
			ESP0	8
	Reserved		Previous Task Link	4
				0

Legend: Reserved bits. Set to 0.

Figure 7-2. 32-Bit Task-State Segment (TSS)

IO protection in xv6

```
void pinit(void) {  
    ..  
    p->tf->eflags = FL_IF;  
}
```

```
void switchuvm(struct proc *p) {  
    mycpu()->gdt[SEG_TSS] = SEG16(STS_T32A, &mycpu()->ts,  
                                    sizeof(mycpu()->ts)-1, 0);  
    mycpu()->ts.ss0 = SEG_KDATA << 3;  
    mycpu()->ts.esp0 = (uint)p->kstack + KSTACKSIZE;  
    // setting IOPL=0 in eflags *and* iomb beyond the tss segment limit  
    // forbids I/O instructions (e.g., inb and outb) from user space  
    mycpu()->ts.iomb = (ushort) 0xFFFF;  
    ltr(SEG_TSS << 3);  
}
```

- Processes cannot directly do IO
 - MMIO: Do not map IO addresses in process address space
 - PIO: Running in and out instructions will generate a trap (jump to OS)