Processes

Abhilash Jindal

Agenda

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- Vocabulary (OSTEP Ch. 4)
  - What is a process? System calls? Scheduler? Address space?

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  - How to manage and isolate memory? What are memory APIs? How are they implemented?

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- Processes in action (xv6 Ch. 3: system calls, x86 protection, trap handlers)
  - Process control block, user stack<>kernel stack, sys call handling

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- Memory management (OSTEP Ch. 13-17)
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- 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

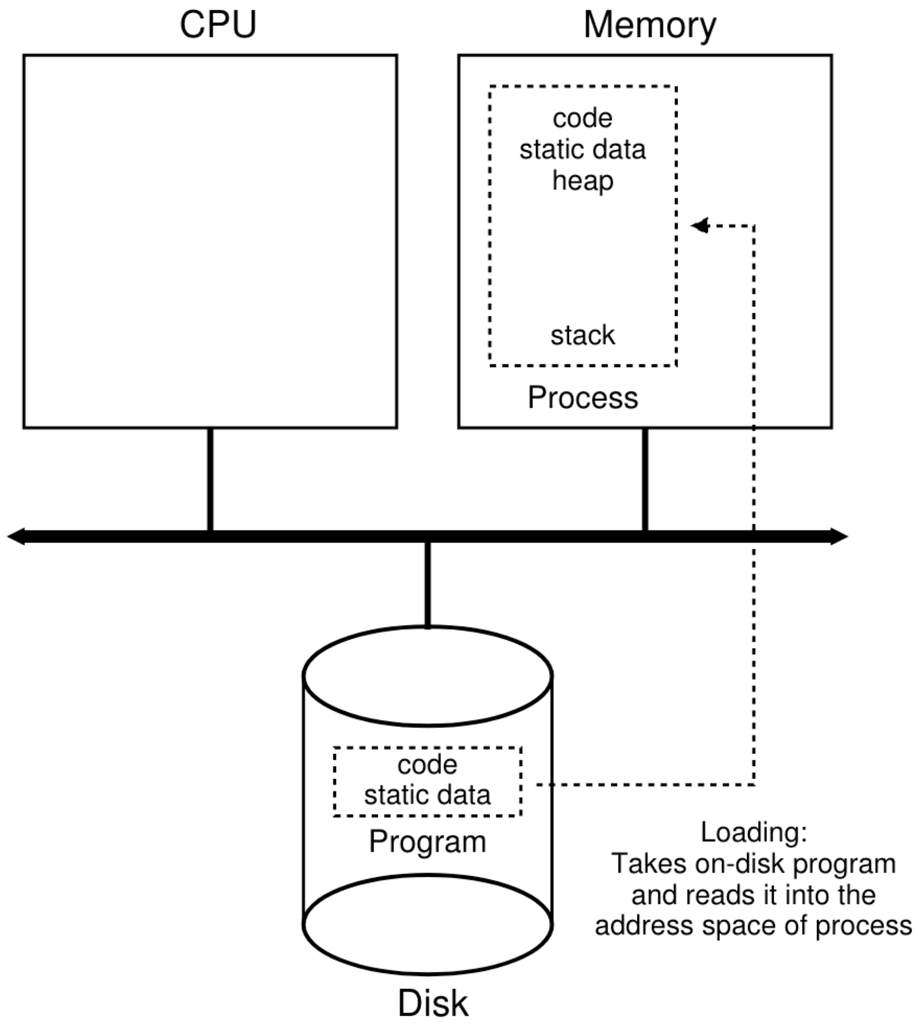


Figure 4.1: **Loading: From Program To Process**

Processes can ask OS to do work for them

System calls

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

OS maintains process states

Scheduler switches between processes

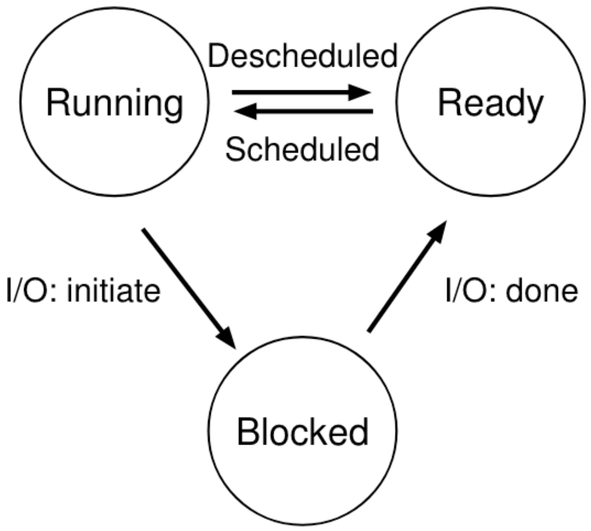


Figure 4.2: **Process: State Transitions**

OS maintains process states

Scheduler switches between processes

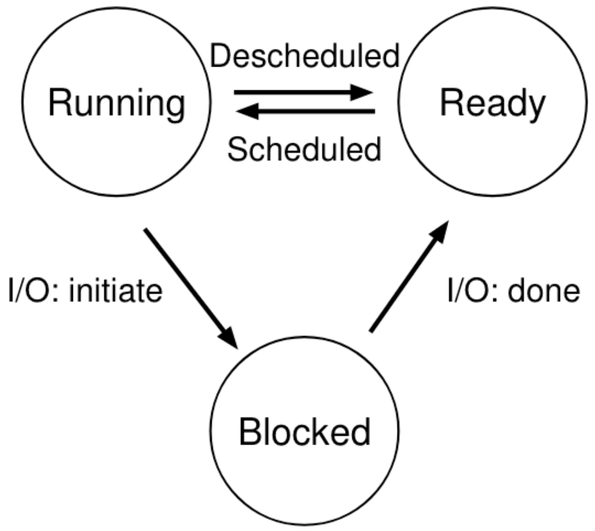
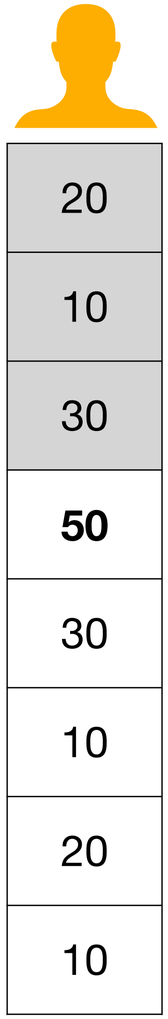


Figure 4.2: **Process: State Transitions**

Time	Process_0	Process_1	Notes
1	Running	Ready	
2	Running	Ready	
3	Running	Ready	Process_0 initiates I/O
4	Blocked	Running	Process_0 is blocked,
5	Blocked	Running	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

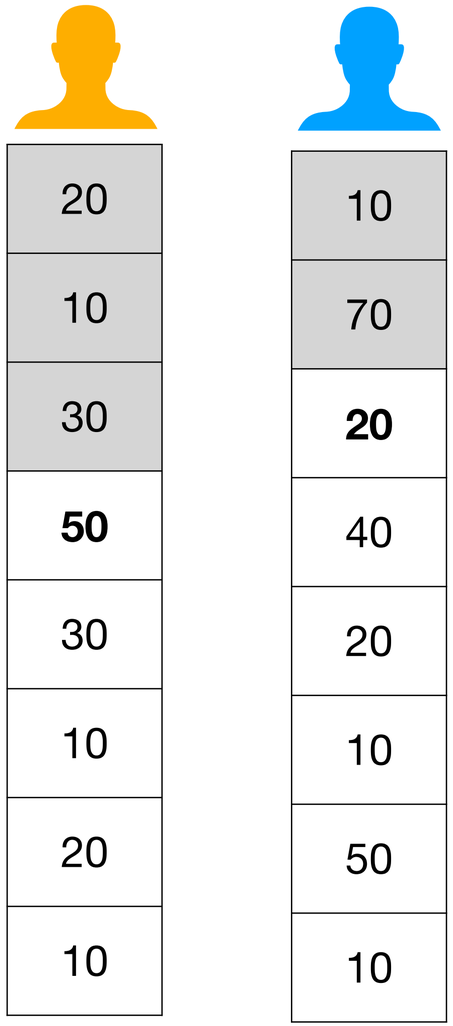
Figure 4.4: **Tracing Process State: CPU and I/O**

Calculator analogy: Computing long sum



- 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



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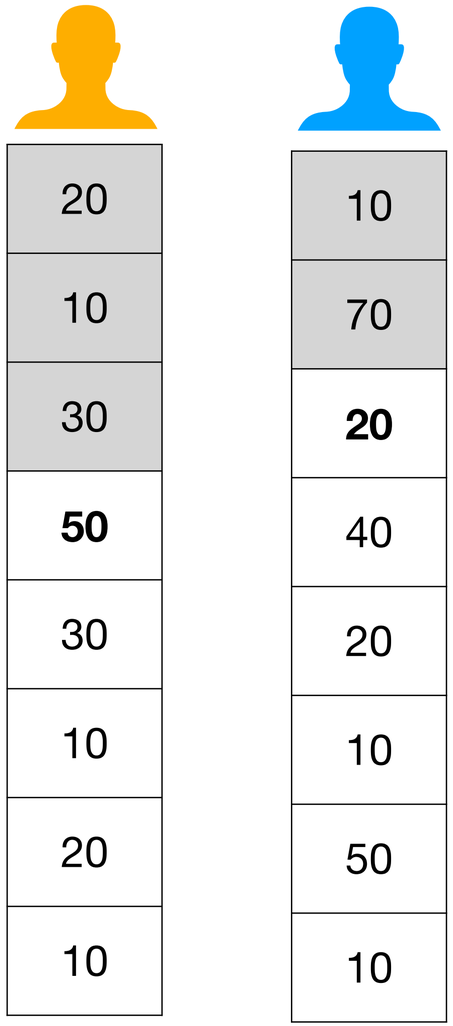


- Steps to share the calculator:
  - 20 + 10 = 30 + 30 = 60
  - Write 60 in notebook, remember that we were done till 30, give calculator
  - 10 + 70 = 80
  - Write 80 in notebook, remember that we were done till 70, give the calculator back

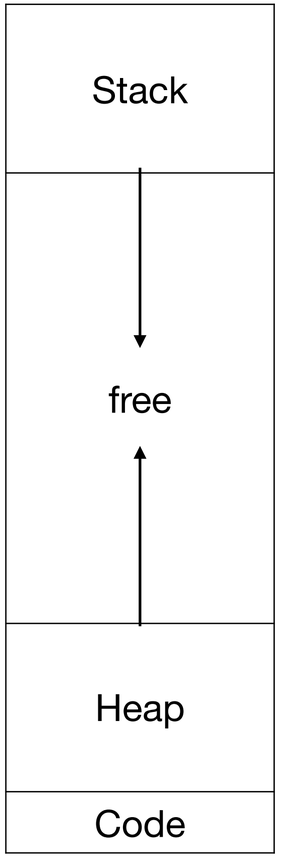
Memory isolation and management

OSTEP Ch. 13-17

Abhilash Jindal

Process Address Space

Code, Heap, Stack



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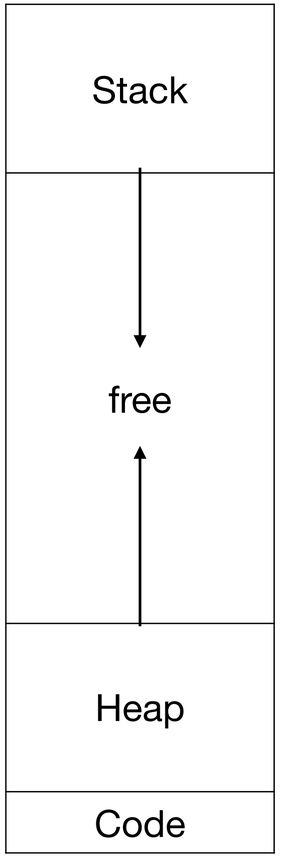

Process address space

Function calling in action

Stack

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02.s

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  movl  %esp, %ebp          ebp = esp
  movl  8(%ebp), %eax       eax = *(ebp + 8)
  addl  12(%ebp), %eax      eax = eax + *(ebp + 12)
  popl  %ebp                Restore caller's base pointer
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  .p2align  4, 0x90
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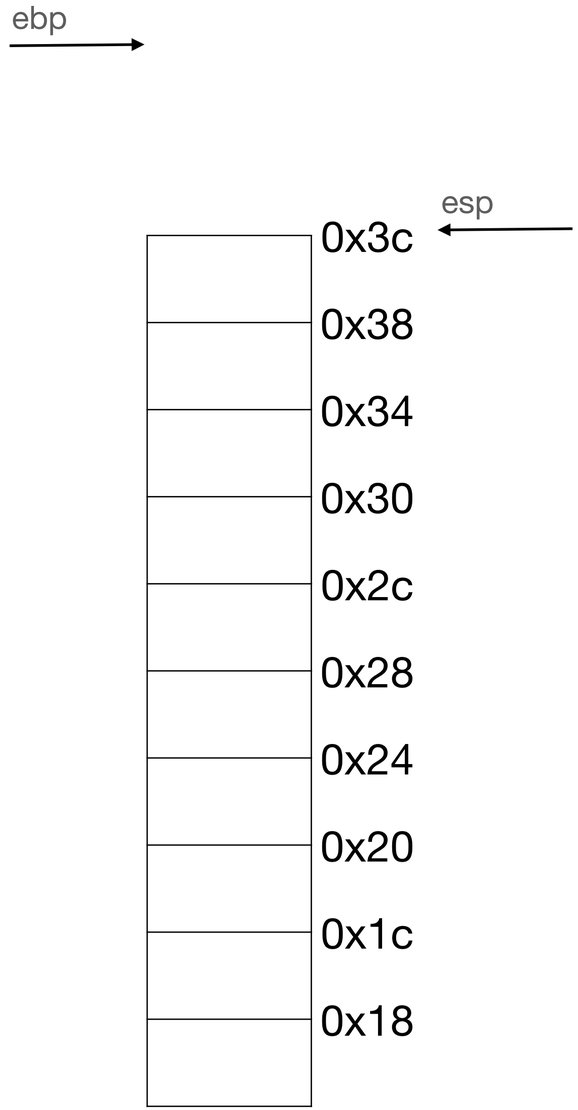

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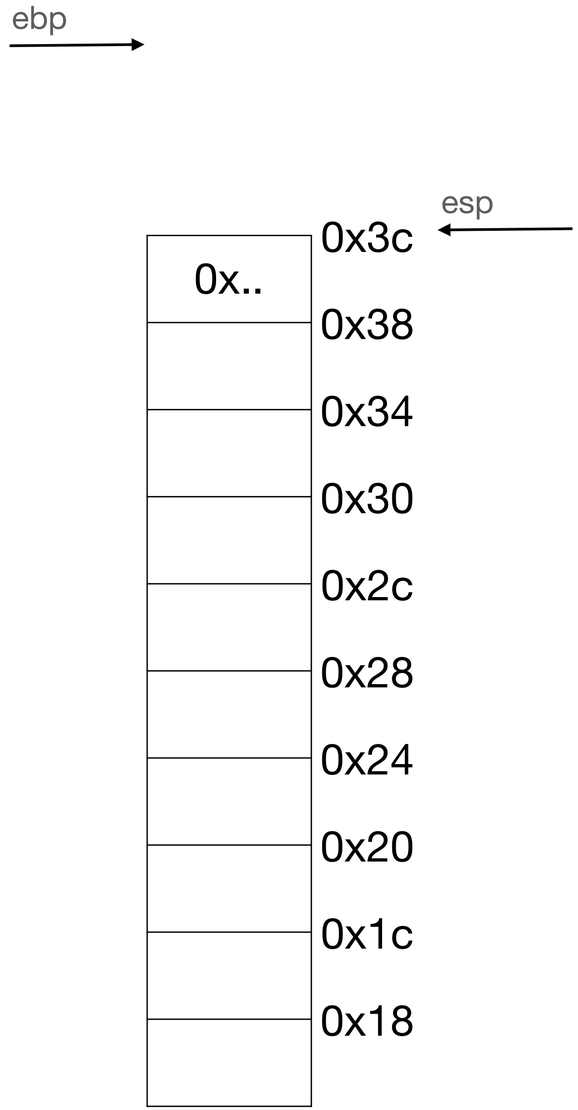

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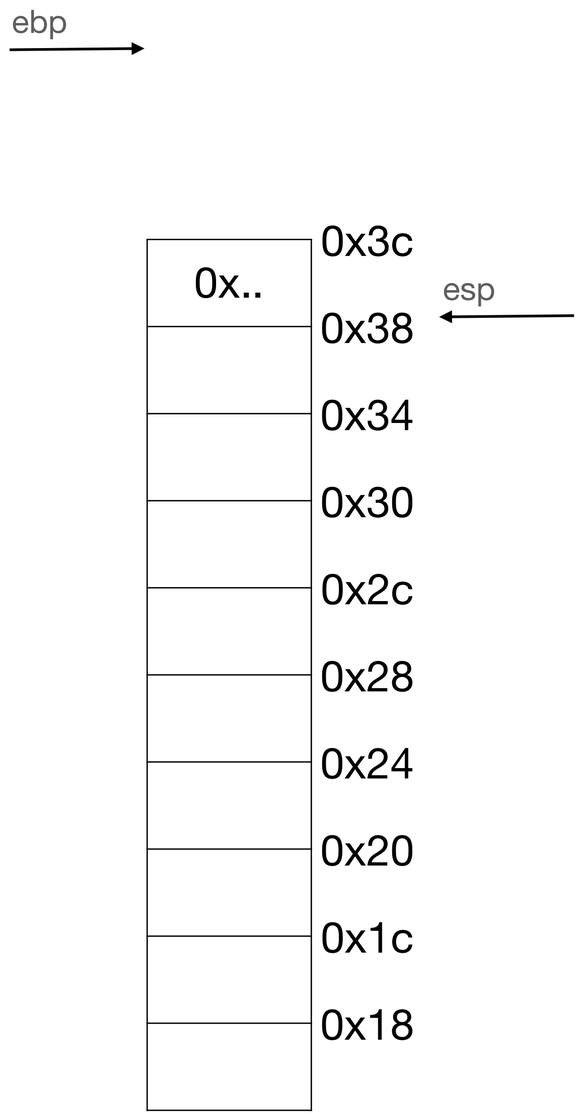

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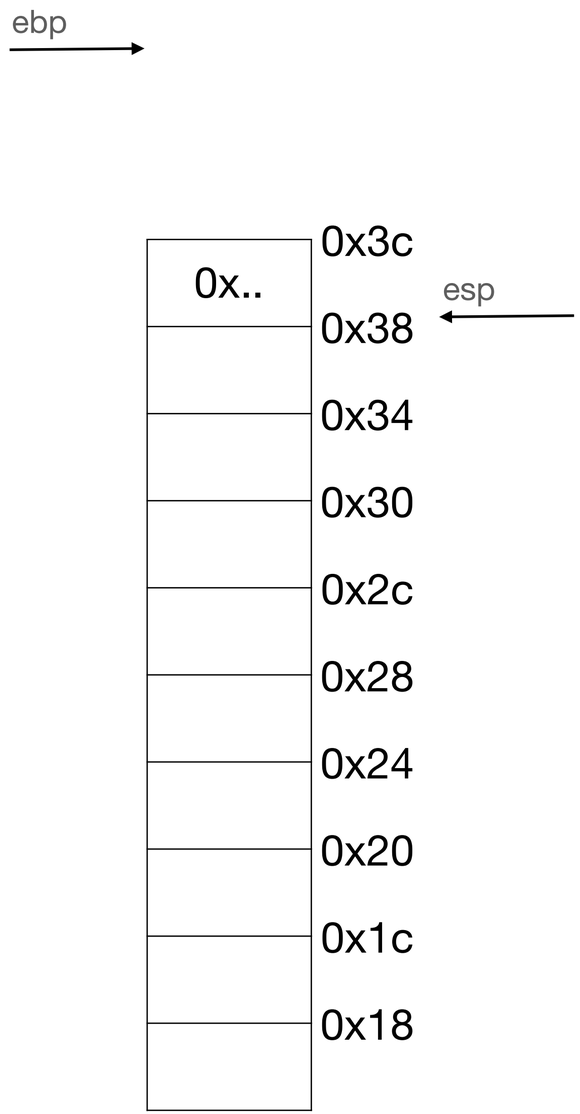

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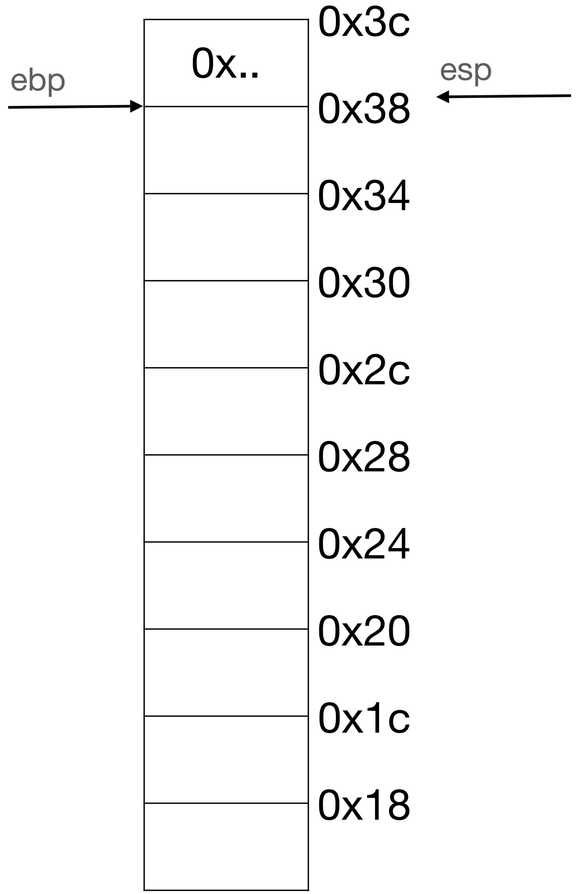
eip → movl %esp, %ebp



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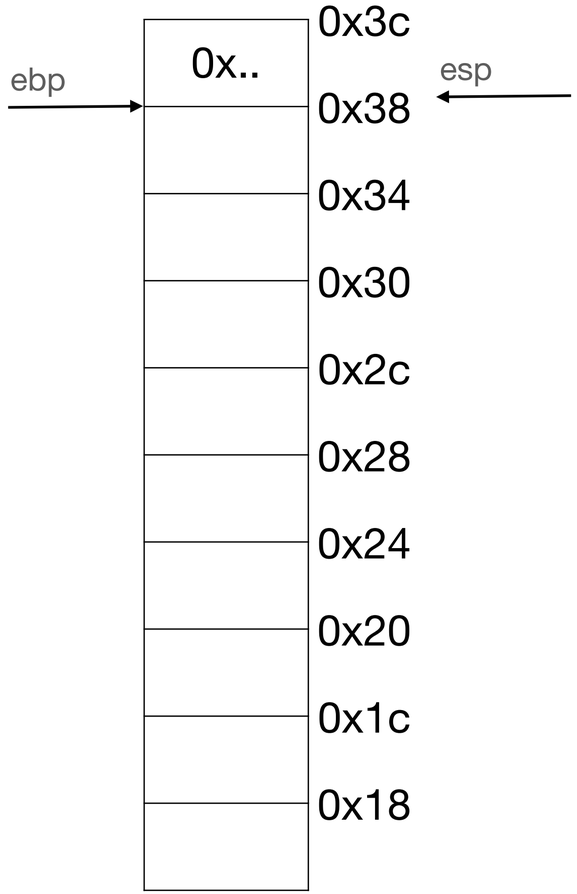

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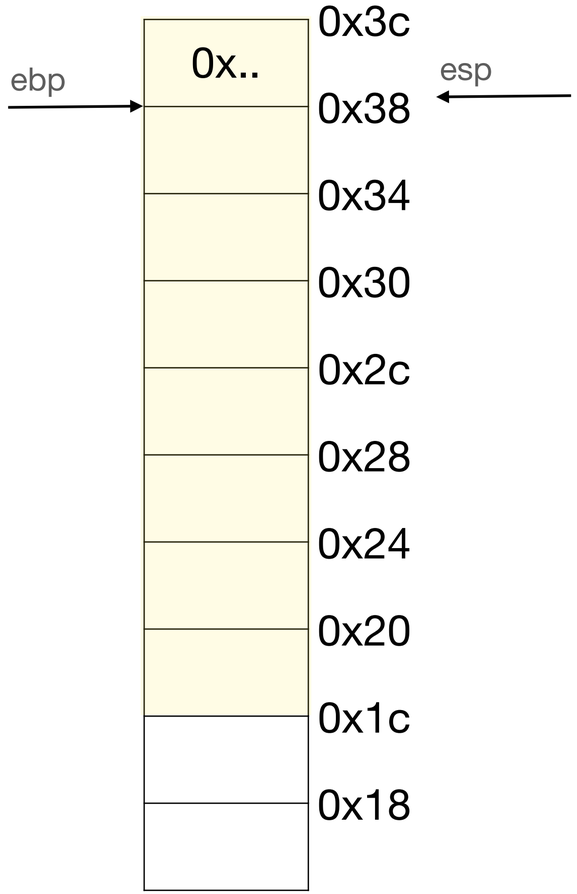

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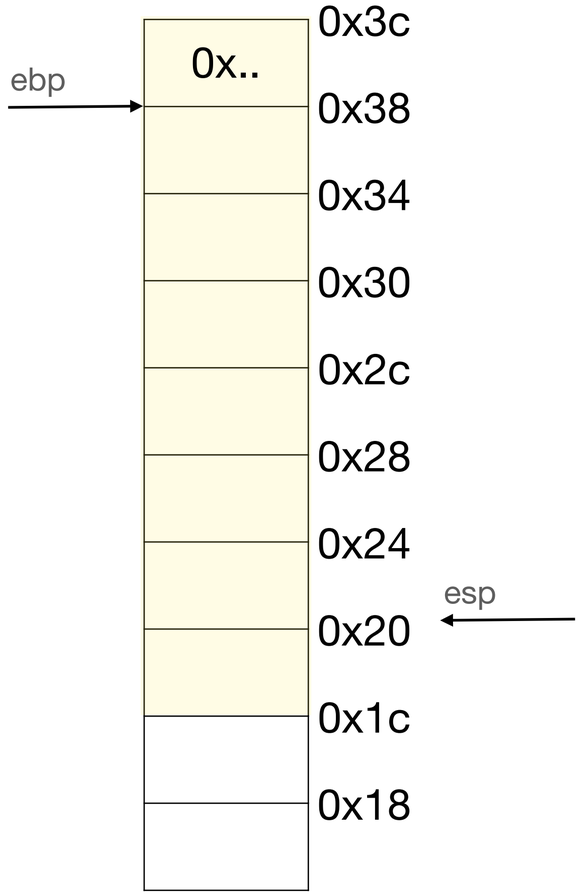

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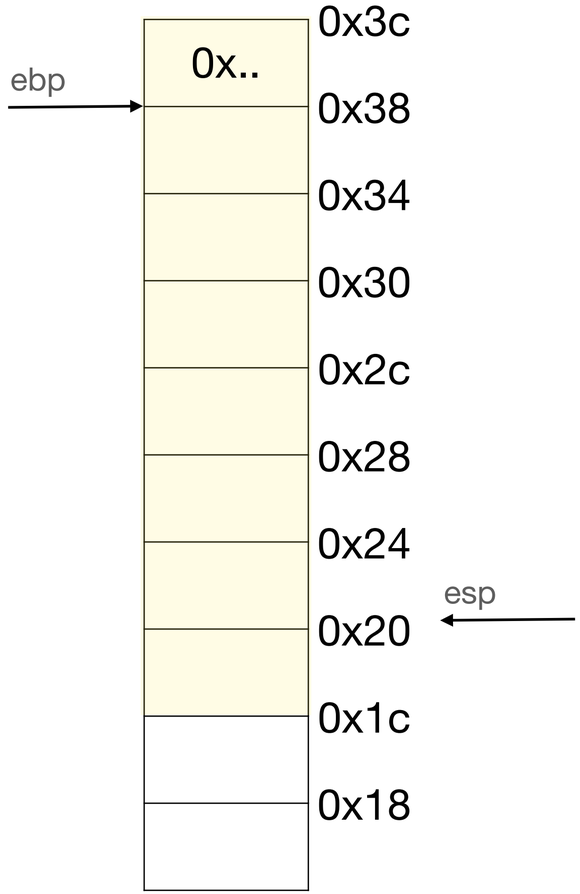

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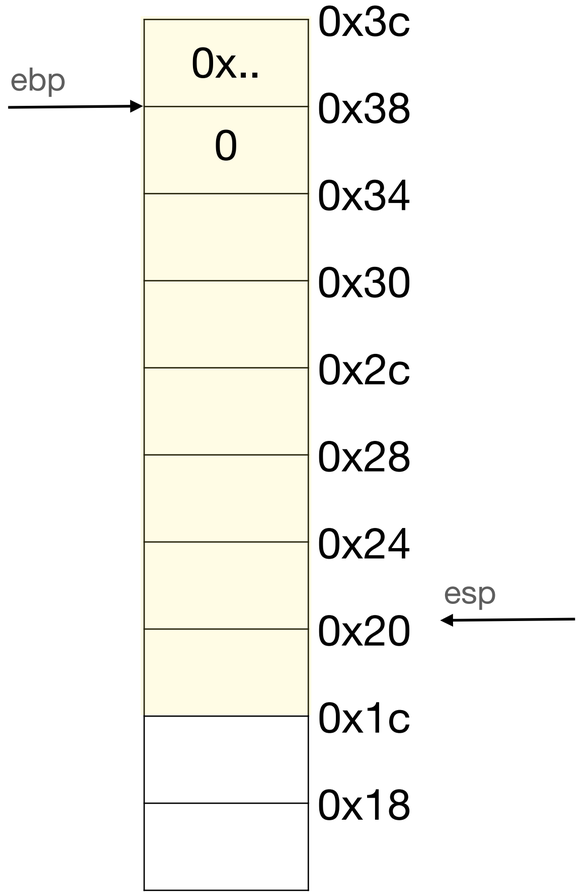

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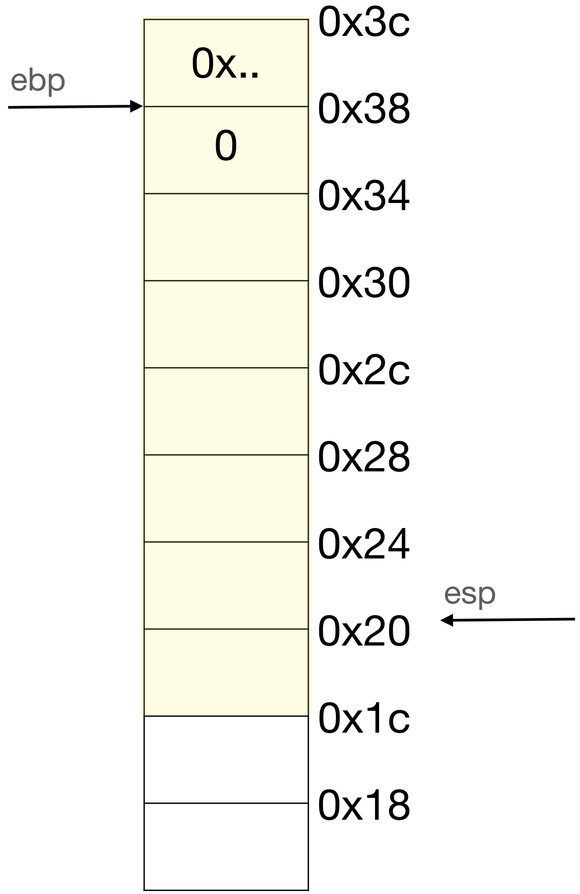

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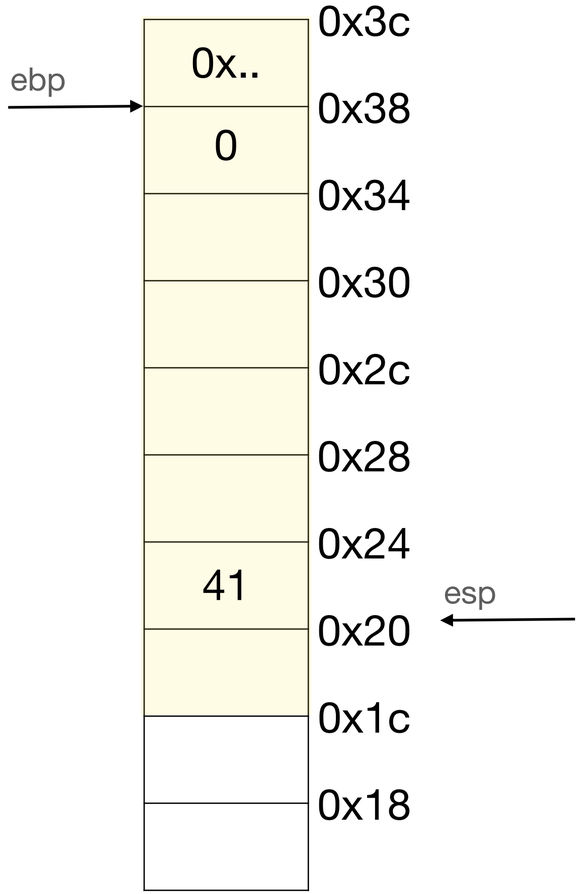

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  movl  $41, (%esp)         *(esp) = 41
  movl  $42, 4(%esp)        *(esp+4) = 42
  calll _foo                Push current eip on to stack, jump to foo
  addl  $24, %esp           esp = esp + 24 (Restore caller's esp)
  popl  %ebp                Restore caller's ebp
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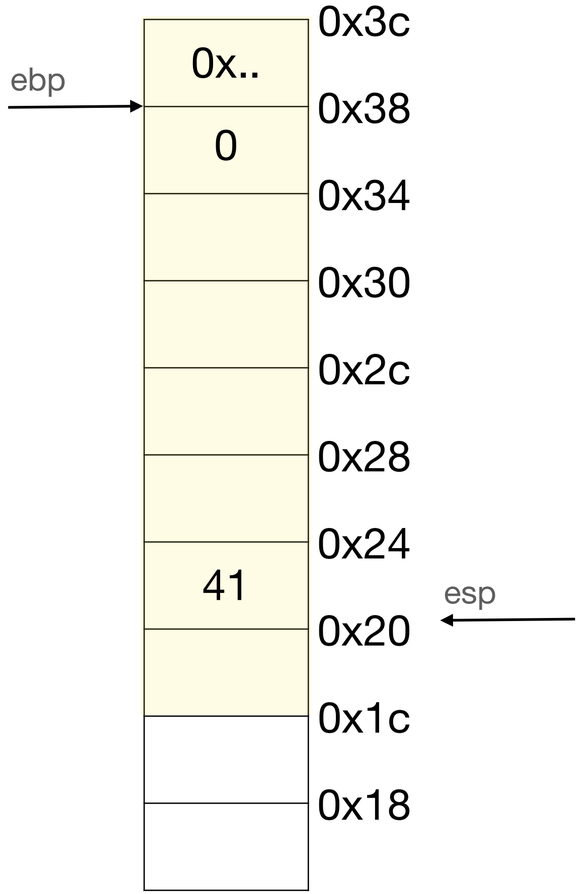
```

eip



Function calling in action

Stack

```
02.s

_foo:
  pushl %ebp                  Save caller's base pointer
  movl  %esp, %ebp            ebp = esp
  movl  8(%ebp), %eax         eax = *(ebp + 8)
  addl  12(%ebp), %eax        eax = eax + *(ebp + 12)
  popl  %ebp                  Restore caller's base pointer
  retl                        change eip to return address

  .globl  _main                           ## -- Begin function main
  .p2align  4, 0x90
_main:
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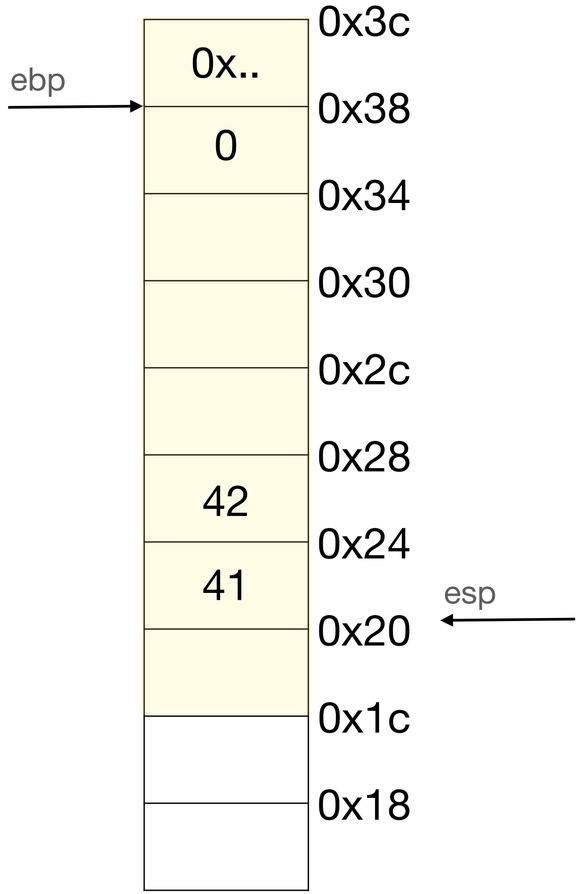

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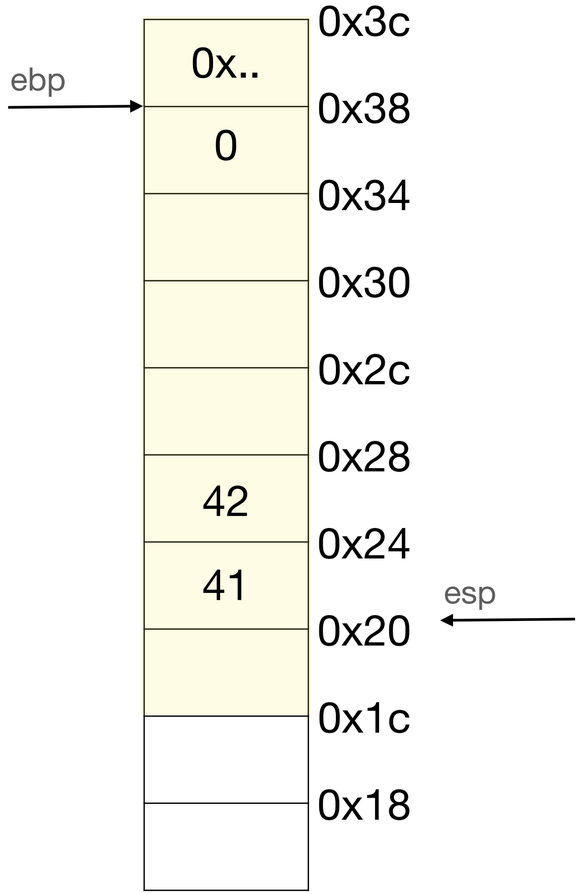

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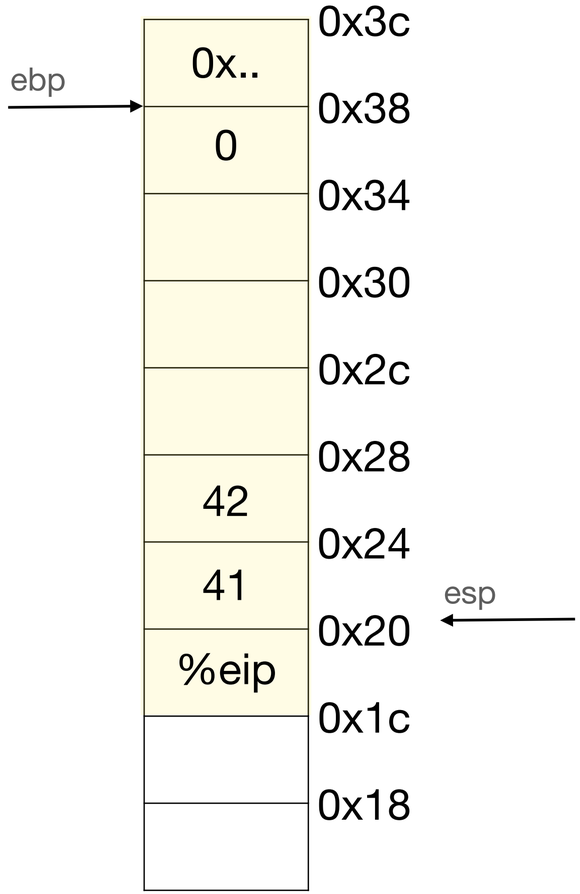

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Stack

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02.s

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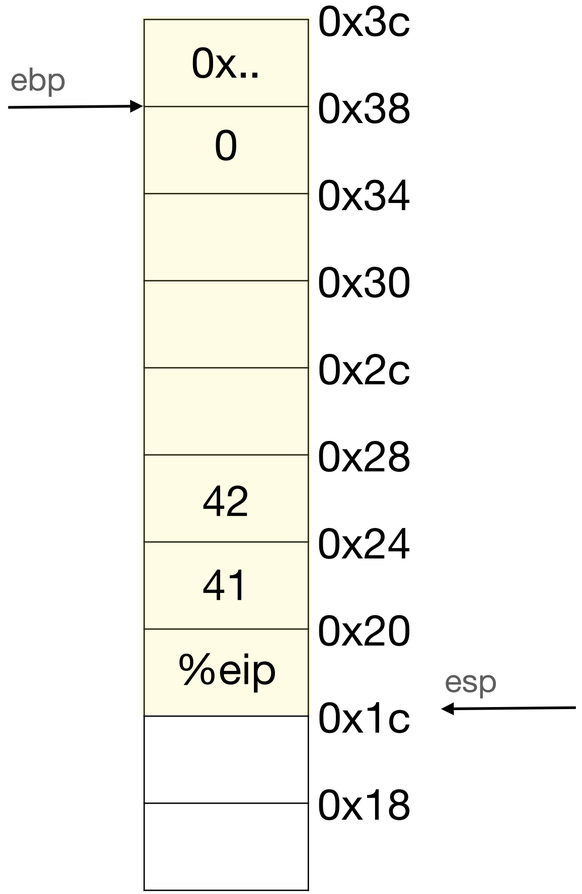

Function calling in action

Stack

02.s

eip

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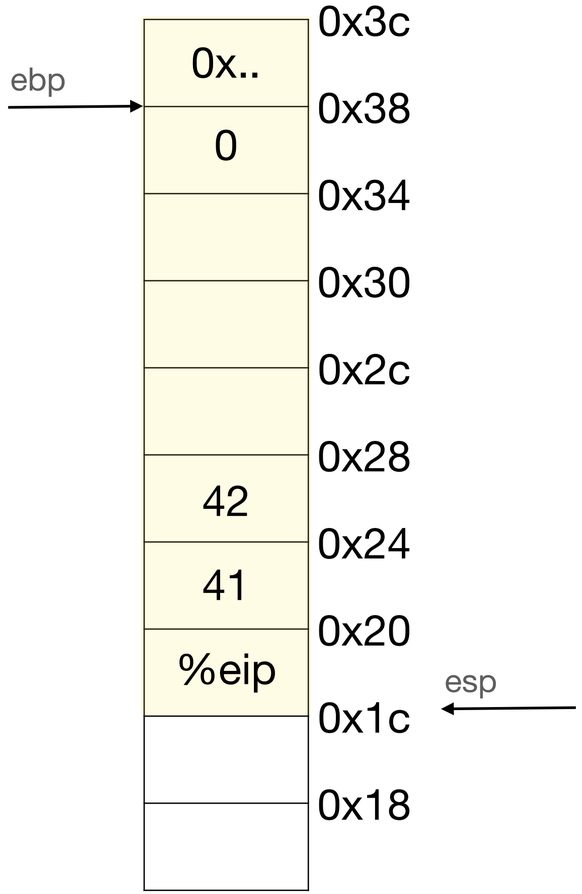

Function calling in action

Stack

02.s

eip

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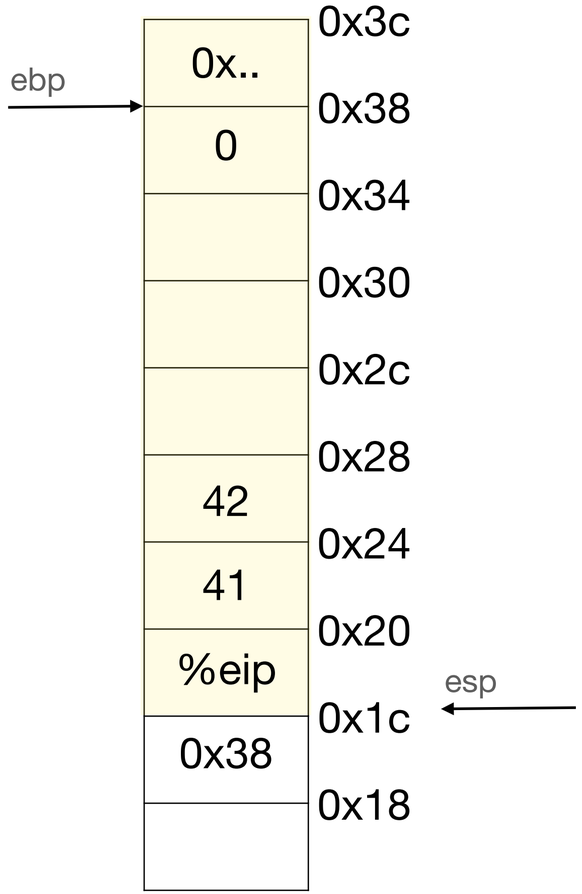

Function calling in action

Stack

02.s

eip

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_foo:
  pushl %ebp                Save caller's base pointer
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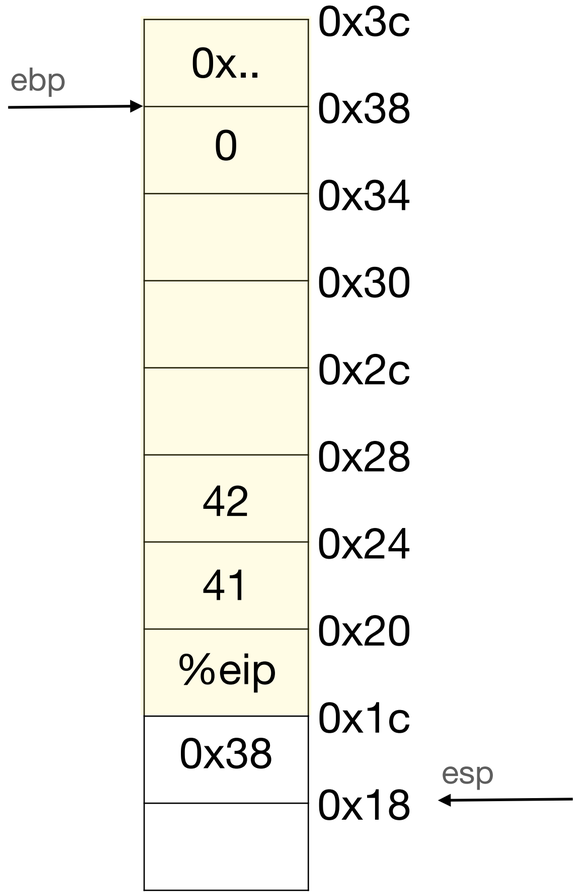

Function calling in action

Stack

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02.s

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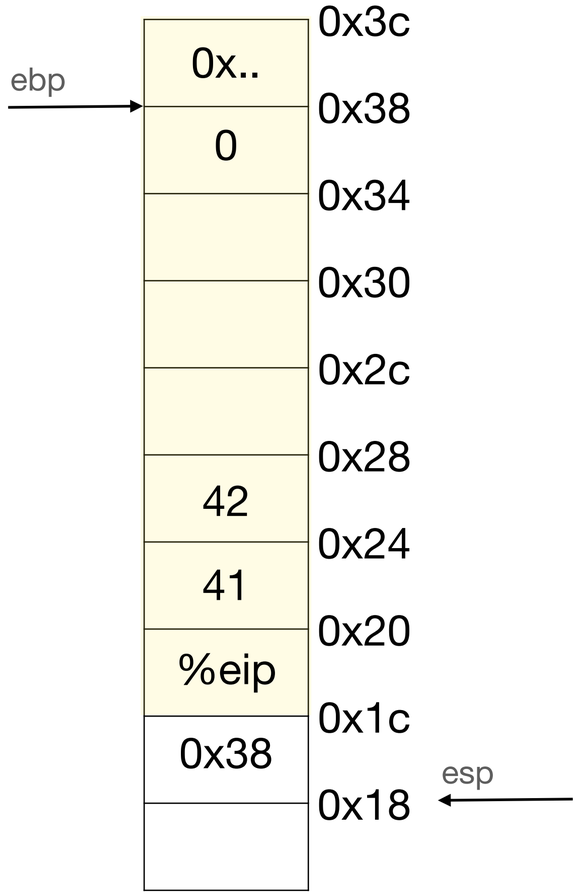
eip



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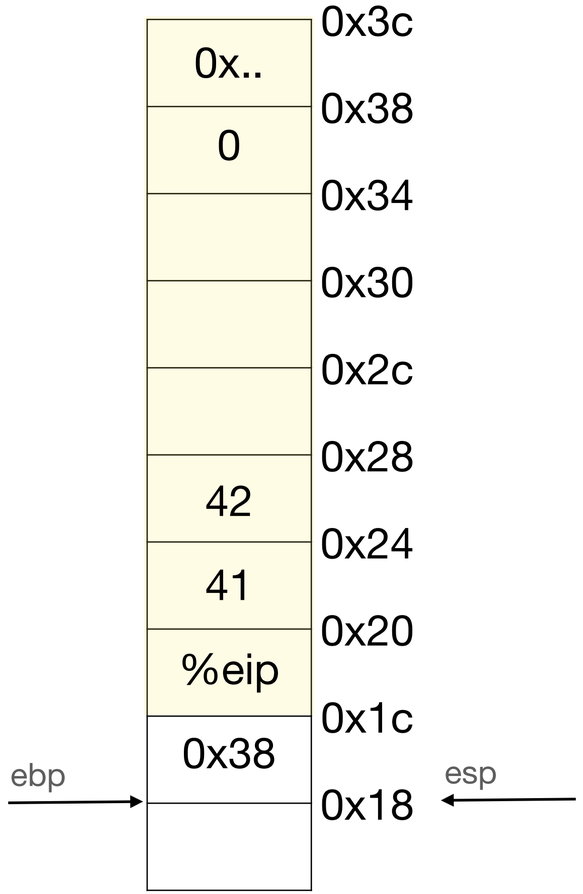
eip



Function calling in action

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02.s

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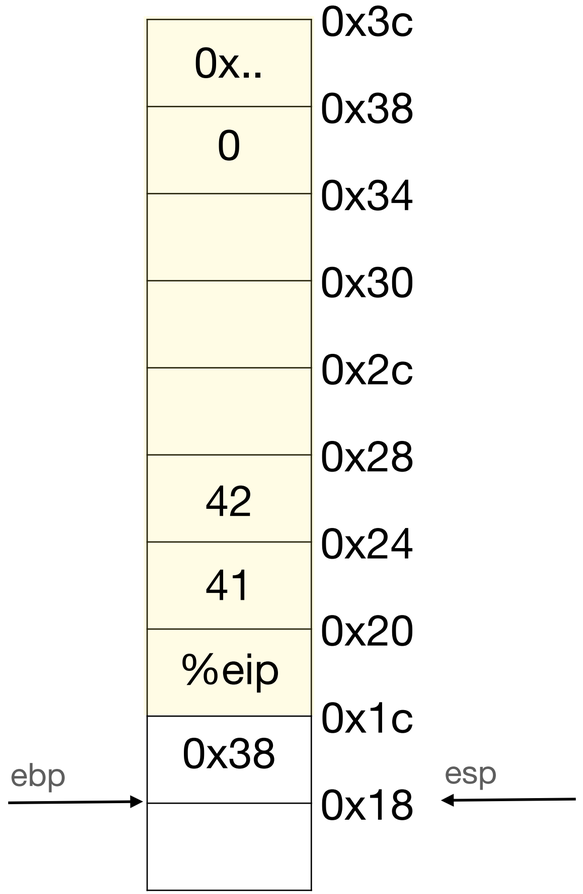
eip



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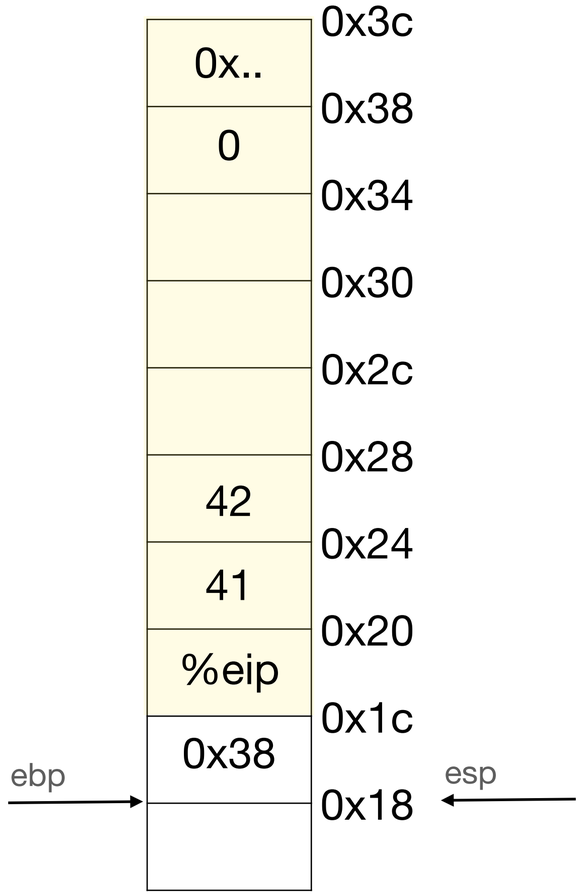

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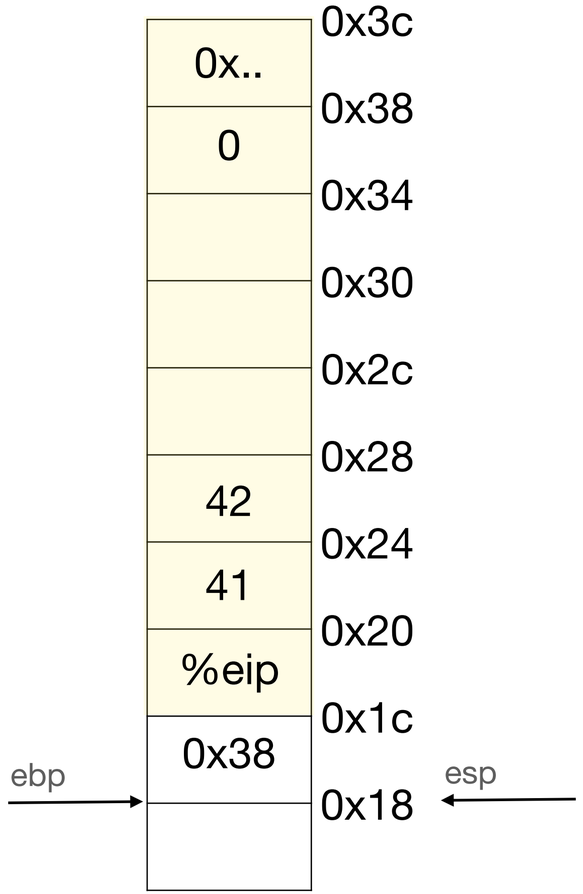

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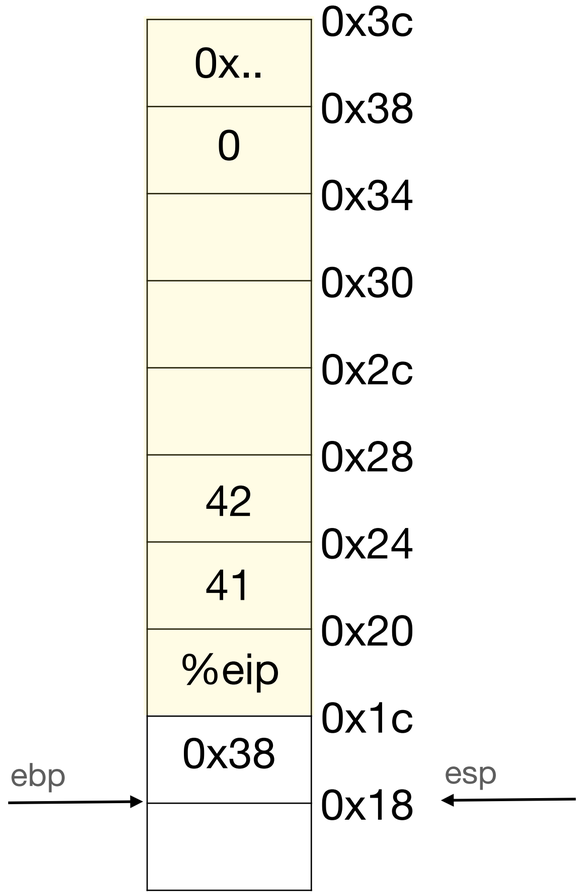

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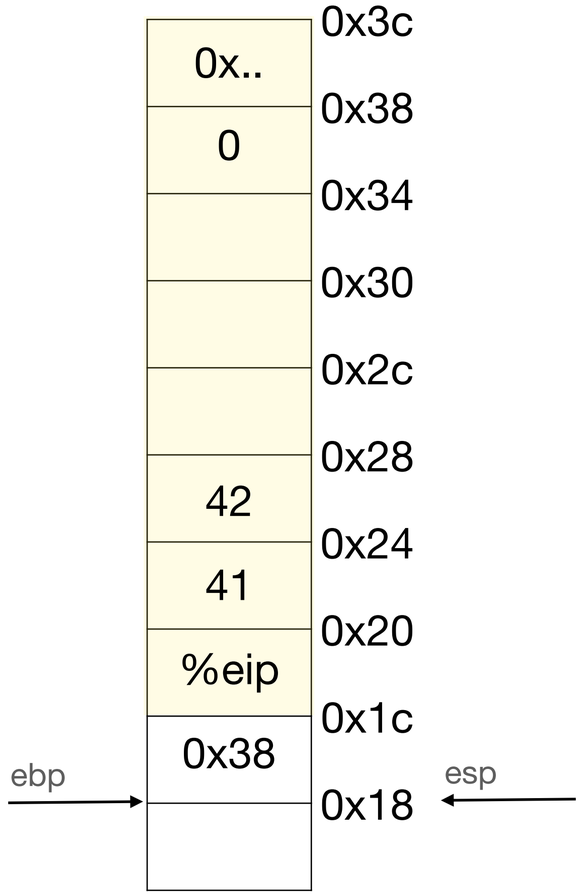

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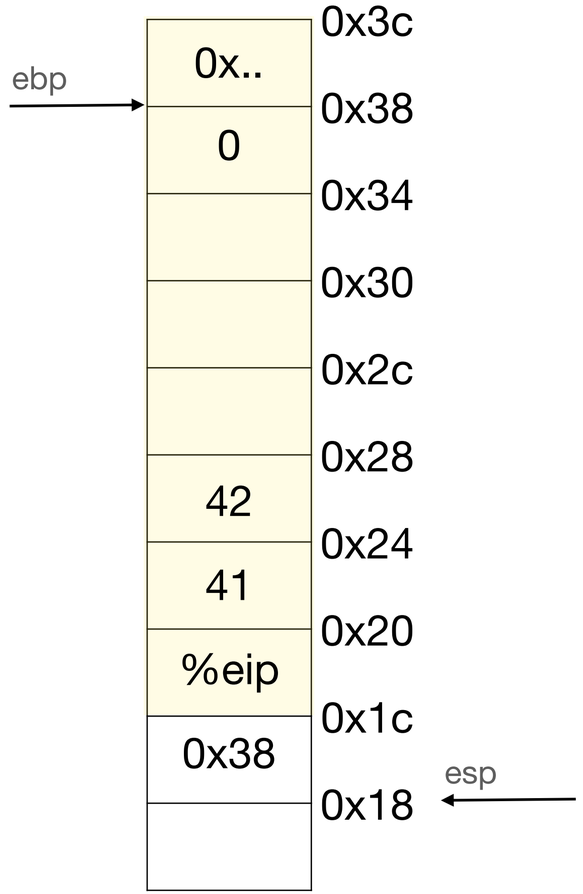

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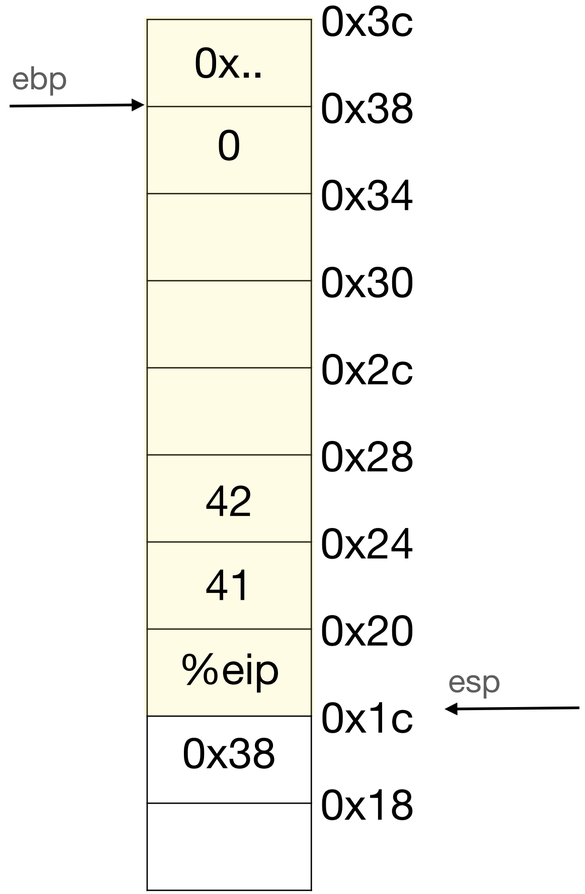

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  .globl  _main                           ## -- Begin function main
  .p2align  4, 0x90
_main:
  pushl %ebp                  Save caller's base pointer
  movl  %esp, %ebp            ebp = esp
  subl  $24, %esp             esp = esp - 0x18
  movl  $0, -4(%ebp)          *(ebp-4)=0
  movl  $41, (%esp)           *(esp) = 41
  movl  $42, 4(%esp)          *(esp+4) = 42
  calll _foo                  Push current eip on to stack, jump to foo
  addl  $24, %esp             esp = esp + 24 (Restore caller's esp)
  popl  %ebp                  Restore caller's ebp
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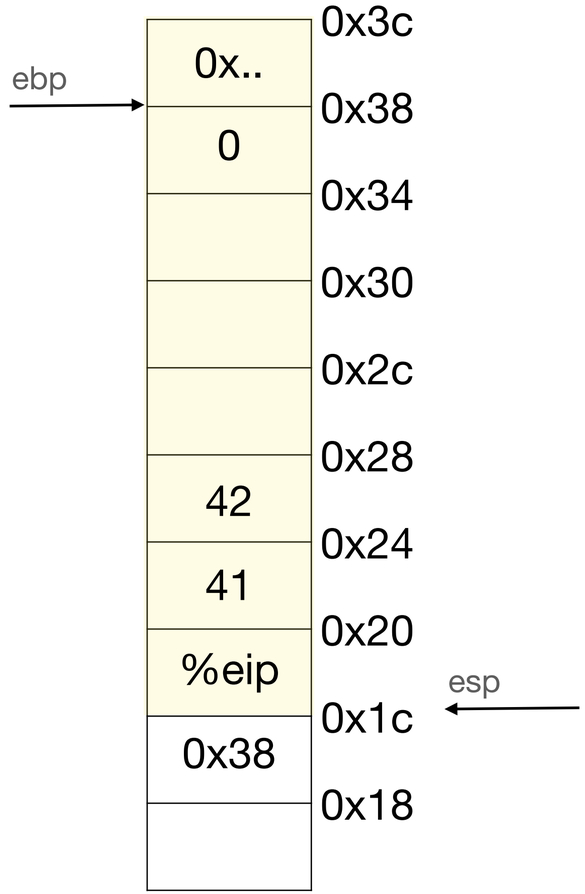
```

eip



Function calling in action

Stack

02.s

```
_foo:
  pushl %ebp                  Save caller's base pointer
  movl  %esp, %ebp            ebp = esp
  movl  8(%ebp), %eax         eax = *(ebp + 8)
  addl  12(%ebp), %eax        eax = eax + *(ebp + 12)
  popl  %ebp                  Restore caller's base pointer
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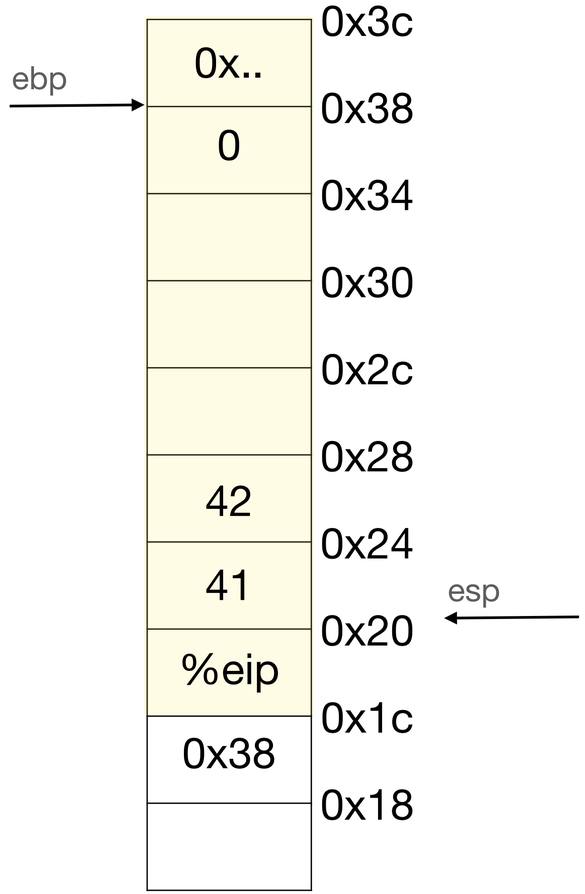
```

eip



Function calling in action

Stack

```
02.s

_foo:
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  movl  %esp, %ebp            ebp = esp
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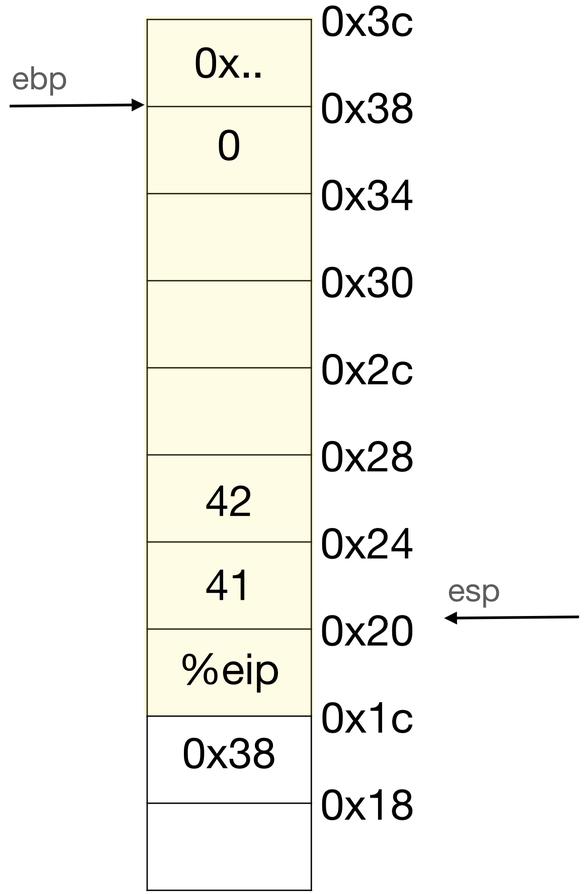
```

eip



Function calling in action

Stack

02.s

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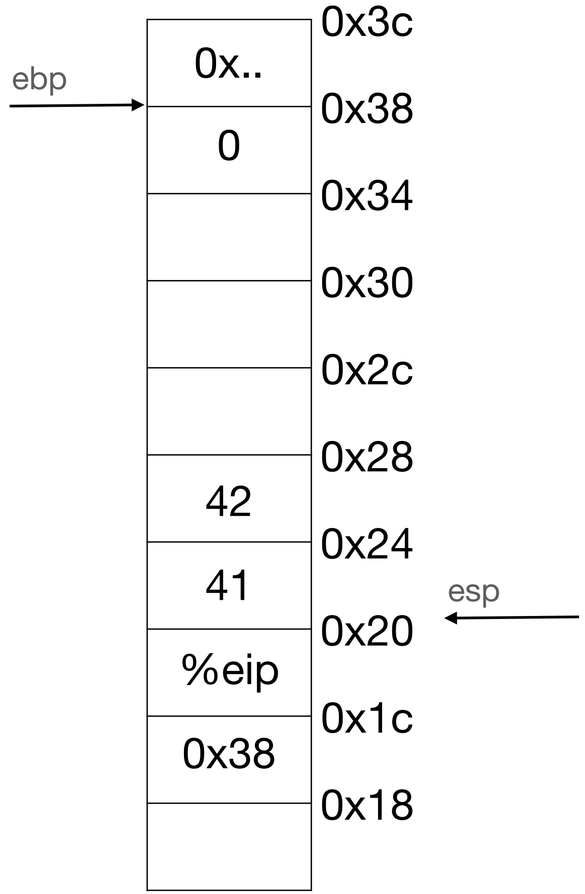
eip



Function calling in action

Stack

02.s

```
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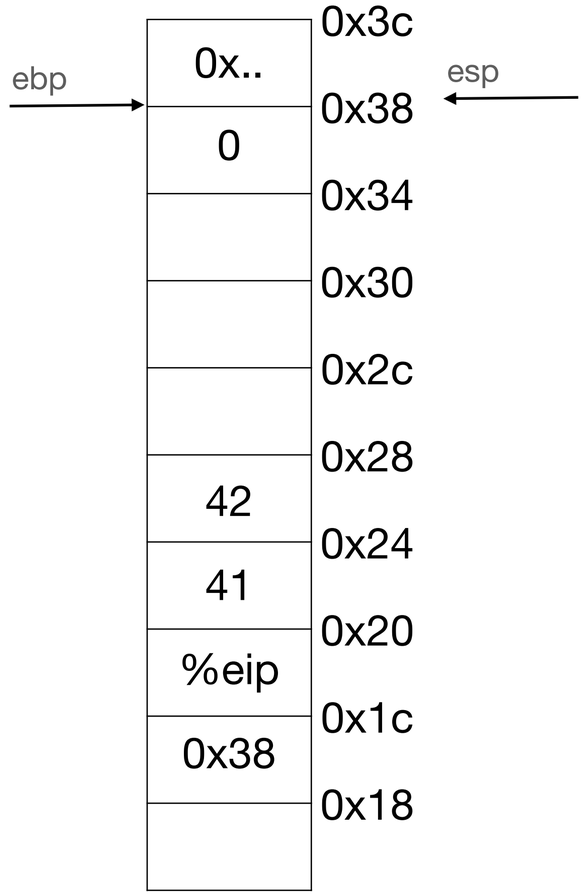
```

eip



Function calling in action

Stack

```
02.s

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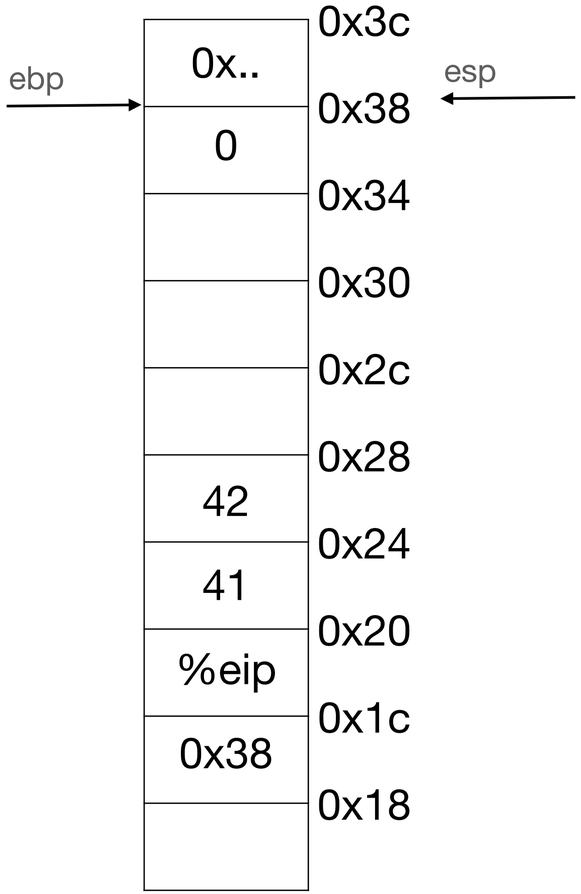
```

eip



Function calling in action

Stack

```
02.s

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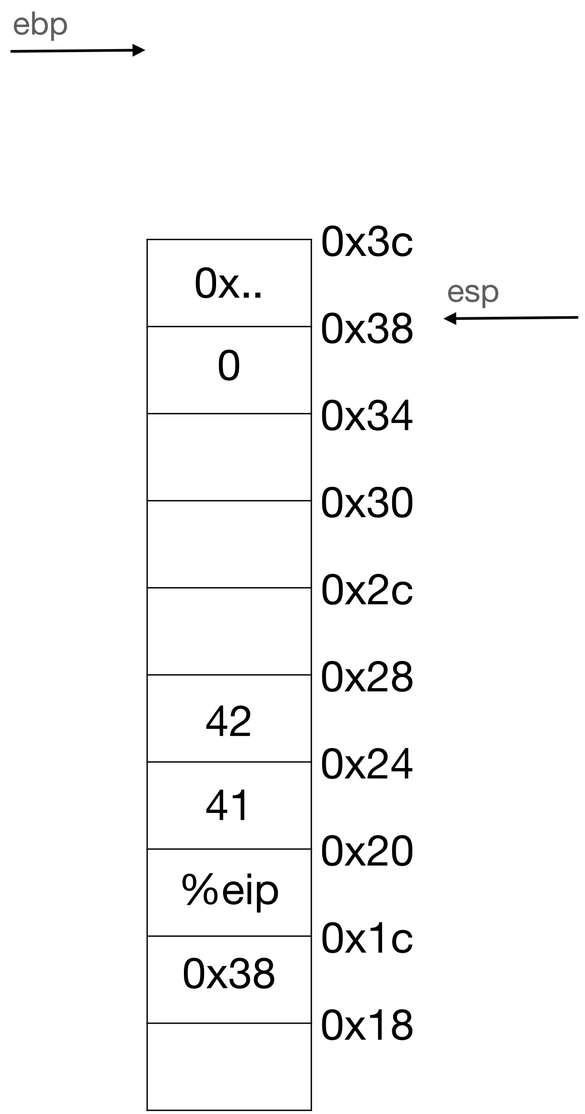
```

eip



Function calling in action

Stack

```
02.s

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  movl  %esp, %ebp          ebp = esp
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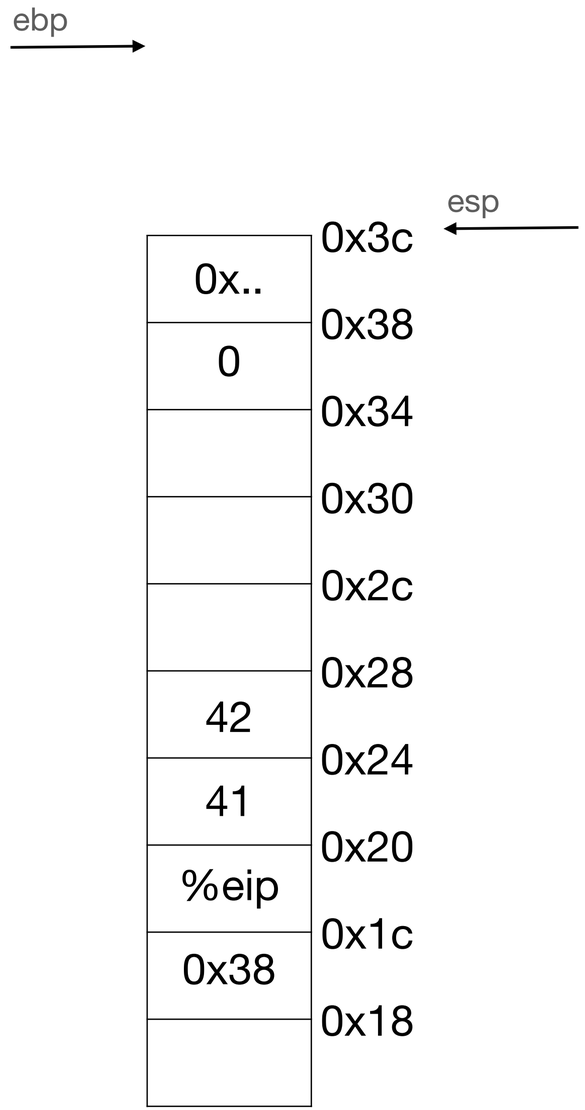
```

eip



Function calling in action

Stack

```
02.s

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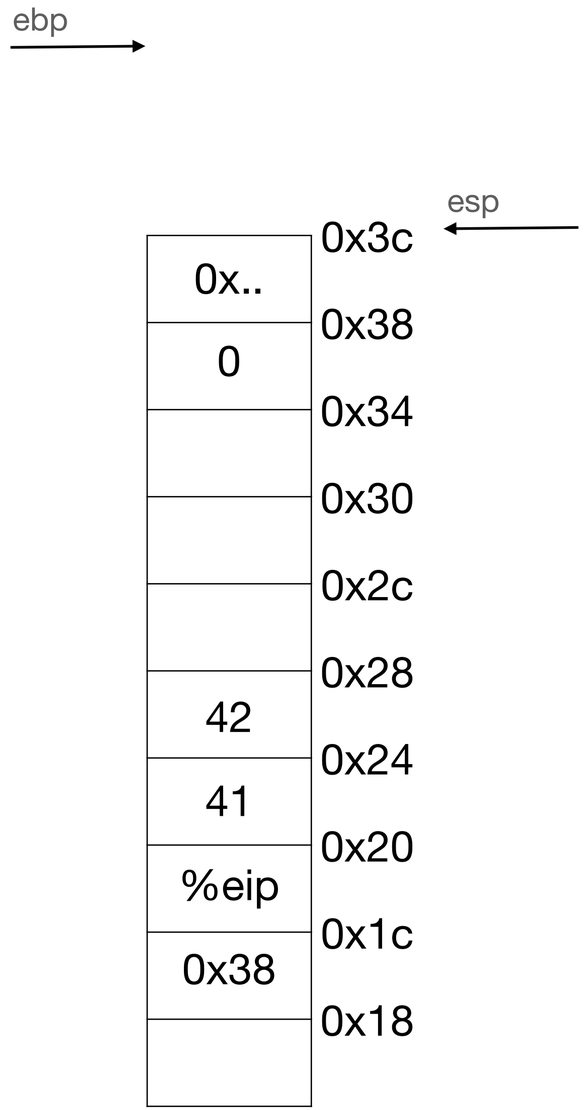
```

eip

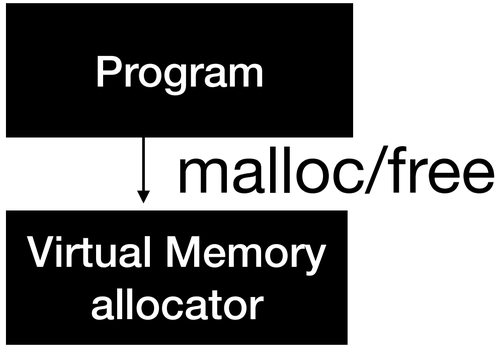


Memory APIs and bugs

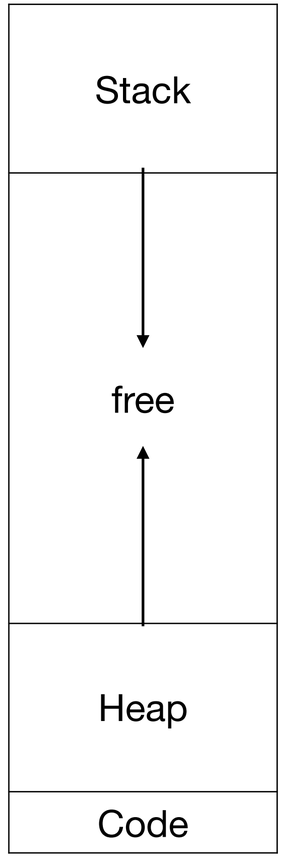
- malloc, free. va.c.
  - malloc is for dynamic allocation. Size is not known at compile time. Slower than stack allocations. Need to find free space.
- Null pointer dereference. null.c
- Memory leak. leak.c
- Buffer overflow. overflow.c
- Use after free. useafterfree.c
- Invalid free. invalidfree.c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

Memory allocator

Works with virtual memory

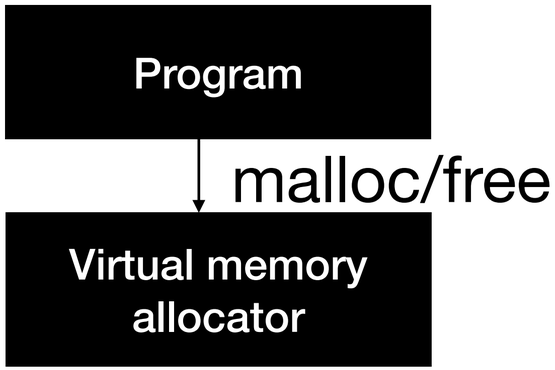


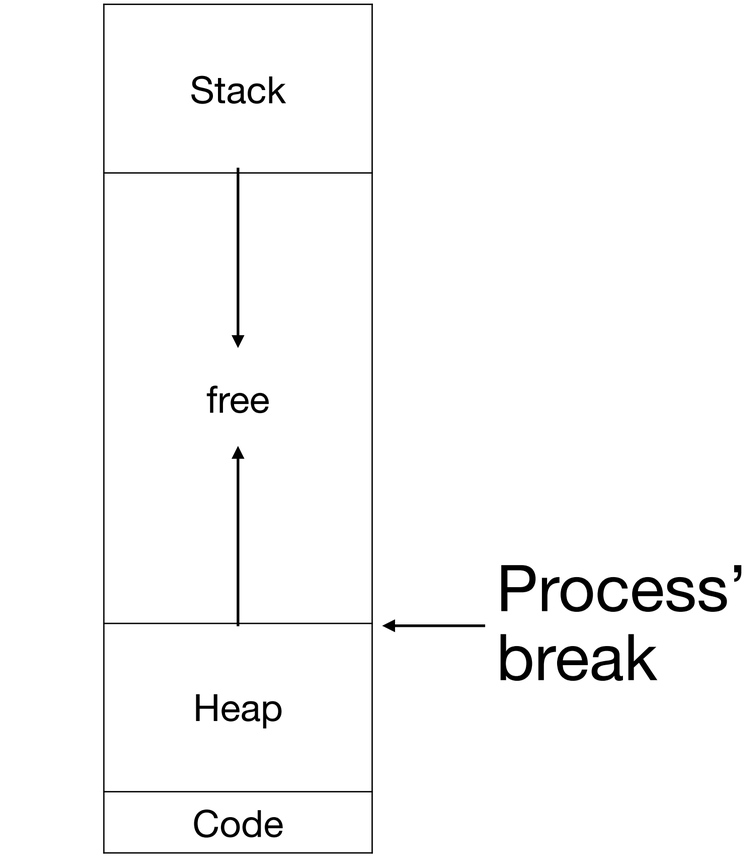
Manages heap memory



Process address space

OS memory allocator

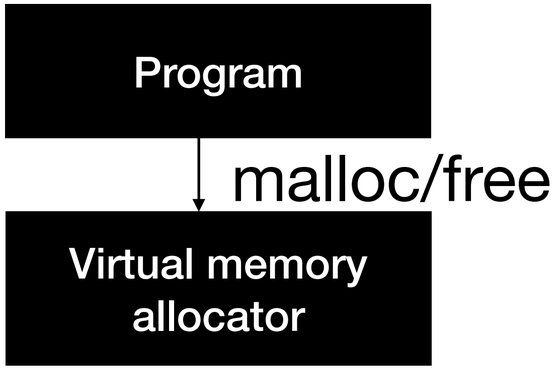


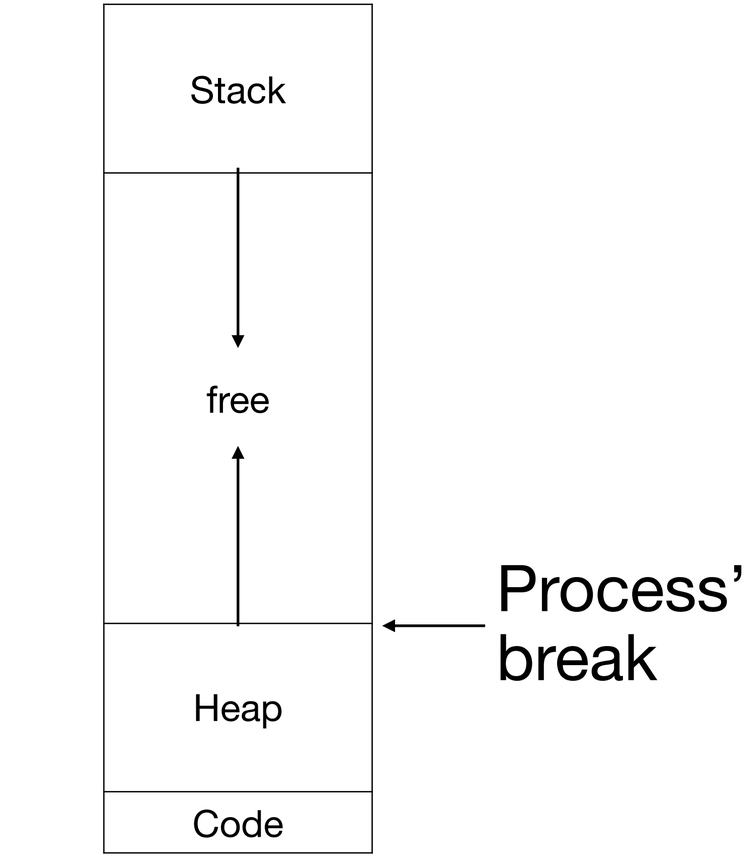


Process address space

OS memory allocator

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





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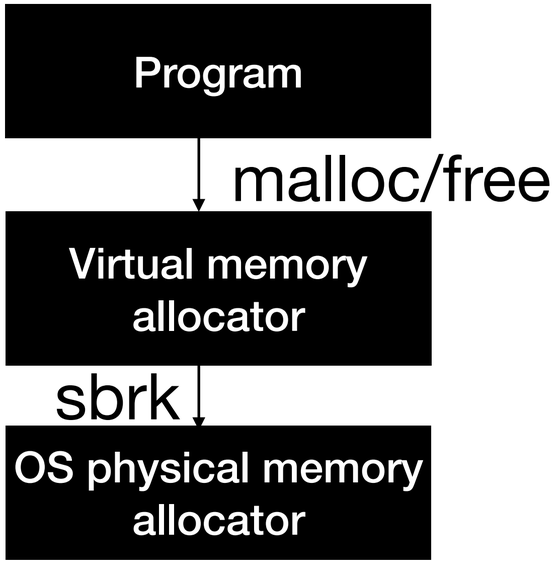

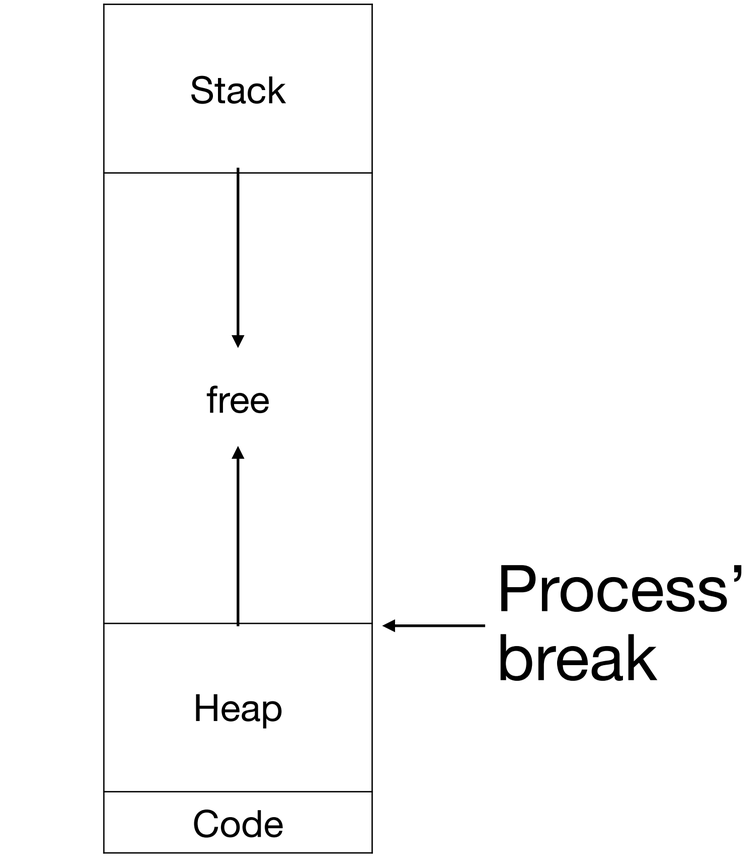

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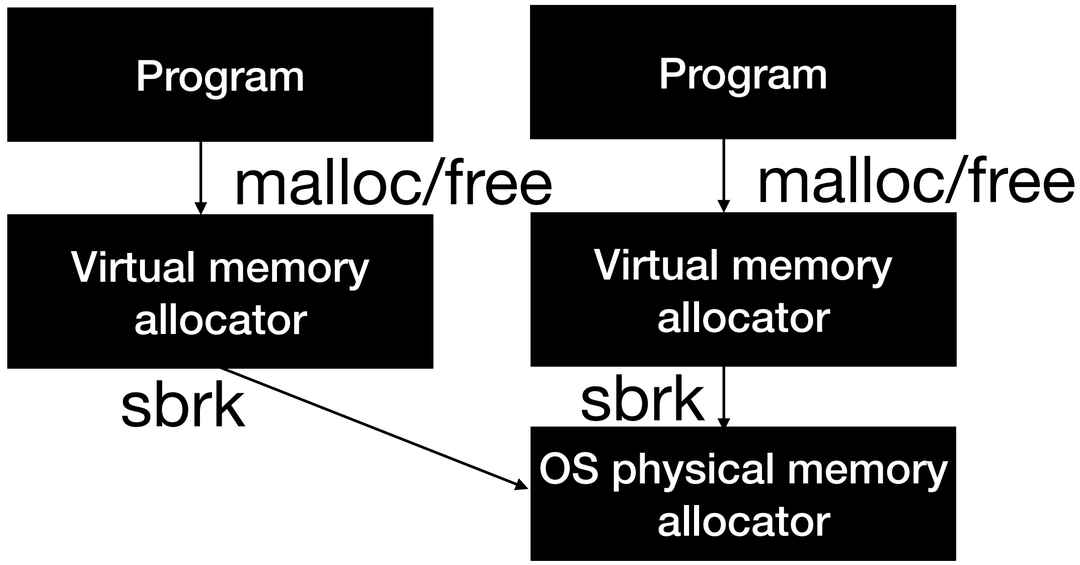

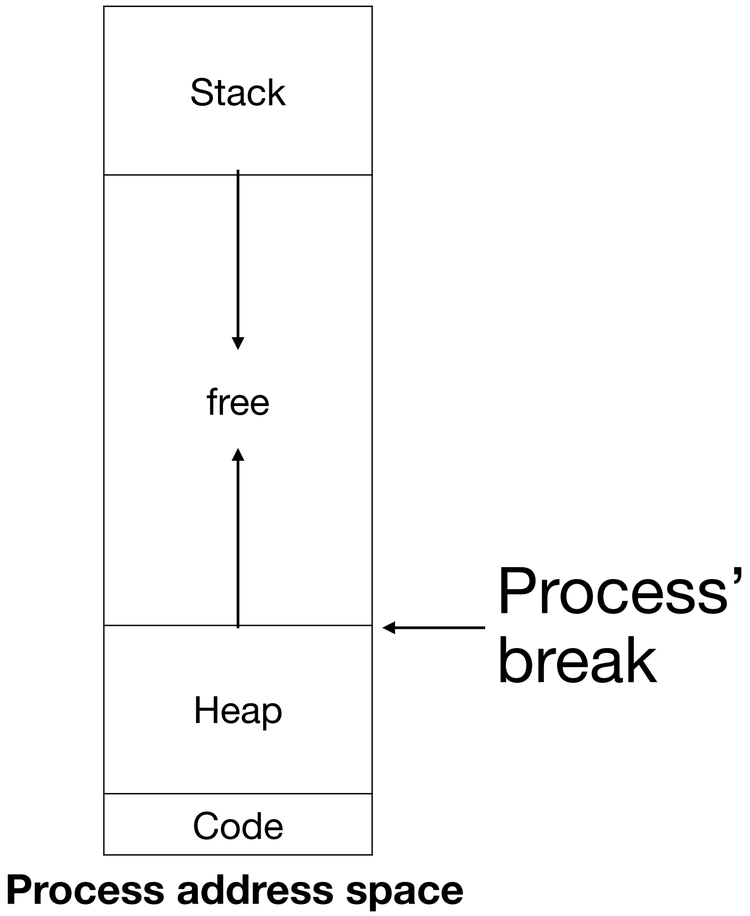

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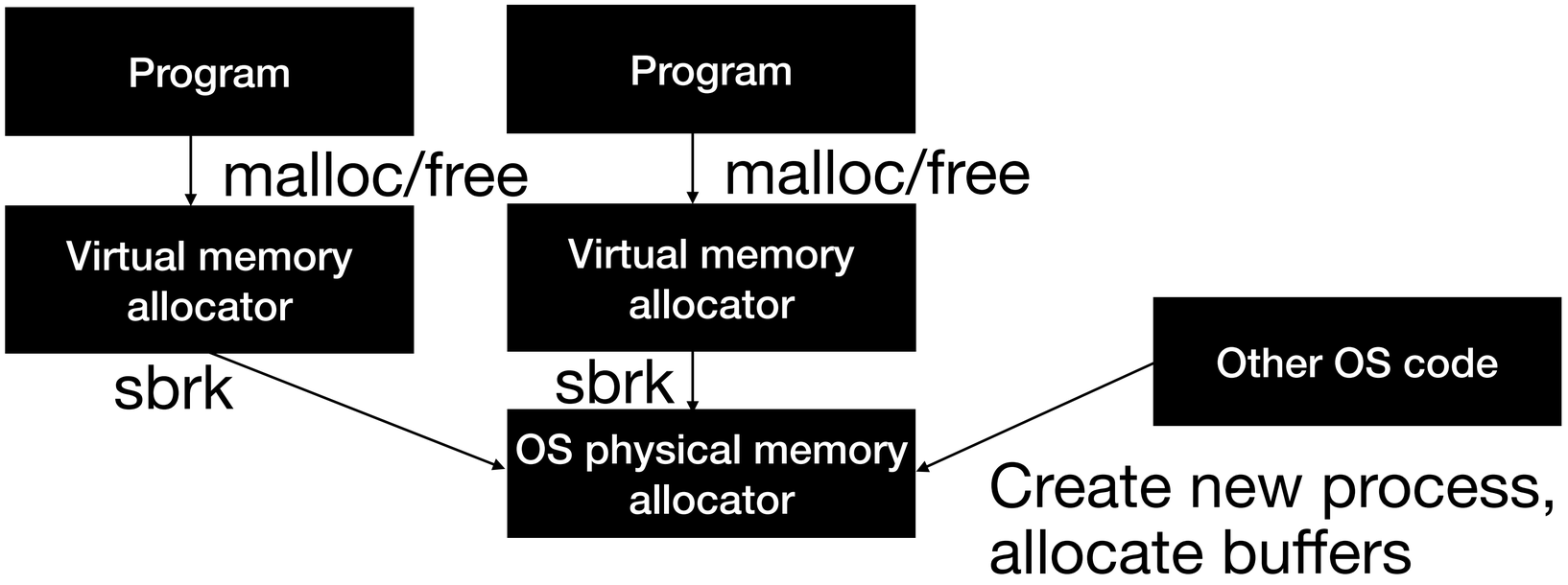

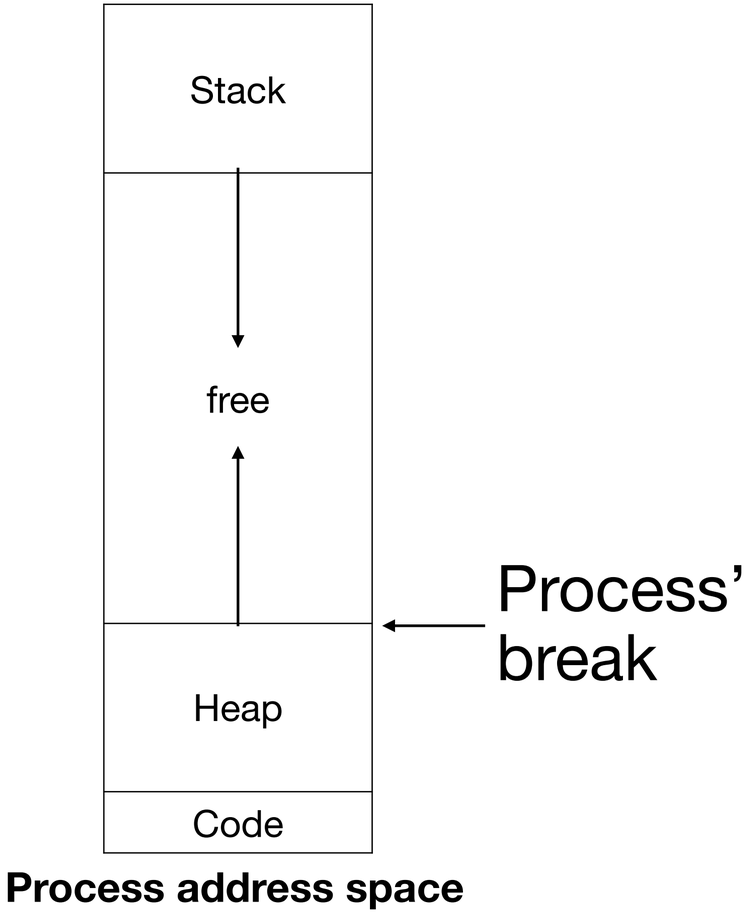

Memory allocation

```
ptr=malloc(size_t size);

free(ptr);
```

Memory allocation

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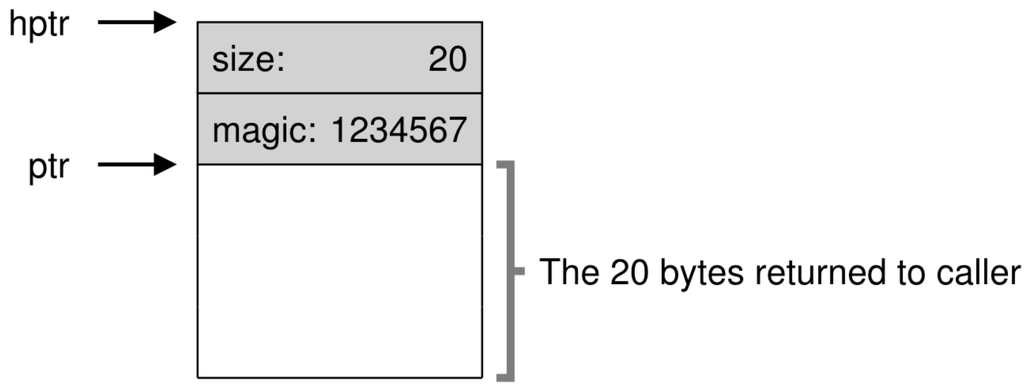


Figure 17.2: **Specific Contents Of The Header**

Memory allocation

```
ptr=malloc(size_t size);

free(ptr);
```

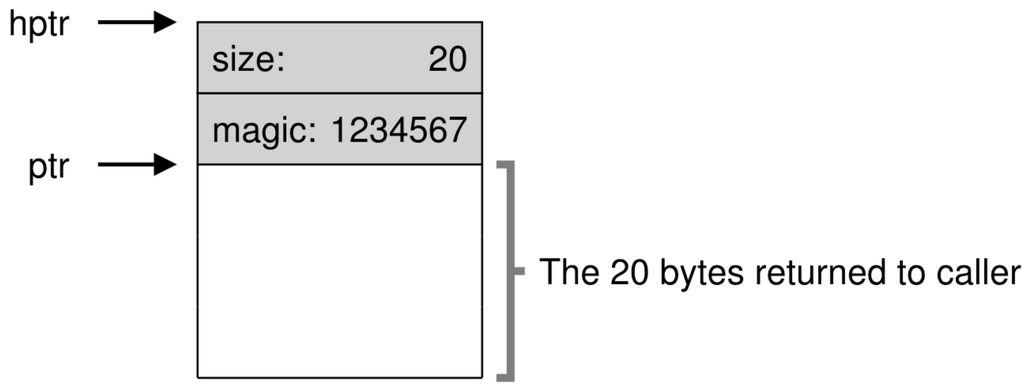
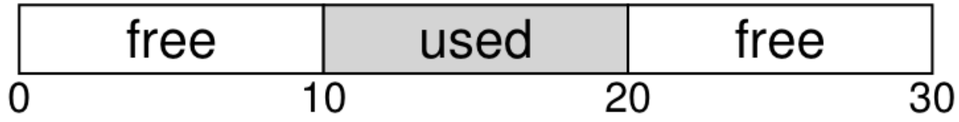


Figure 17.2: **Specific Contents Of The Header**

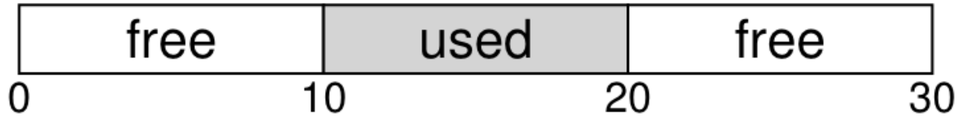
Stack allocations are faster than heap allocations. No need to find space.

Memory allocator



Fragmented heap over time

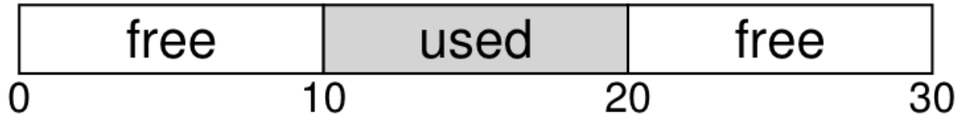
Memory allocator



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.

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

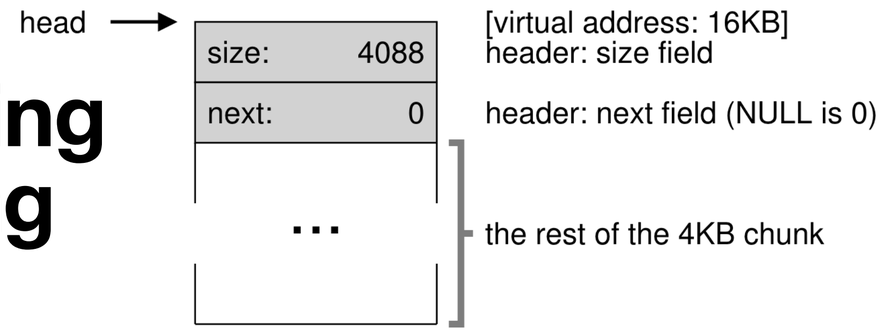


Figure 17.3: **A Heap With One Free Chunk**

```
ptr = malloc(100)

sptr = malloc(100)

optr = malloc(100)

free(sptr)

free(ptr)

free(optr)
```

Free list splitting and coalescing

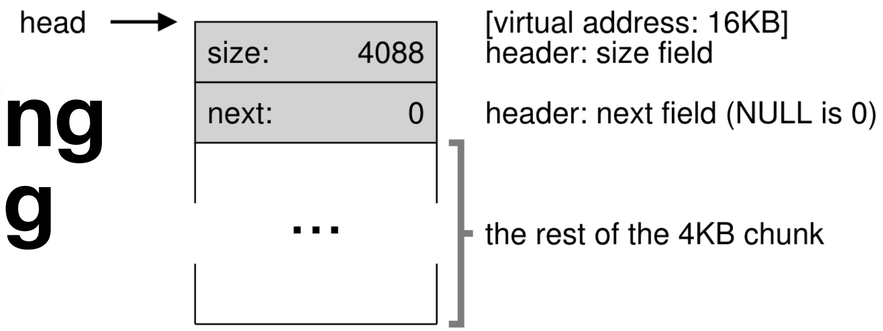


Figure 17.3: **A Heap With One Free Chunk**

```
ptr = malloc(100)

sptr = malloc(100)

optr = malloc(100)

free(sptr)

free(ptr)

free(optr)
```

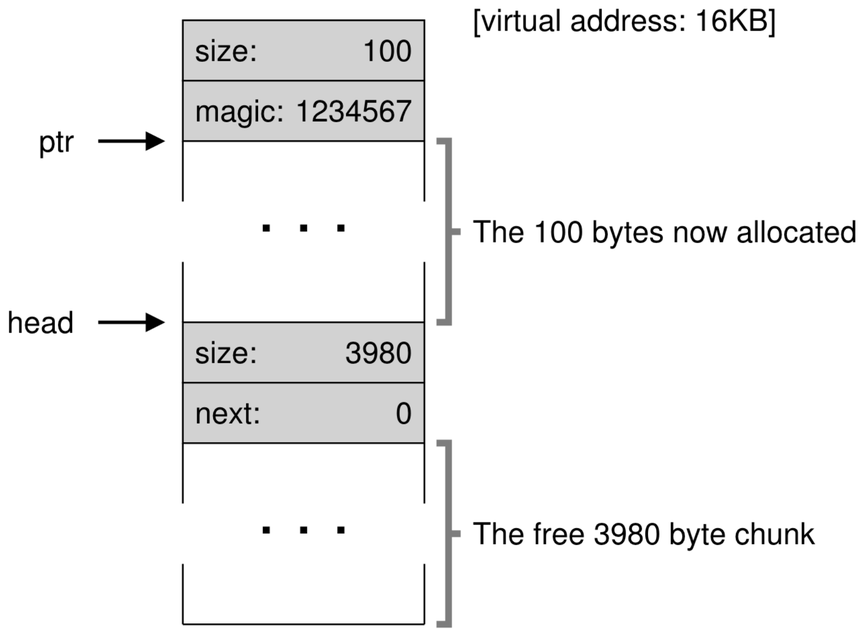


Figure 17.4: **A Heap: After One Allocation**

Free list splitting and coalescing

```
ptr = malloc(100)

sptr = malloc(100)

optr = malloc(100)

free(sptr)

free(ptr)

free(optr)
```

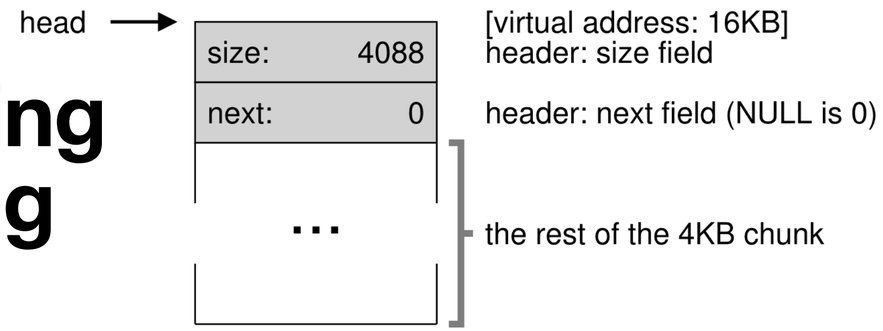


Figure 17.3: **A Heap With One Free Chunk**

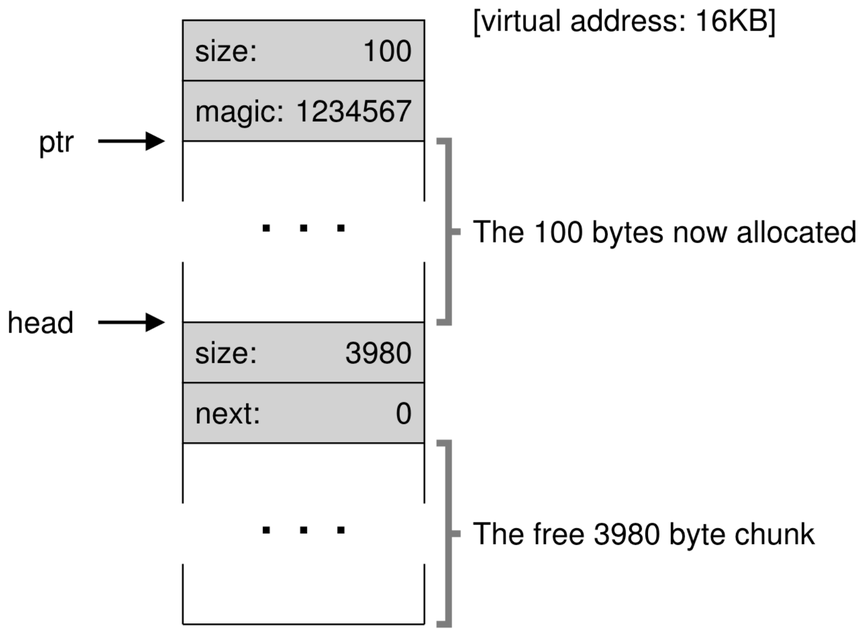


Figure 17.4: **A Heap: After One Allocation**

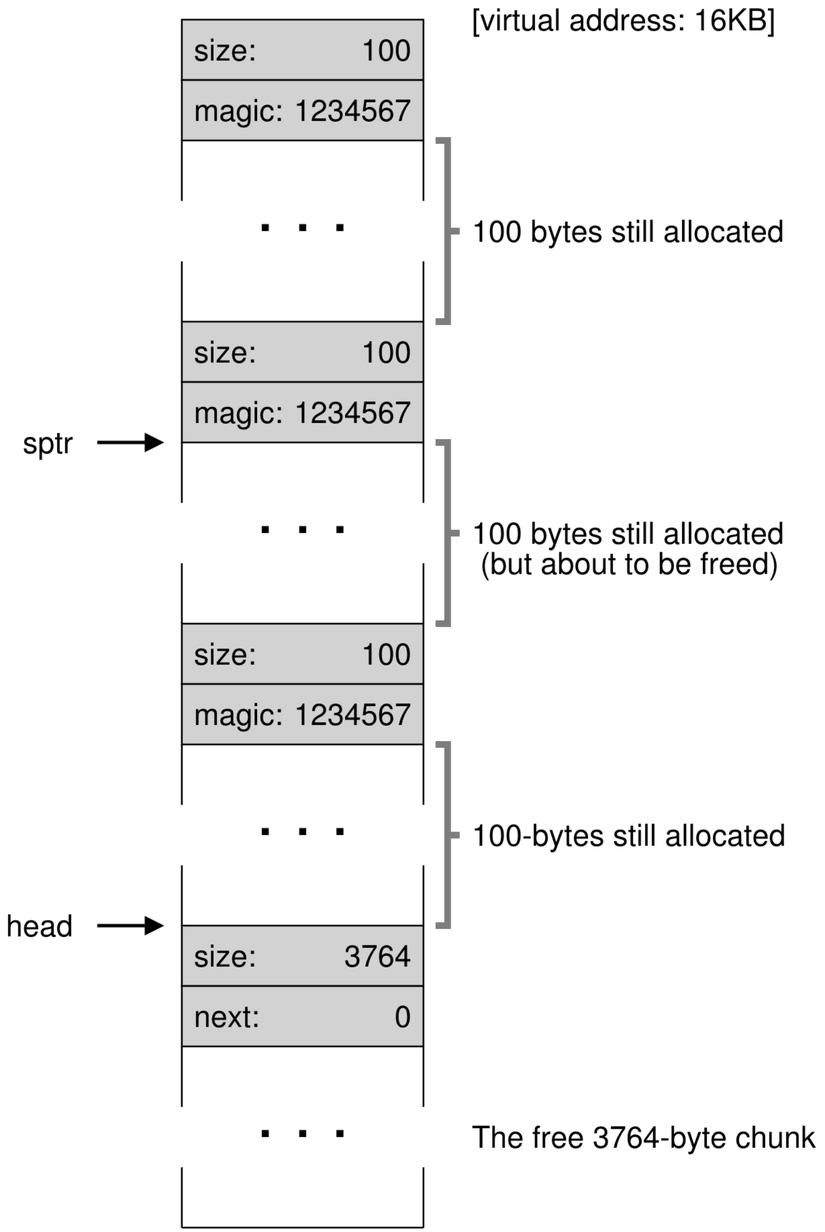


Figure 17.5: **Free Space With Three Chunks Allocated**

Free list splitting and coalescing

```
ptr = malloc(100)

sptr = malloc(100)

optr = malloc(100)

free(sptr)

free(ptr)

free(optr)
```

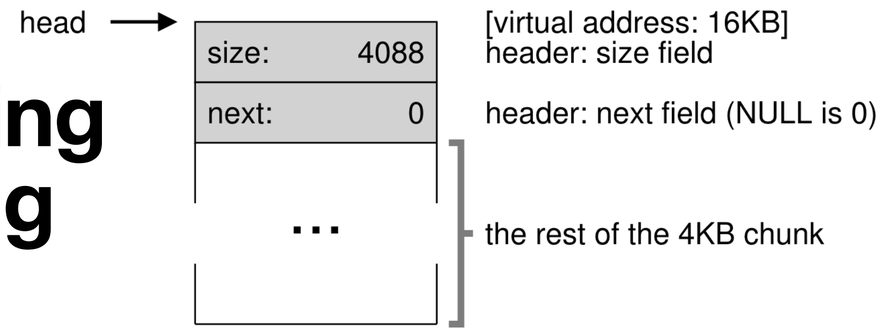


Figure 17.3: **A Heap With One Free Chunk**

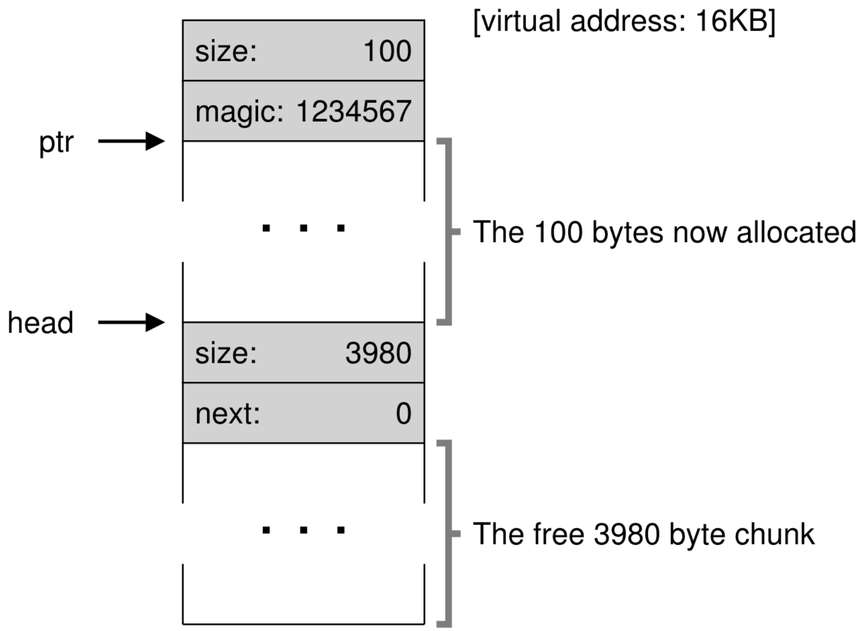


Figure 17.4: **A Heap: After One Allocation**

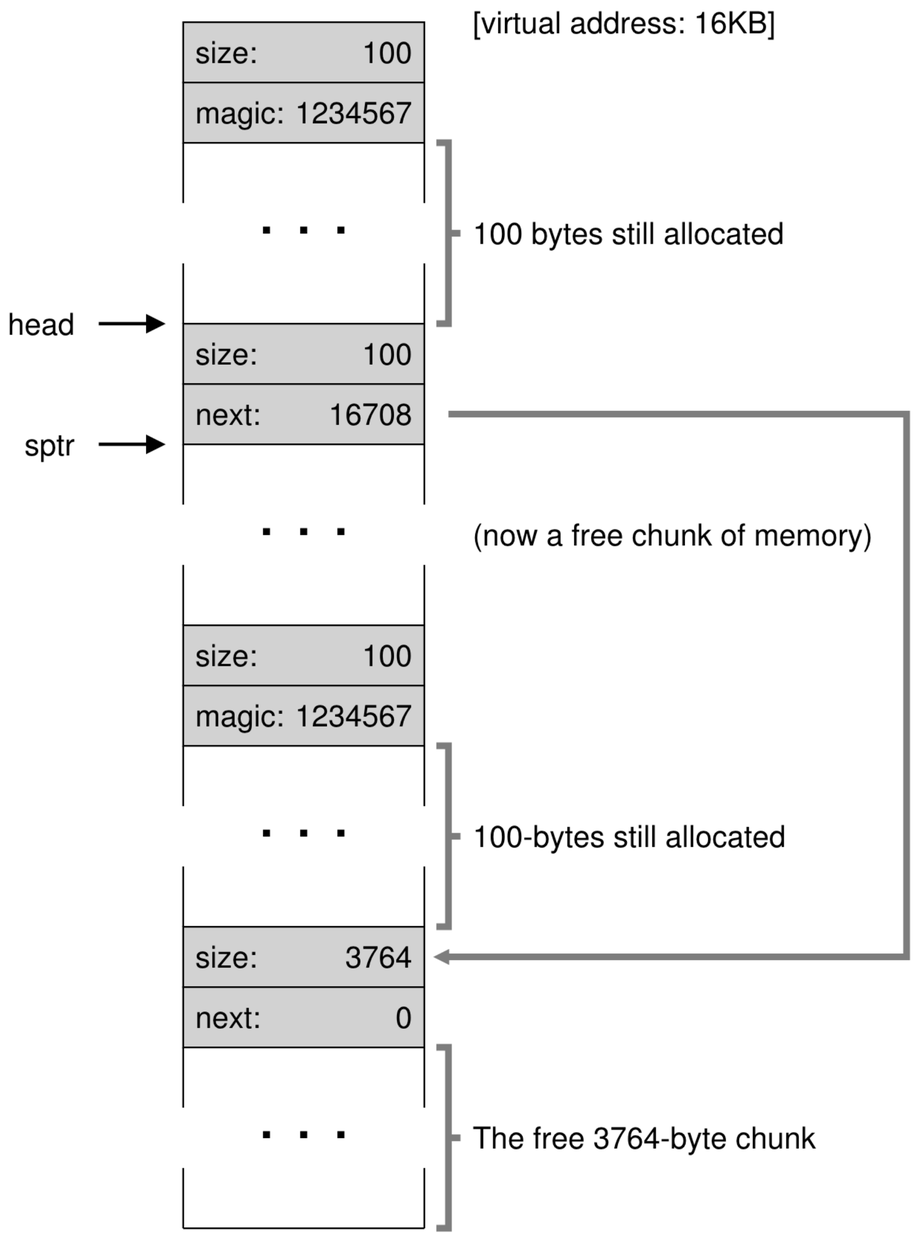


Figure 17.6: **Free Space With Two Chunks Allocated**

Free list splitting and coalescing

```
ptr = malloc(100)

sptr = malloc(100)

optr = malloc(100)

free(sptr)

free(ptr)

free(optr)
```

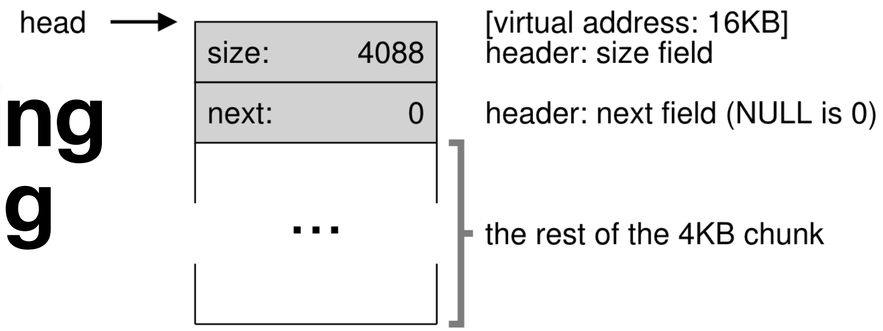


Figure 17.3: **A Heap With One Free Chunk**

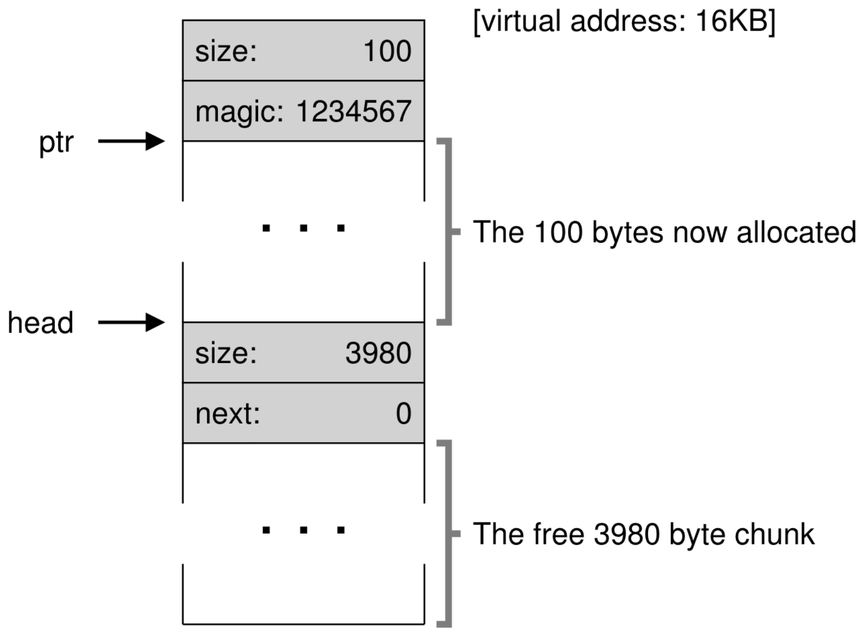


Figure 17.4: **A Heap: After One Allocation**

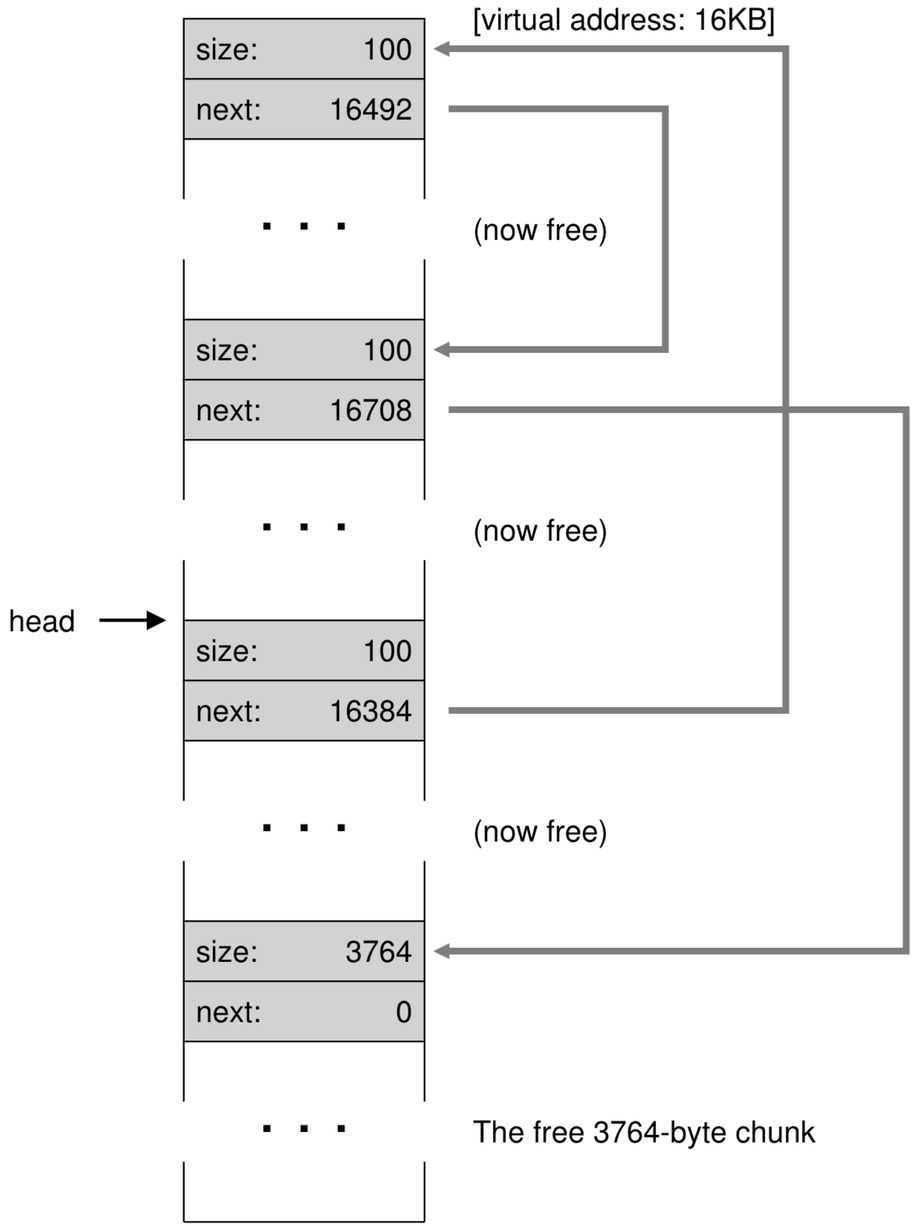


Figure 17.7: **A Non-Coalesced Free List**

Free list splitting and coalescing

```
ptr = malloc(100)

sptr = malloc(100)

optr = malloc(100)

free(sptr)

free(ptr)

free(optr)
```

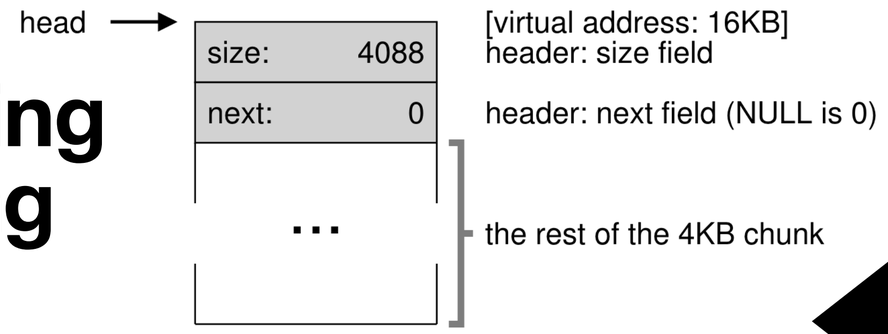


Figure 17.3: **A Heap With One Free Chunk**

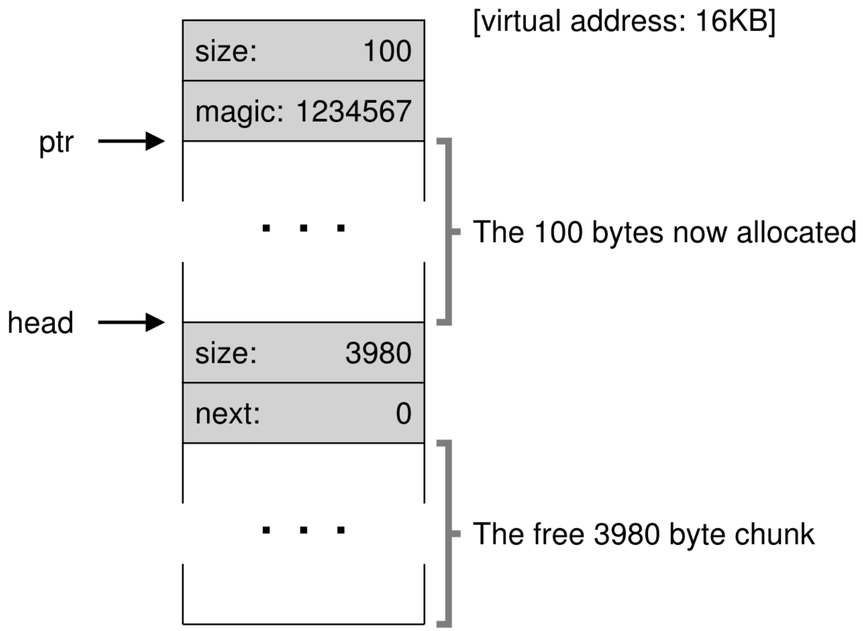


Figure 17.4: **A Heap: After One Allocation**

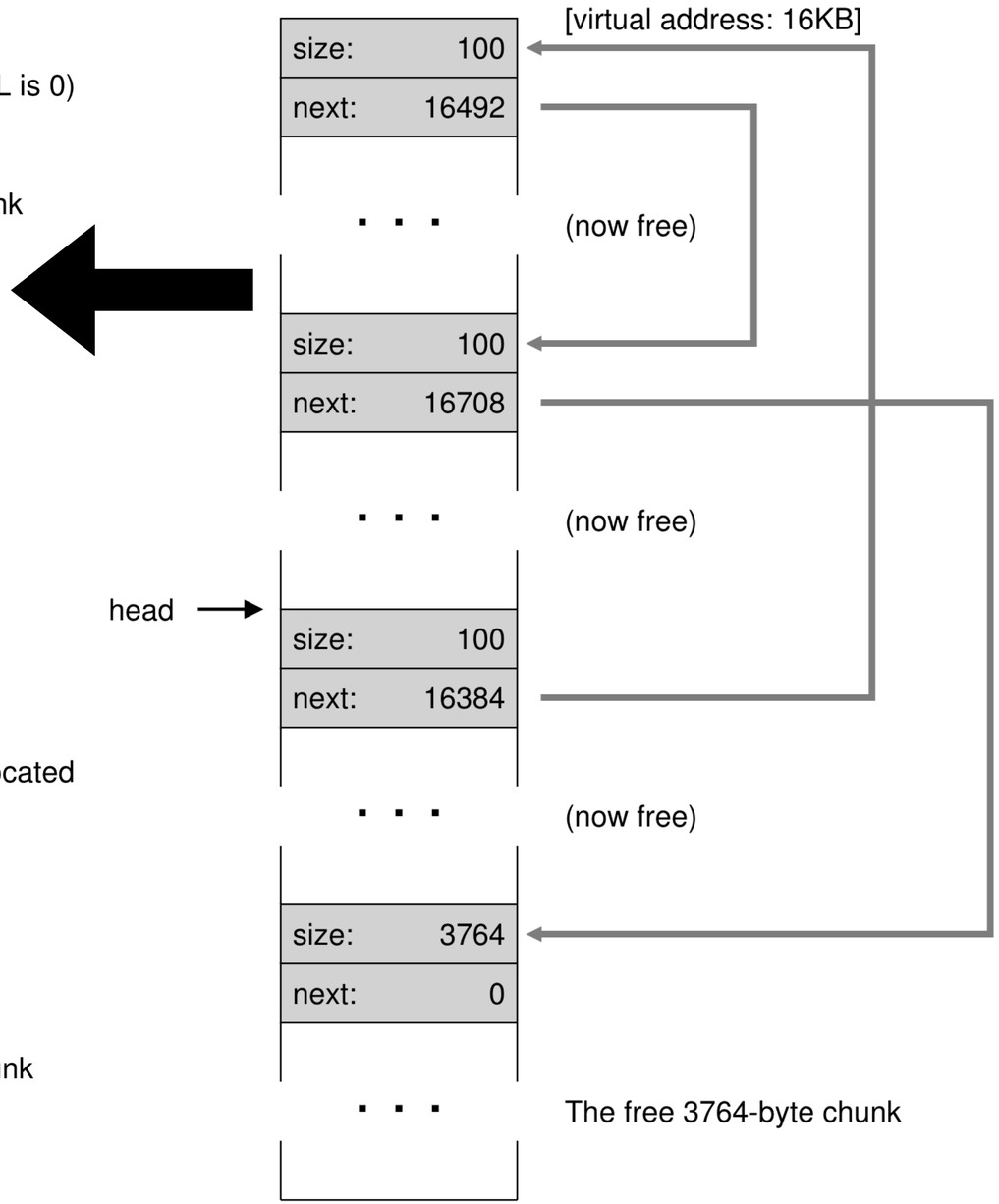


Figure 17.7: **A Non-Coalesced Free List**

Which block to allocate?

Example: malloc(15)

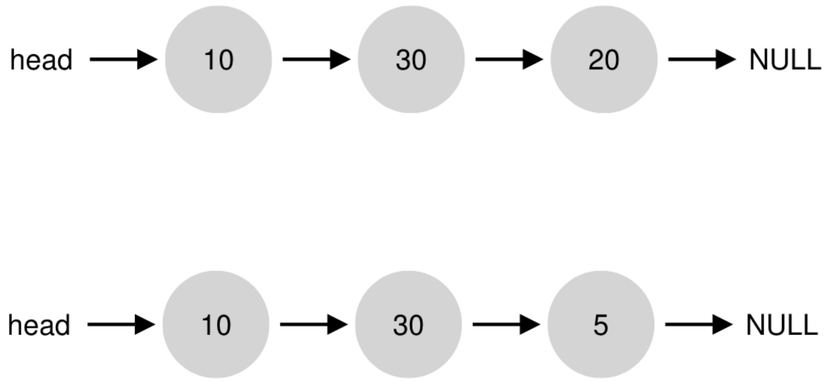
Which block to allocate?

Example: malloc(15)

- Best fit
  - Slow. need to search the whole list

Which block to allocate?

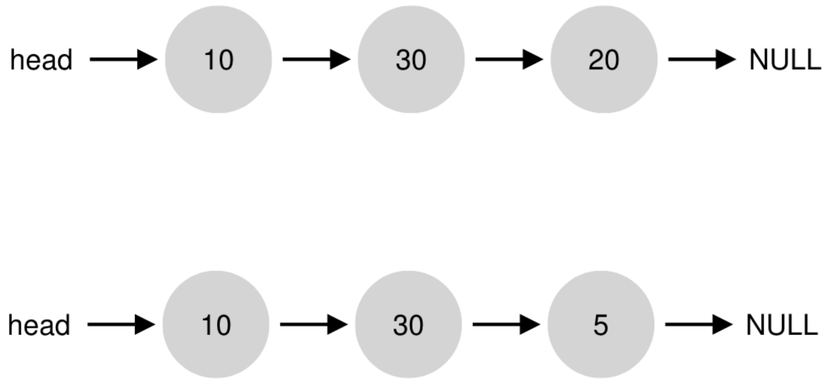
Example: malloc(15)



- Best fit
  - Slow. need to search the whole list

Which block to allocate?

Example: malloc(15)



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

Which block to allocate?

Example: malloc(15)

- Best fit
  - Slow. need to search the whole list
- First fit
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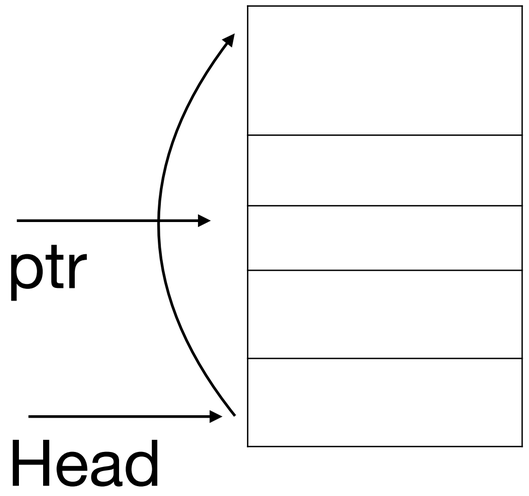
Which block to allocate?

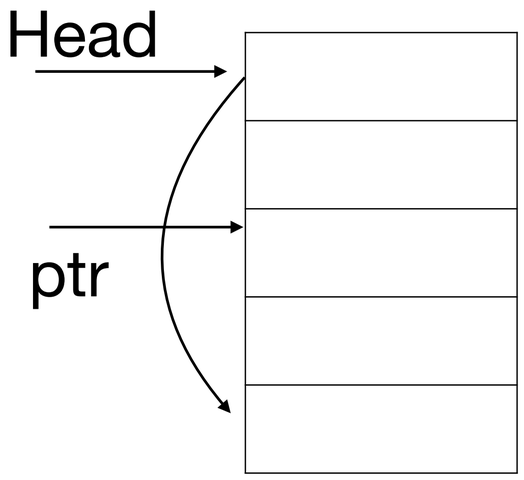
Example: malloc(15)

- 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?

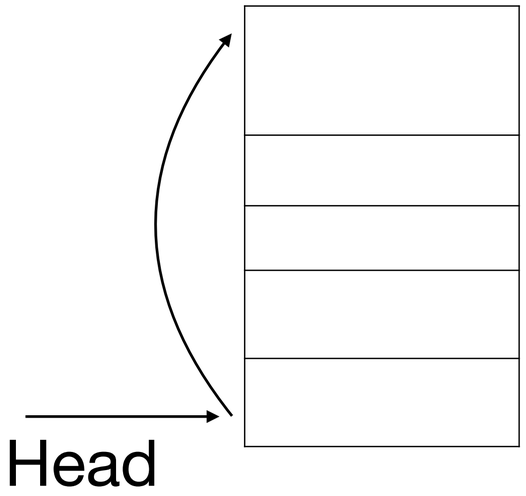
- (De)allocation order

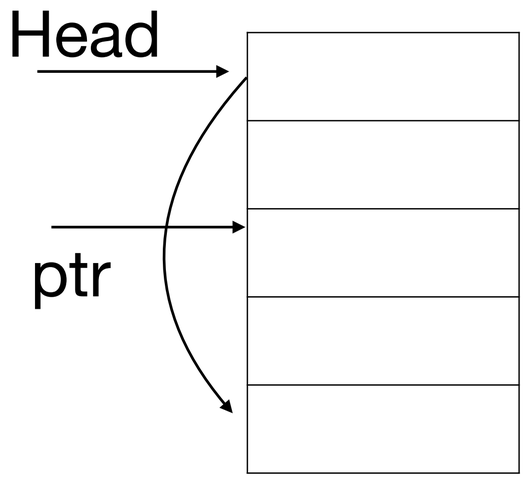




In which order to maintain lists?

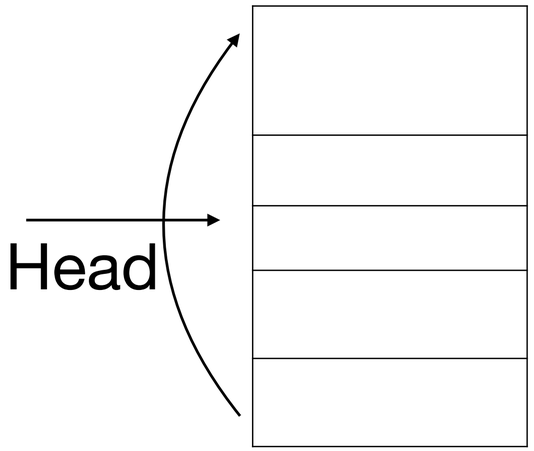
- (De)allocation order

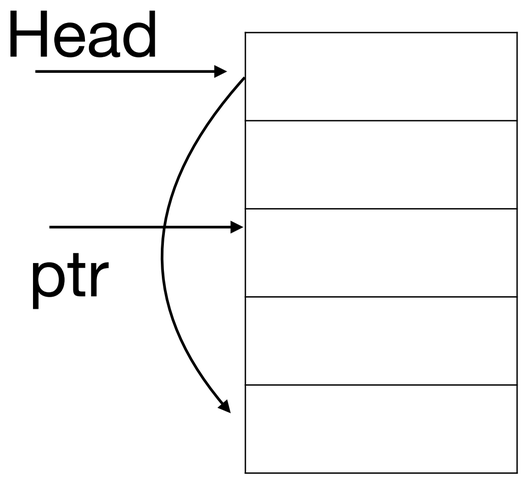




In which order to maintain lists?

- (De)allocation order





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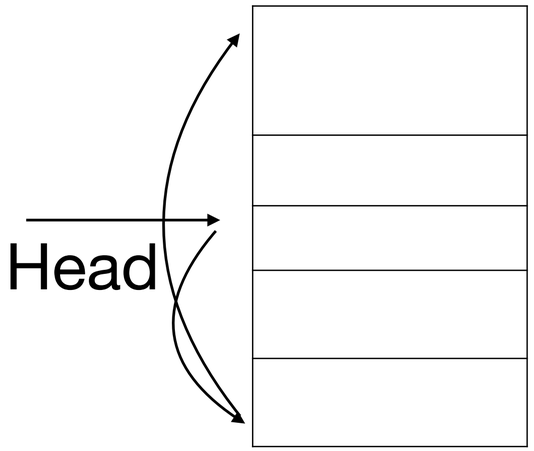

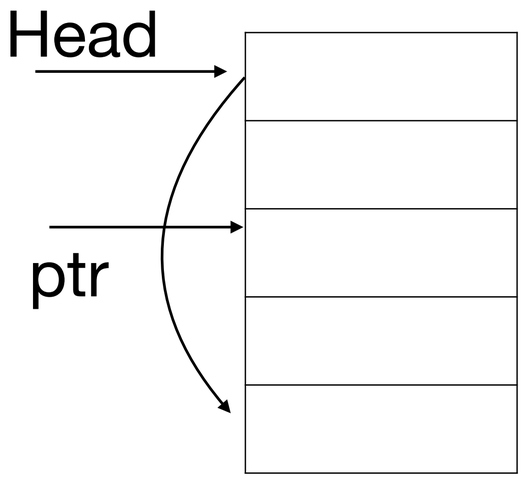

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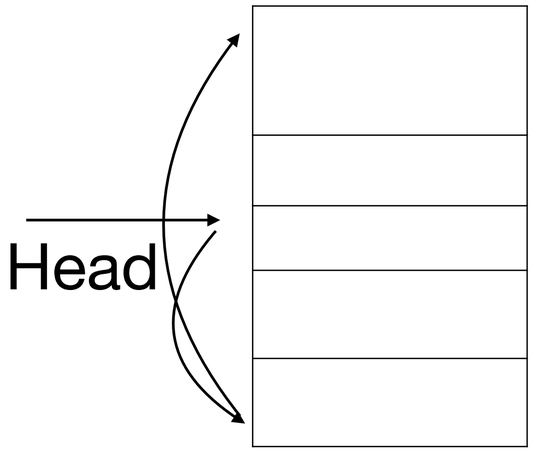
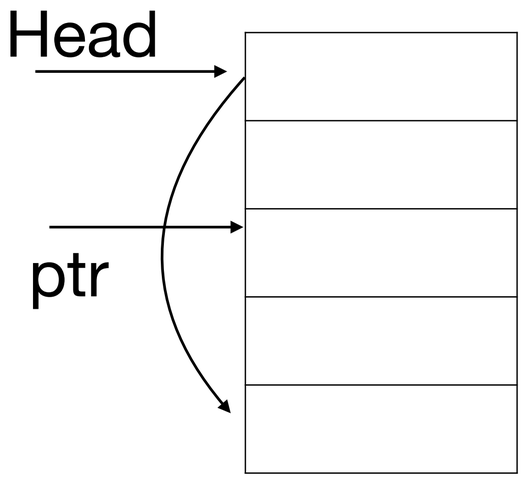
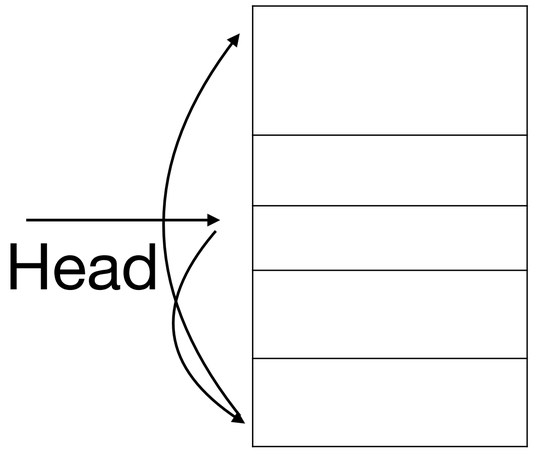


- Address order

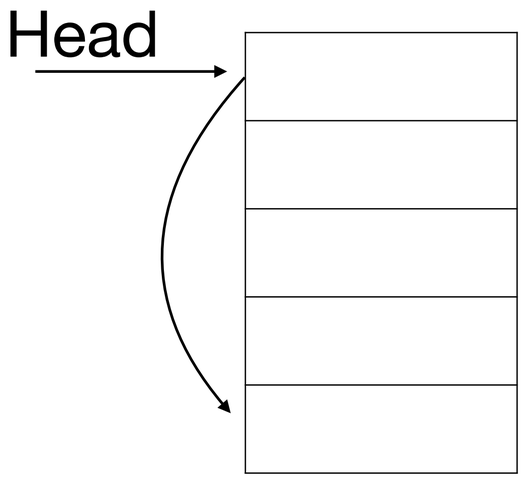


In which order to maintain lists?

- (De)allocation order



- Address order



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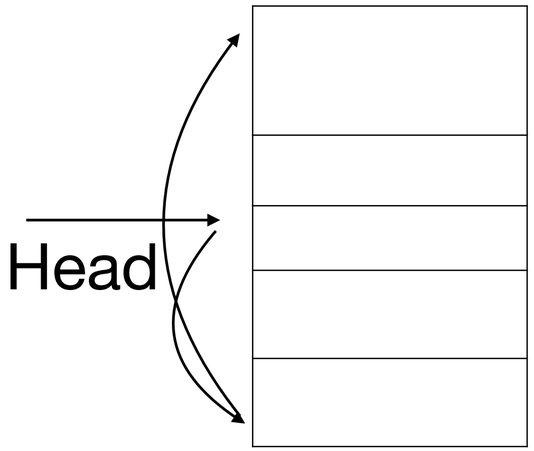

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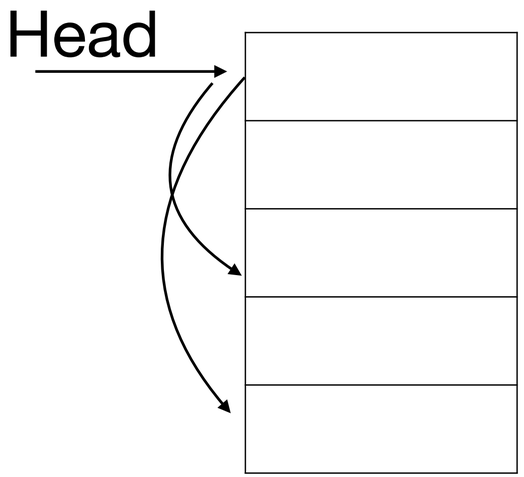
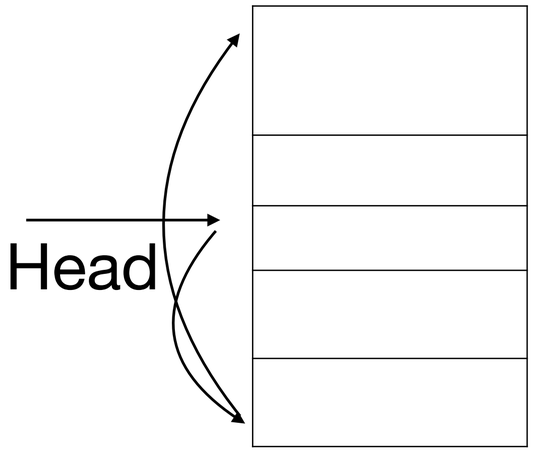
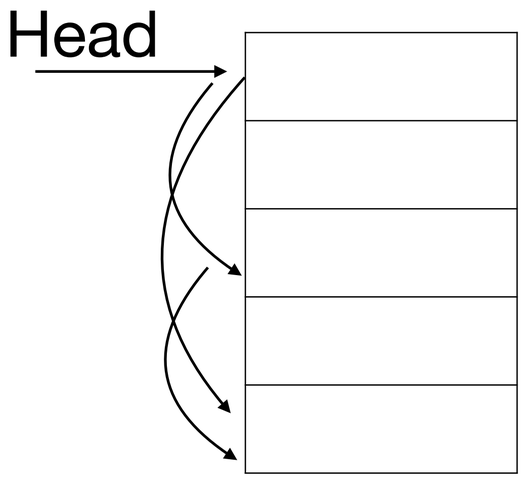


In which order to maintain lists?

- (De)allocation order



- Address order



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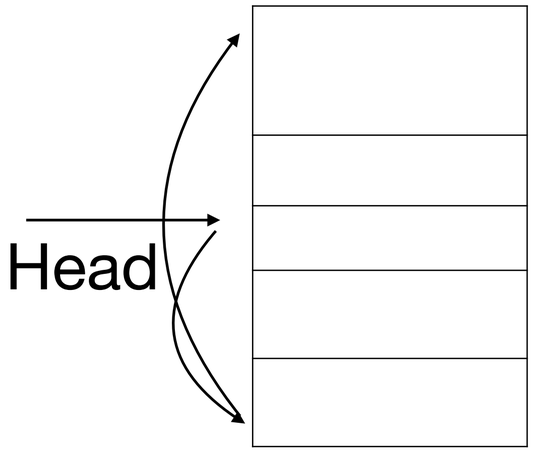
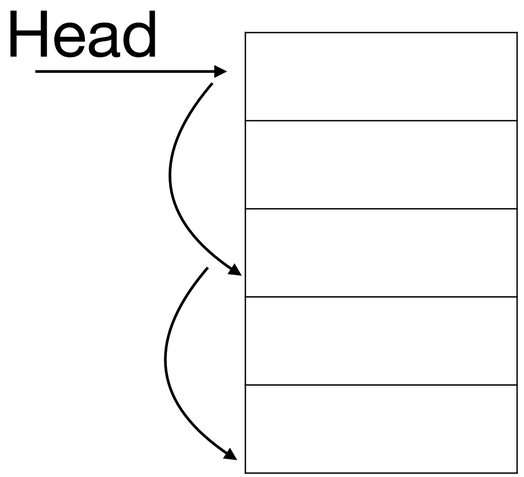
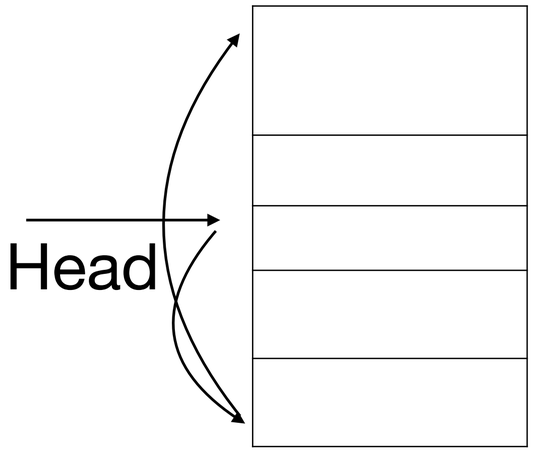


- Address order

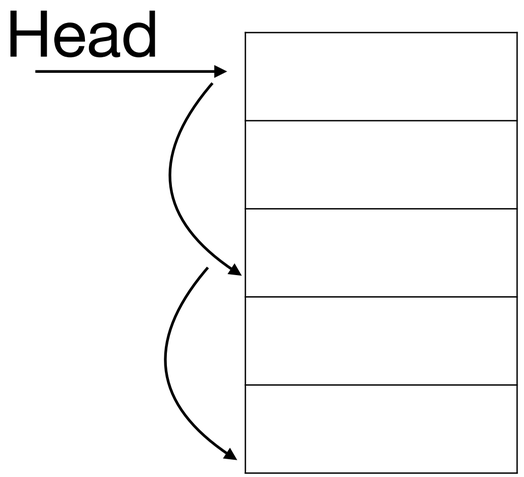


In which order to maintain lists?

- (De)allocation order



- Address order
  - Slow frees: need to traverse the free list



In which order to maintain lists?

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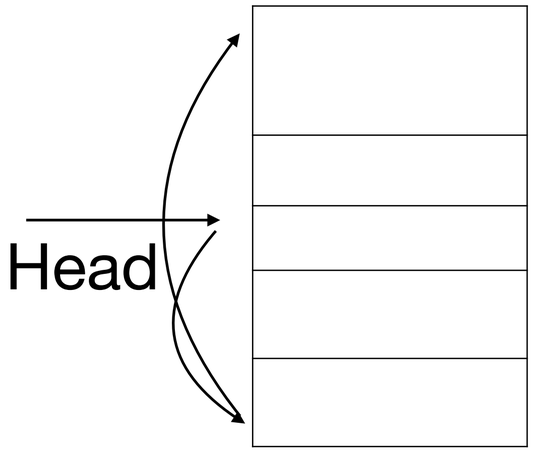
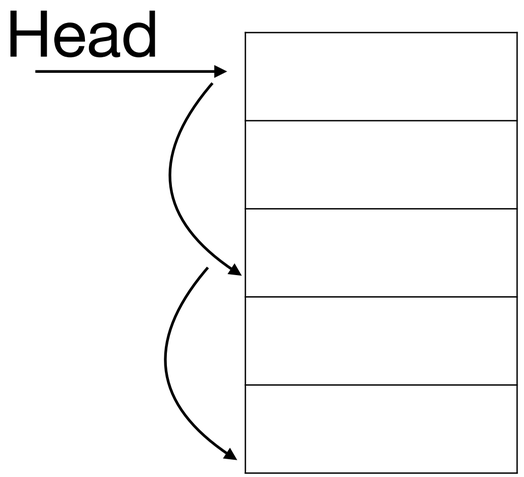


- Address order
  - Slow frees: need to traverse the free list
  - (xv6: umalloc.c)



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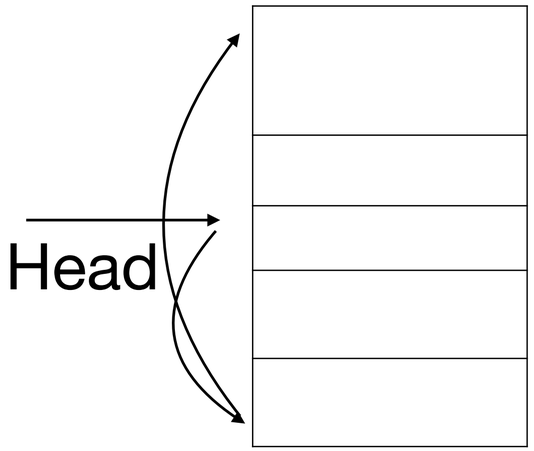
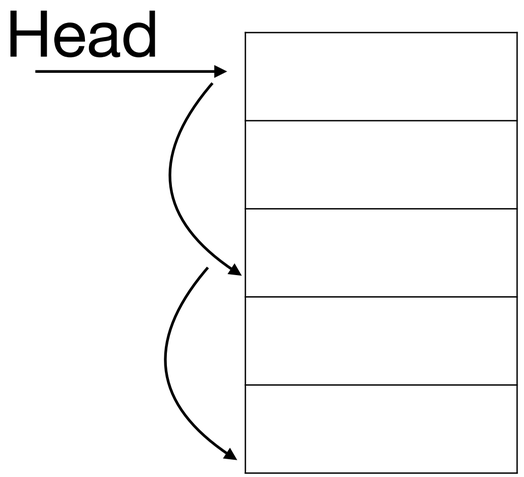
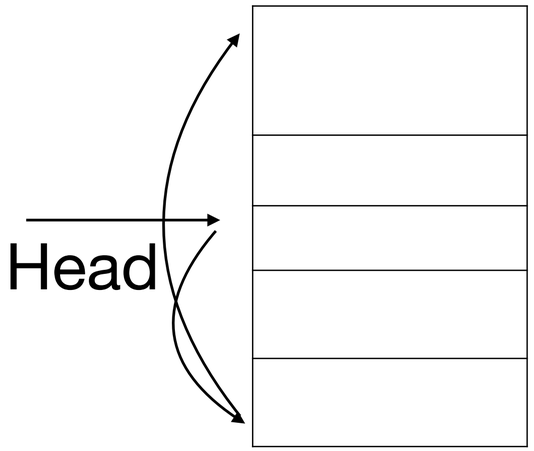


- Address order
  - Slow frees: need to traverse the free list
  - (xv6: umalloc.c)
  - Address order, first fit will allocate back-to-back allocations contiguously.

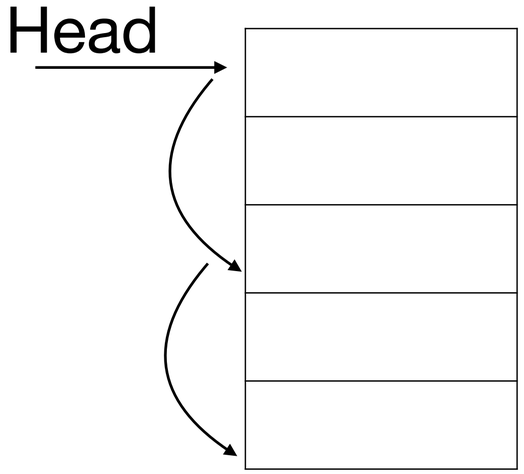


In which order to maintain lists?

- (De)allocation order

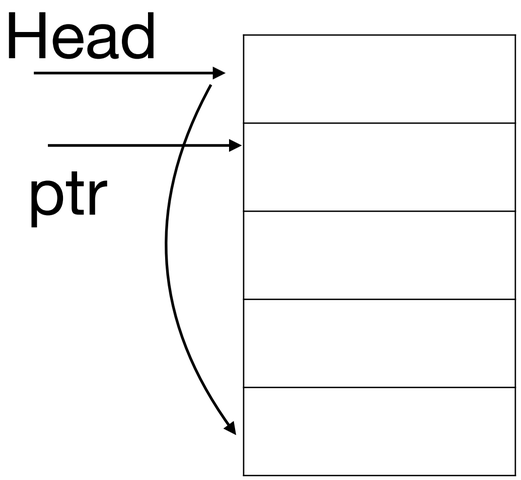


- Address order
  - Slow frees: need to traverse the free list
  - (xv6: umalloc.c)
  - Address order, first fit will allocate back-to-back allocations contiguously.
    - Due to “clustered deaths”, we may get better chances of coalescing



How to do coalescing?

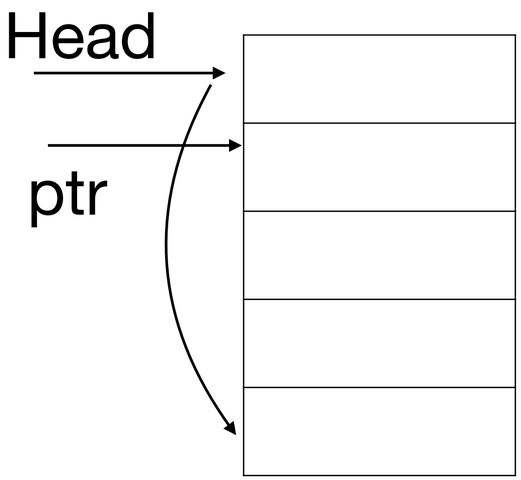
Example: free(ptr)



- Straightforward in address order since we are traversing the free list in address order

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

How to do coalescing?

Example: free(ptr)

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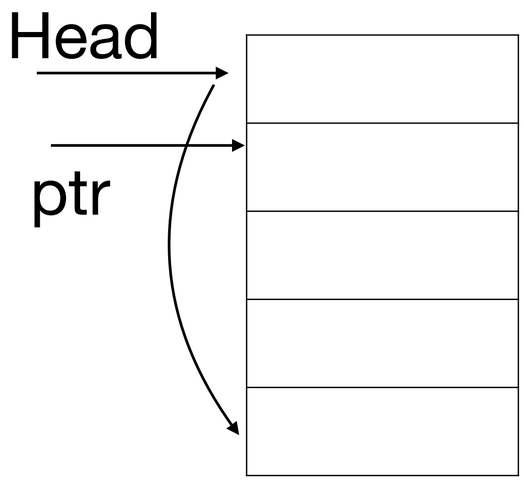
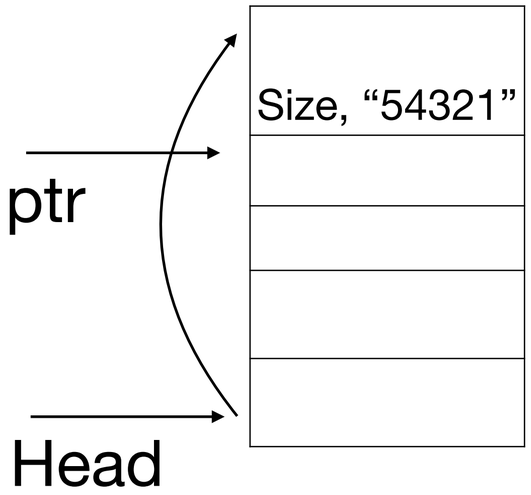
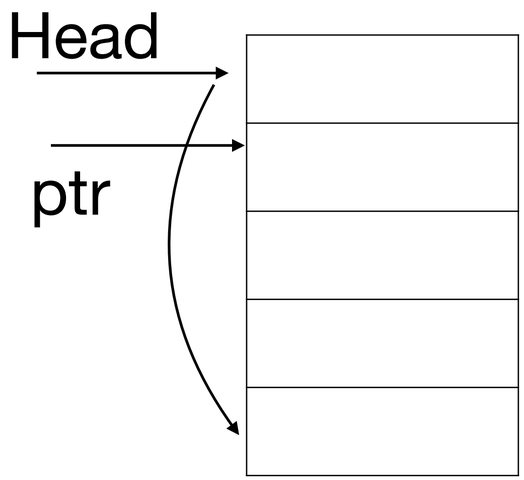
- In deallocation order: when an area is freed, check if the “boundary tag” is present in the footer above



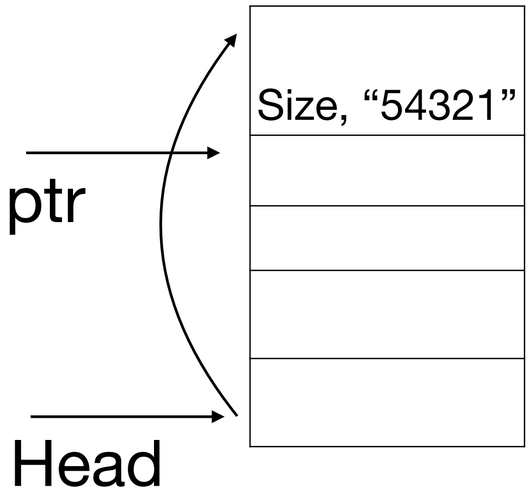


How to do coalescing?

Example: free(ptr)

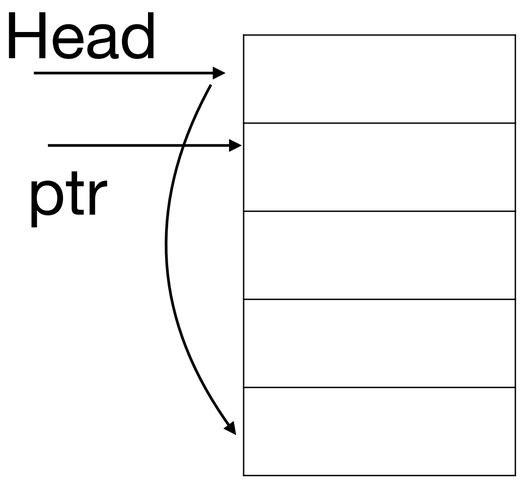


- Straightforward in address order since we are traversing the free list in address order
- In deallocation order: when an area is freed, check if the “boundary tag” is present in the footer above
- First fit and address order

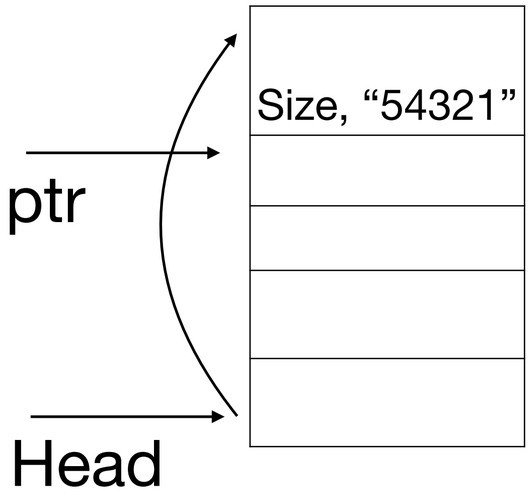


How to do coalescing?

Example: free(ptr)

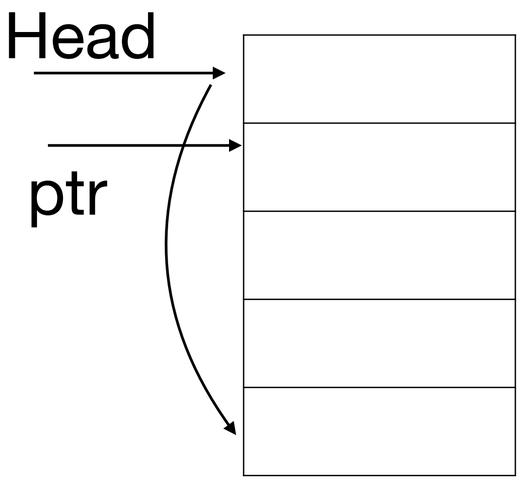


- Straightforward in address order since we are traversing the free list in address order
- In deallocation order: when an area is freed, check if the “boundary tag” is present in the footer above
- First fit and address order
  - Better chances of coalescing for clustered deaths, simpler coalescing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

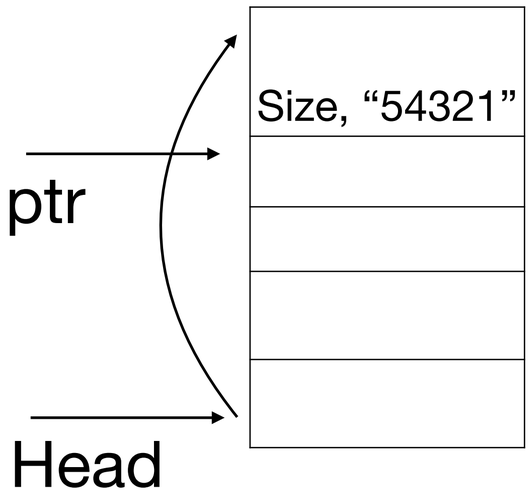


How to do coalescing?

Example: free(ptr)

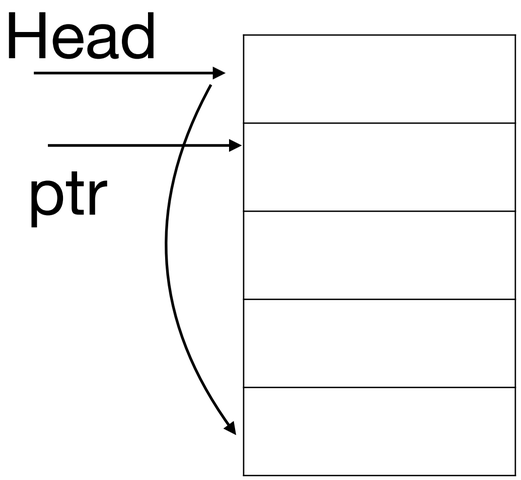


- Straightforward in address order since we are traversing the free list in address order
- In deallocation order: when an area is freed, check if the “boundary tag” is present in the footer above
- First fit and address order
  - Better chances of coalescing for clustered deaths, simpler coalescing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



How to do coalescing?

Example: free(ptr)



- Straightforward in address order since we are traversing the free list in address order
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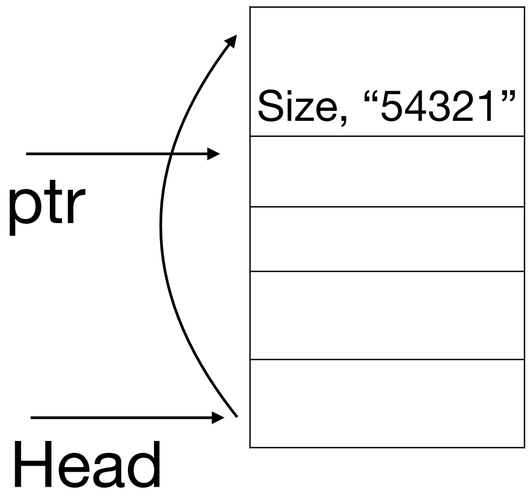
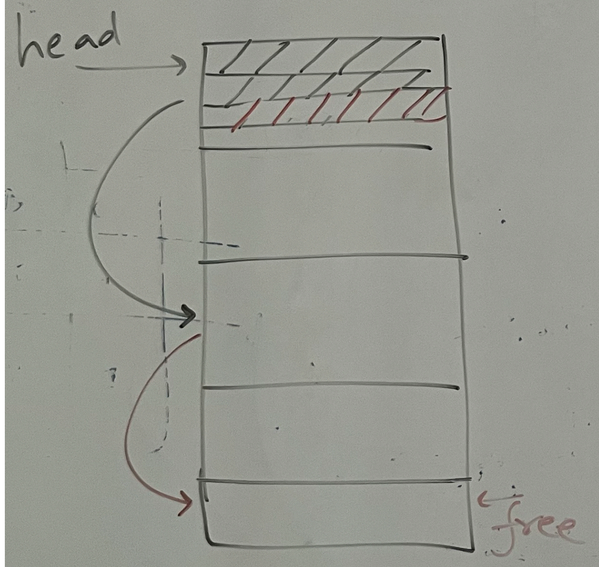
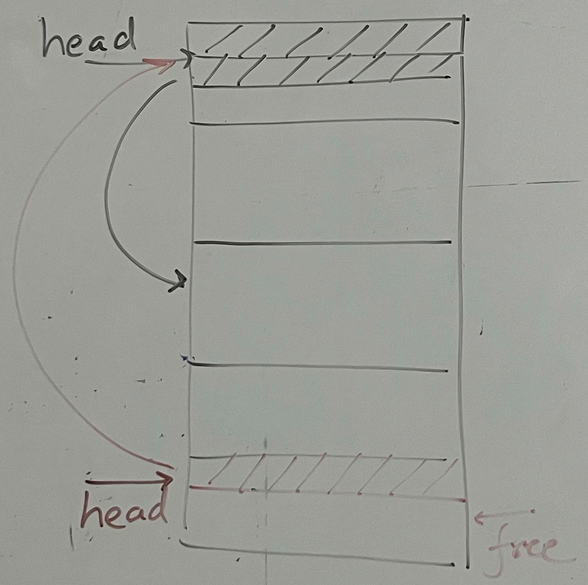
- First fit and address order
  - Better chances of coalescing for clustered deaths, simpler coalescing (no boundary tag)
  - First fit causes fragmentation
  - Address order slows frees due to traversing free list



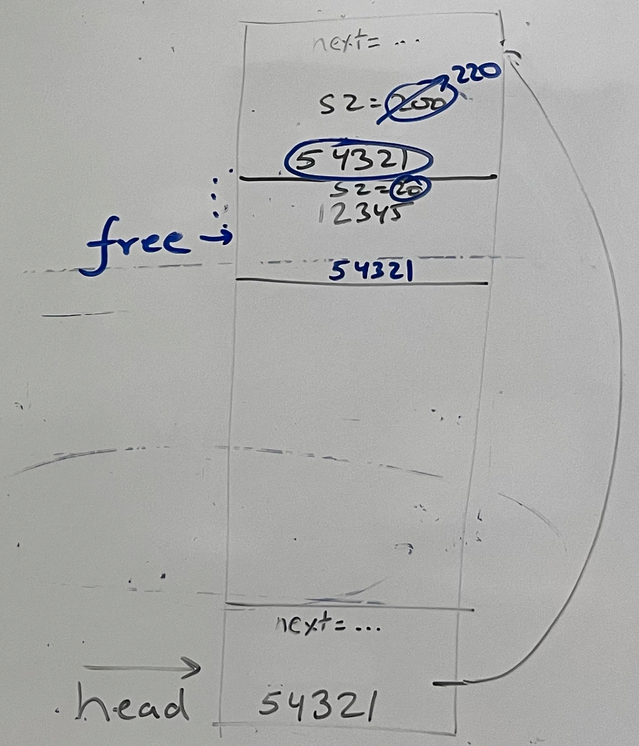
First fit
address order



First fit
(de) allocation order

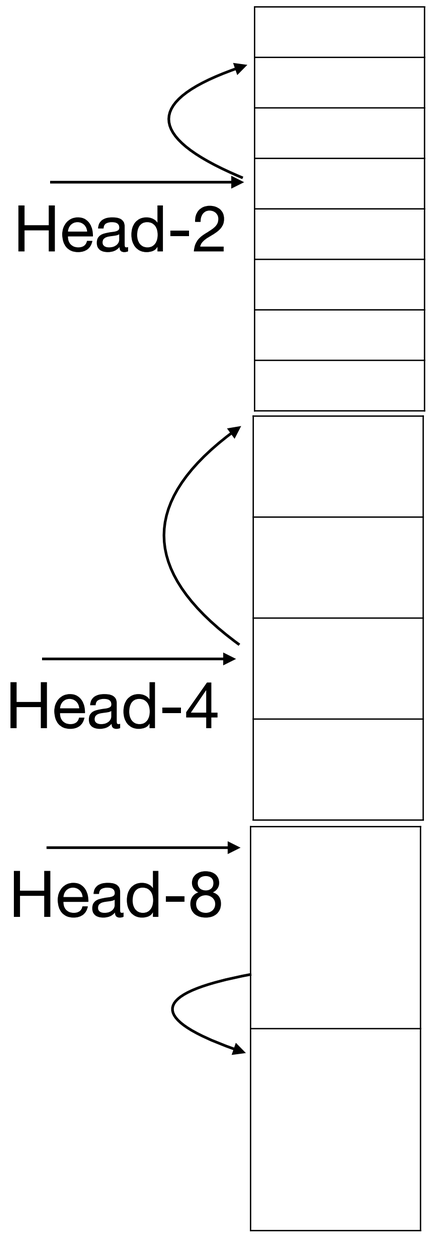


Boundary tag



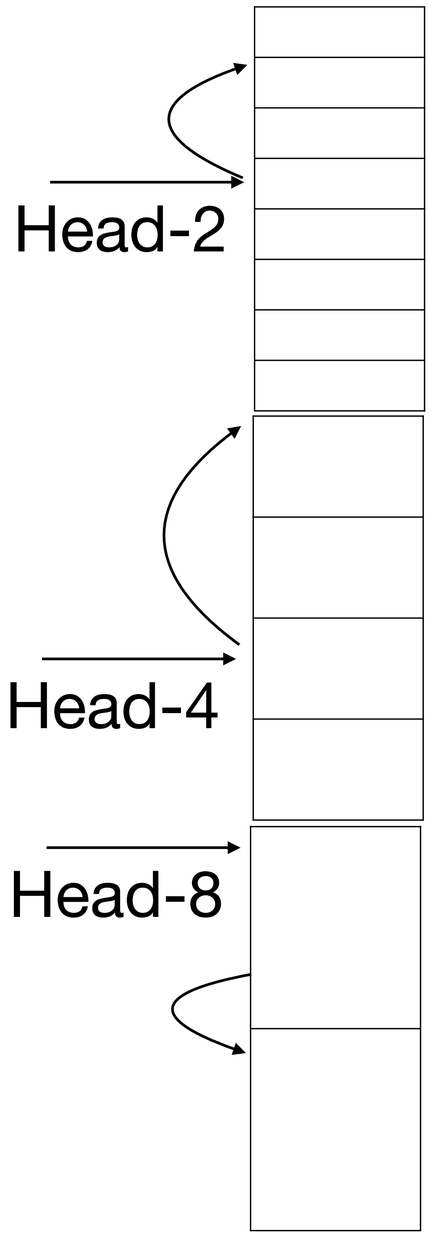
Segregated lists

- Separate lists for each size.



Segregated lists

- Separate lists for each size.
- “Segregated fit”: First fit in the smallest object list that can fit the object. Approximates best fit.



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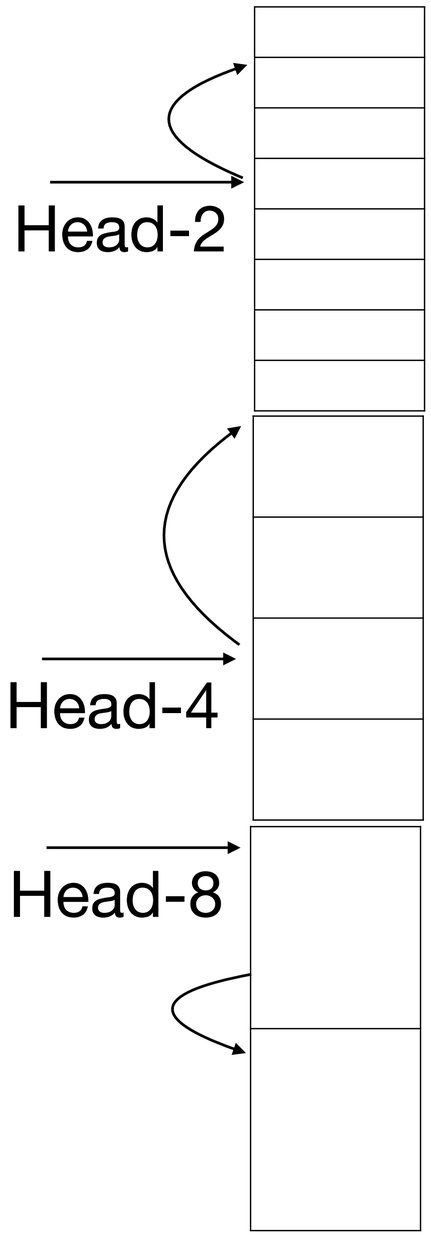

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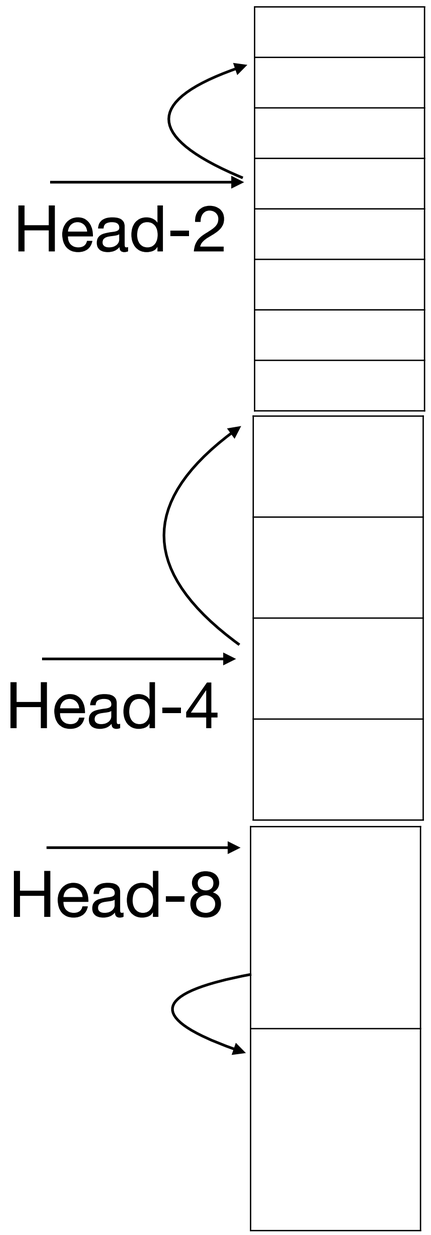
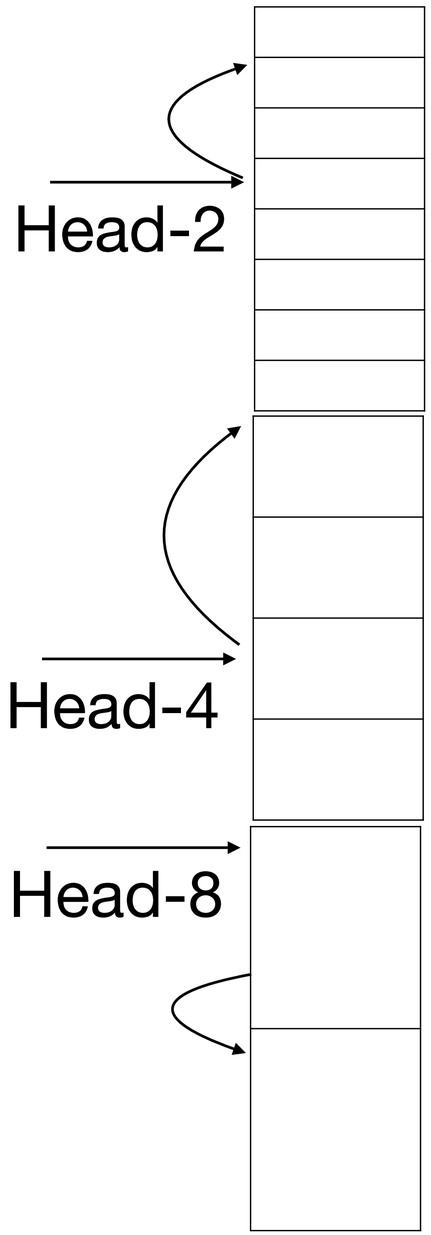
- Internal fragmentation: allocates more than asked



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



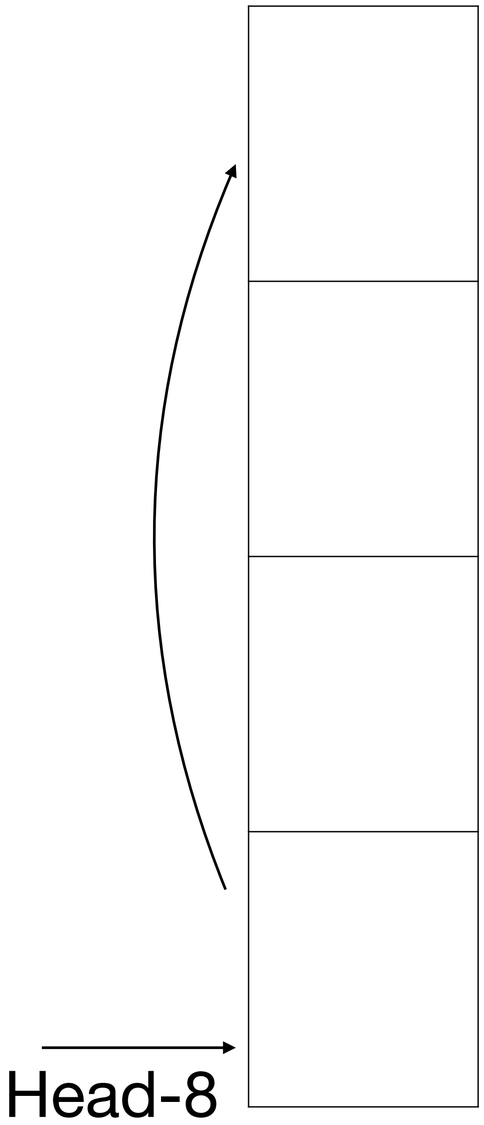
Slab allocator

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 = malloc(3)
  - p2 = malloc(2)



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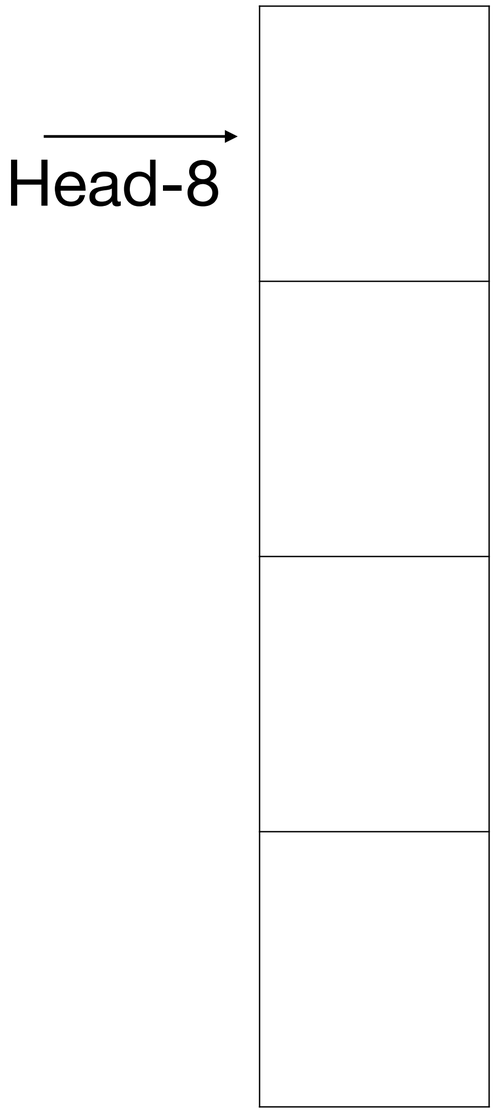

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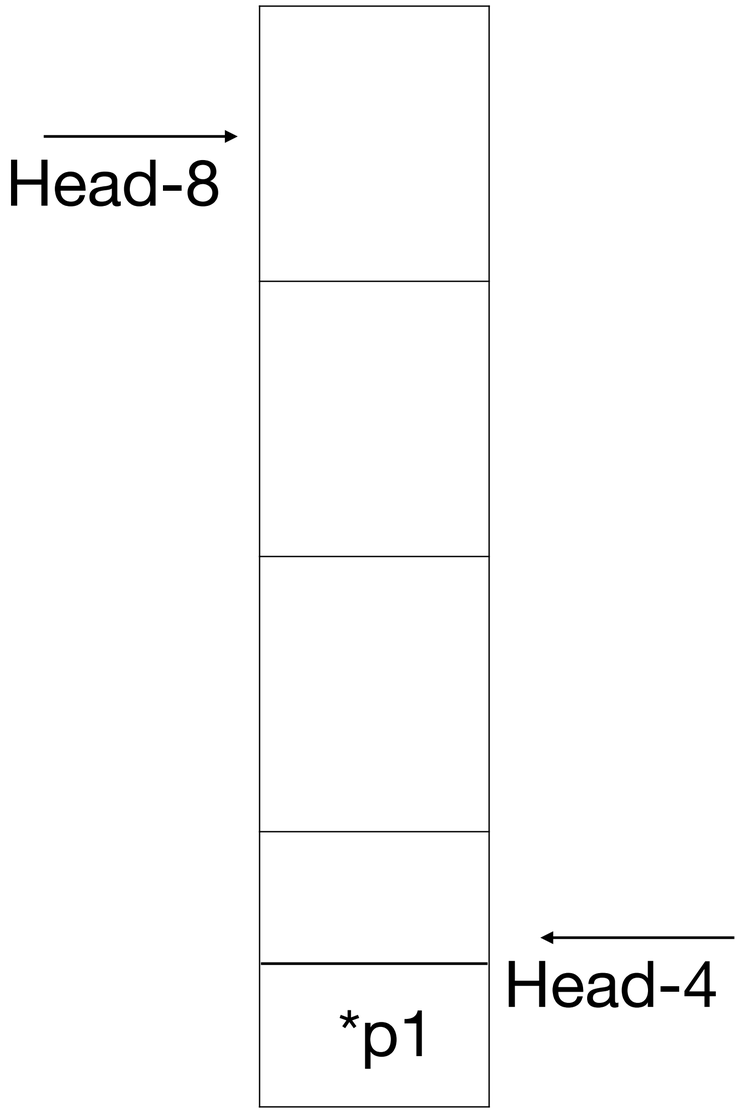

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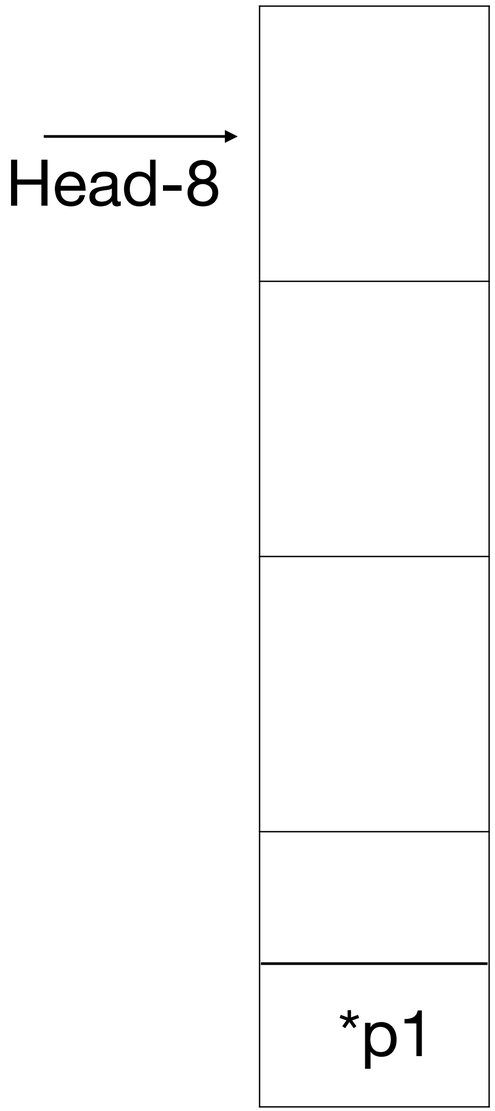

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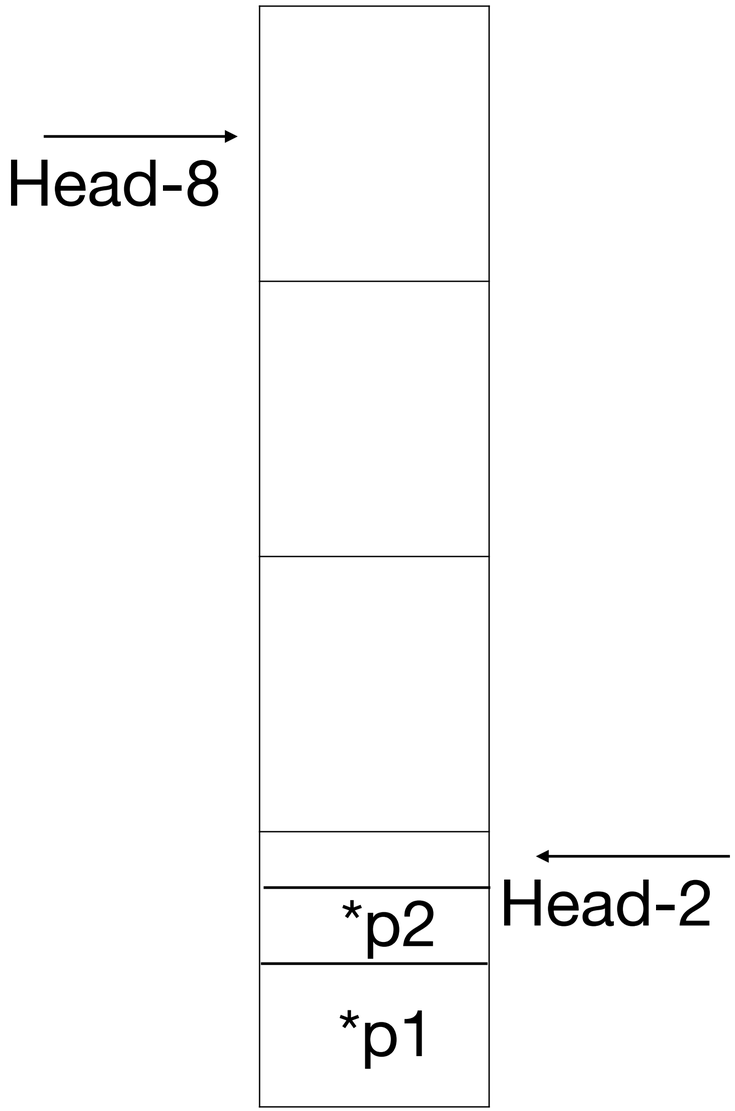

Buddy allocator

- Example:
  - p1 = malloc(3)
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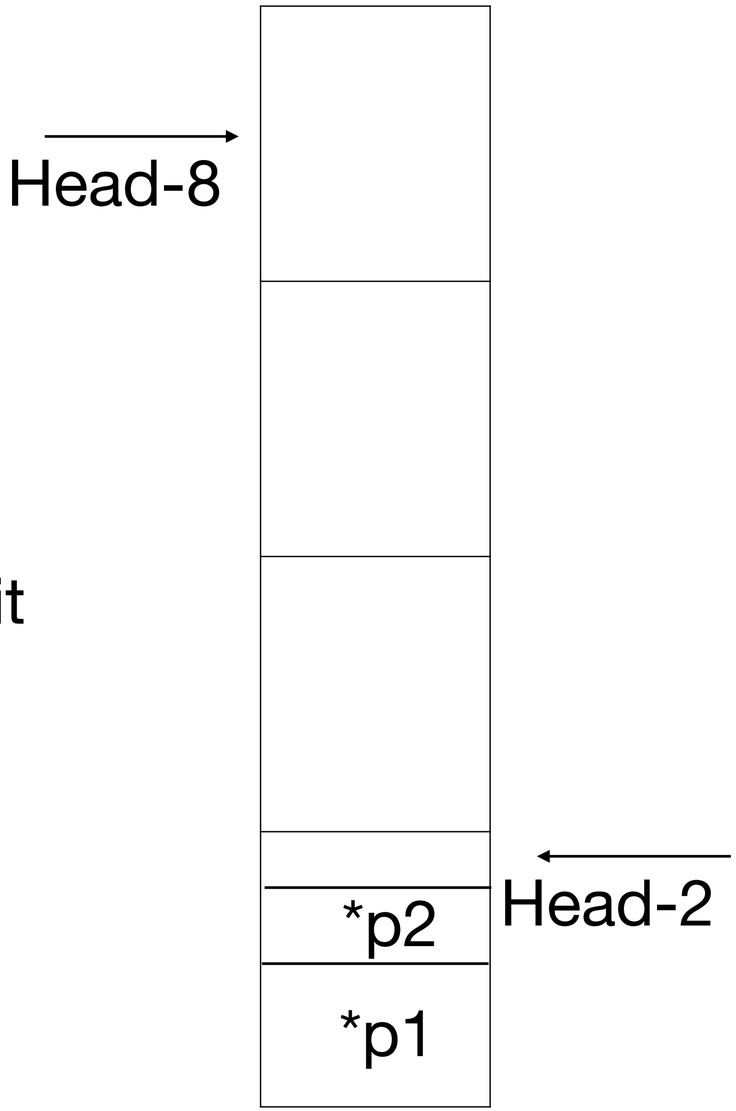
- First fit with segregated lists approximates best fit



Buddy allocator

- Example:
  - p1 = malloc(3)
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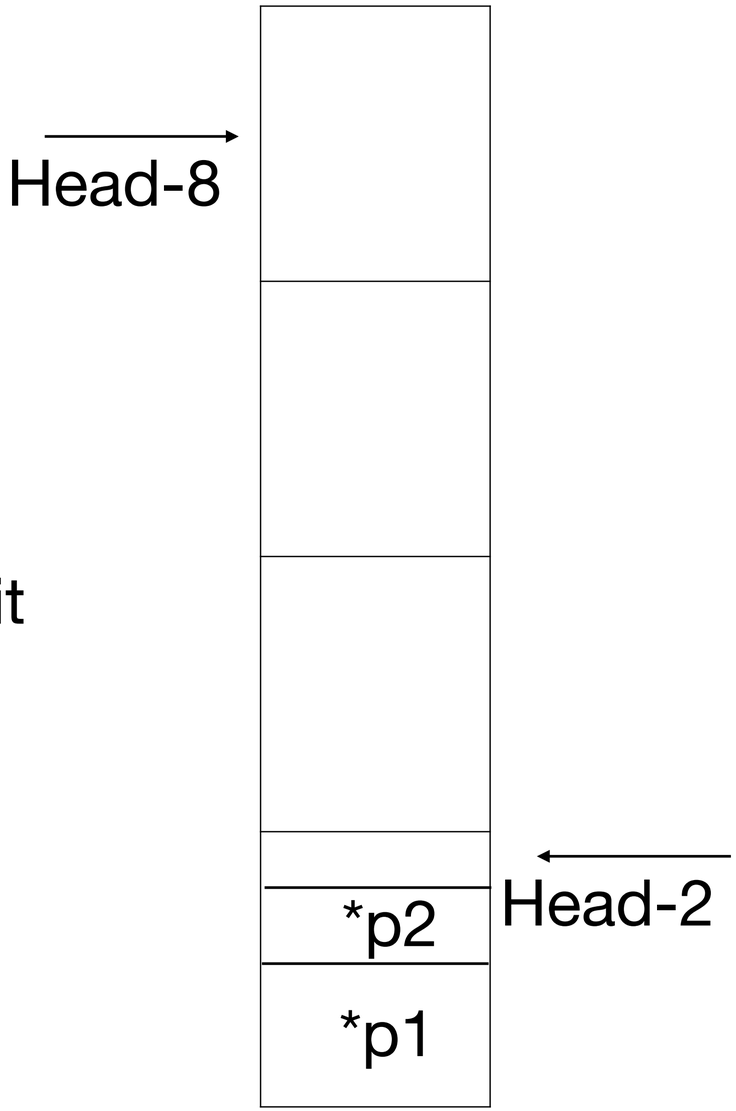
- Straightforward splitting and coalescing



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  - p1 = malloc(3)
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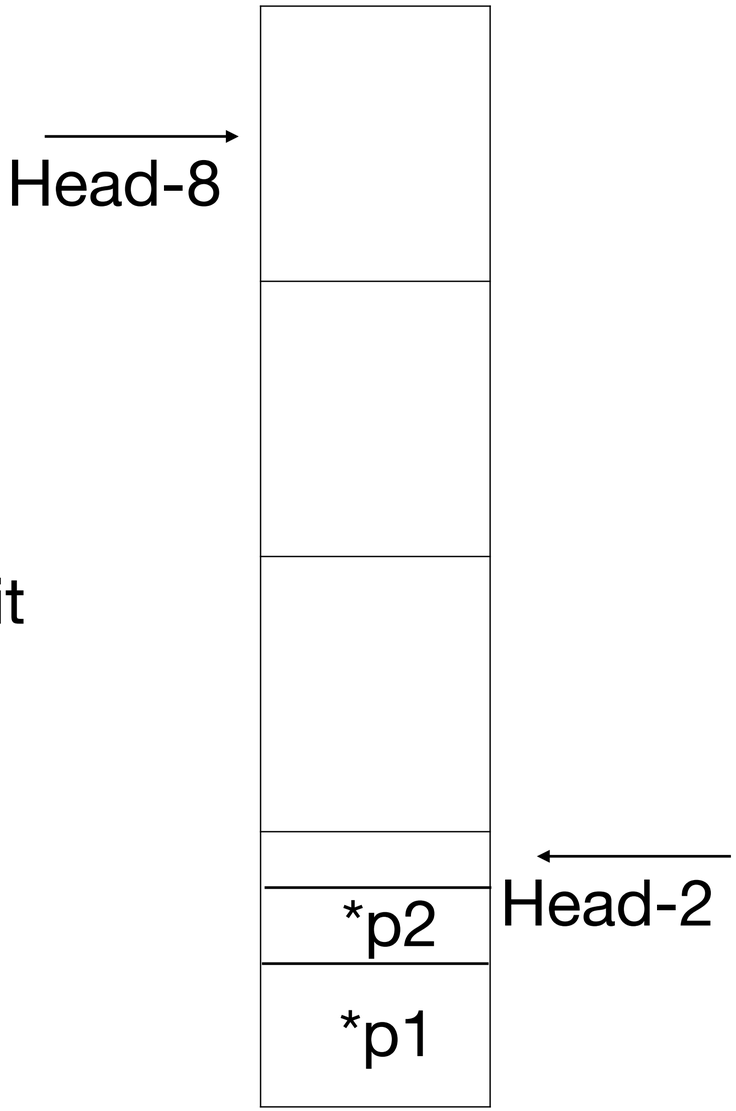
- Deallocation order: fast frees



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- Example:
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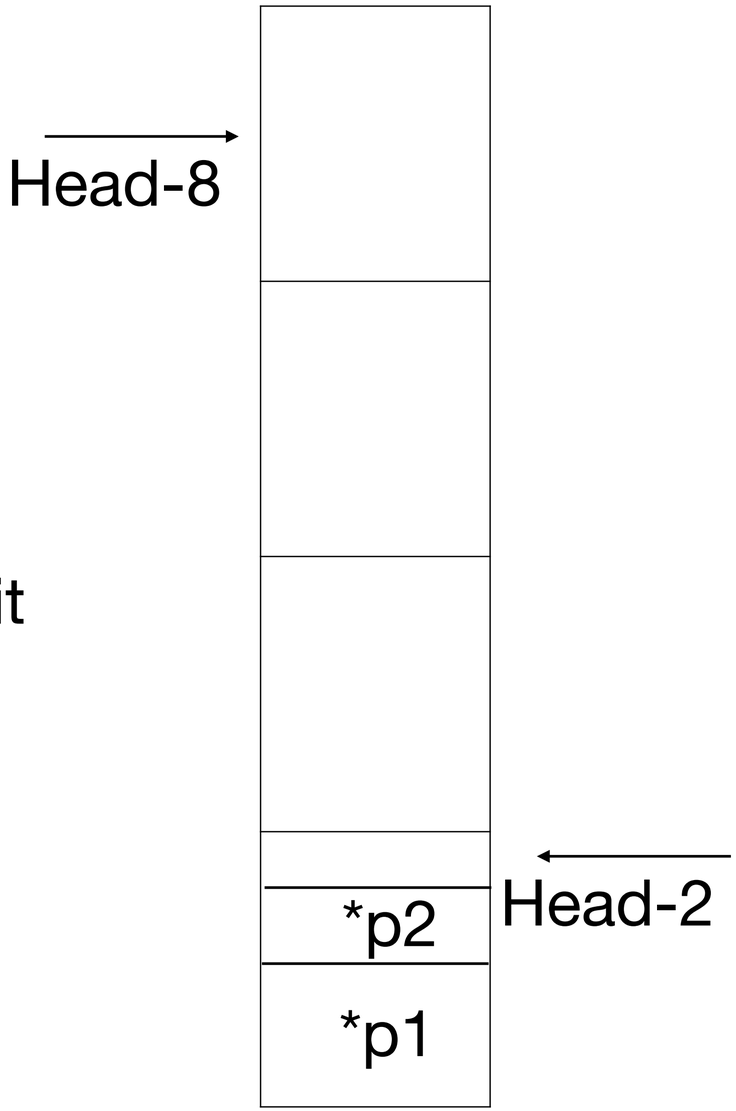
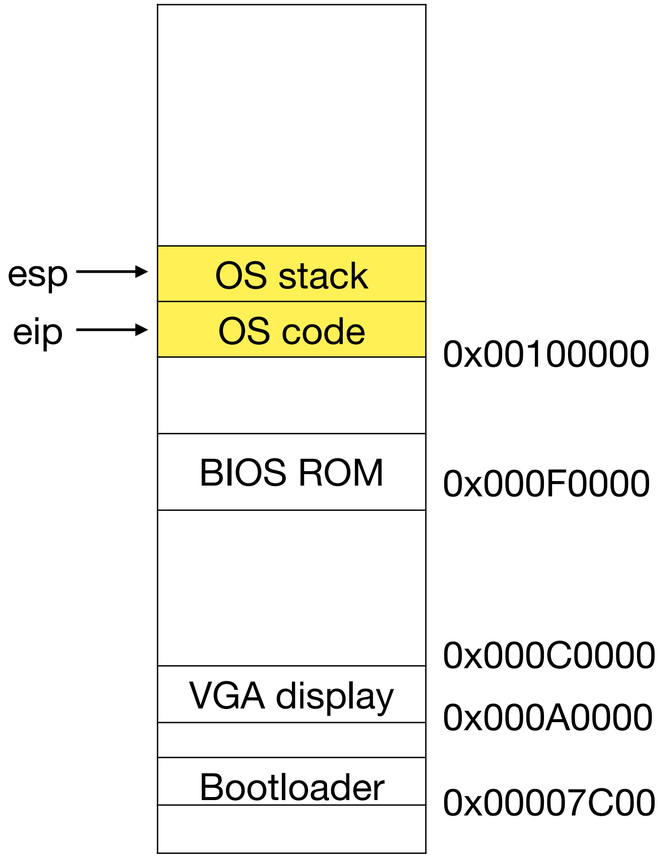
- Straightforward splitting and coalescing
- Deallocation order: fast frees
- Used in Linux kernel



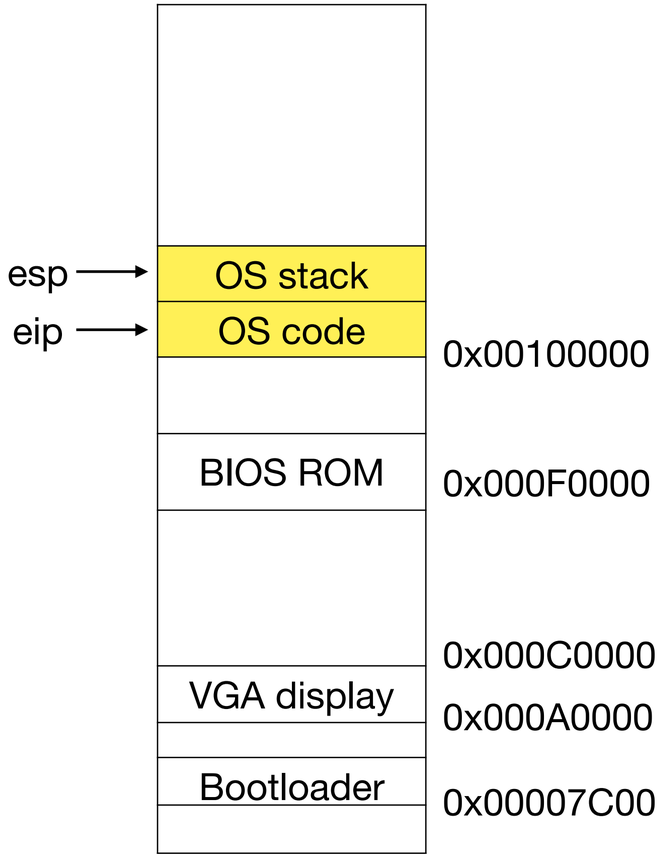
Aside: automatic memory management

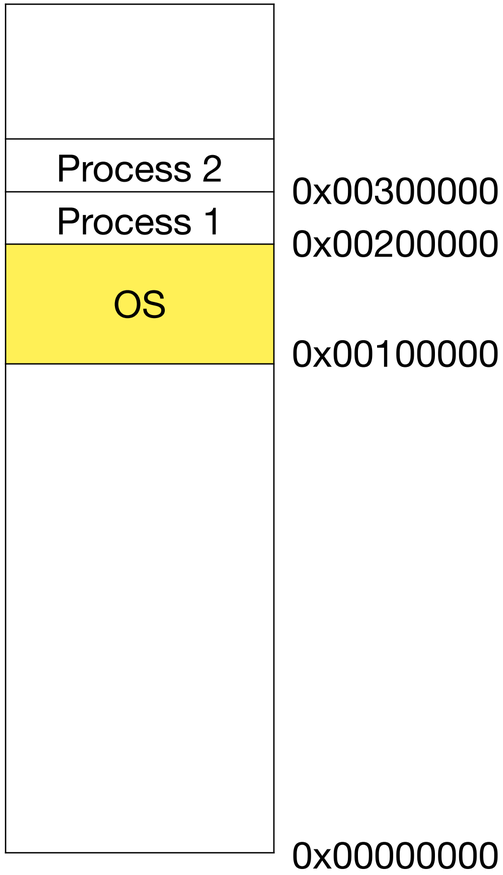
- “Higher level” languages do not expose raw pointers to programmers. Example: Java, Python, Go
  - The language runtime manages memory. Programmer need not call free.
  - Largely prevents memory leaks, dangling references, double free, null pointer dereference
  - Mark and sweep garbage collector, reference 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

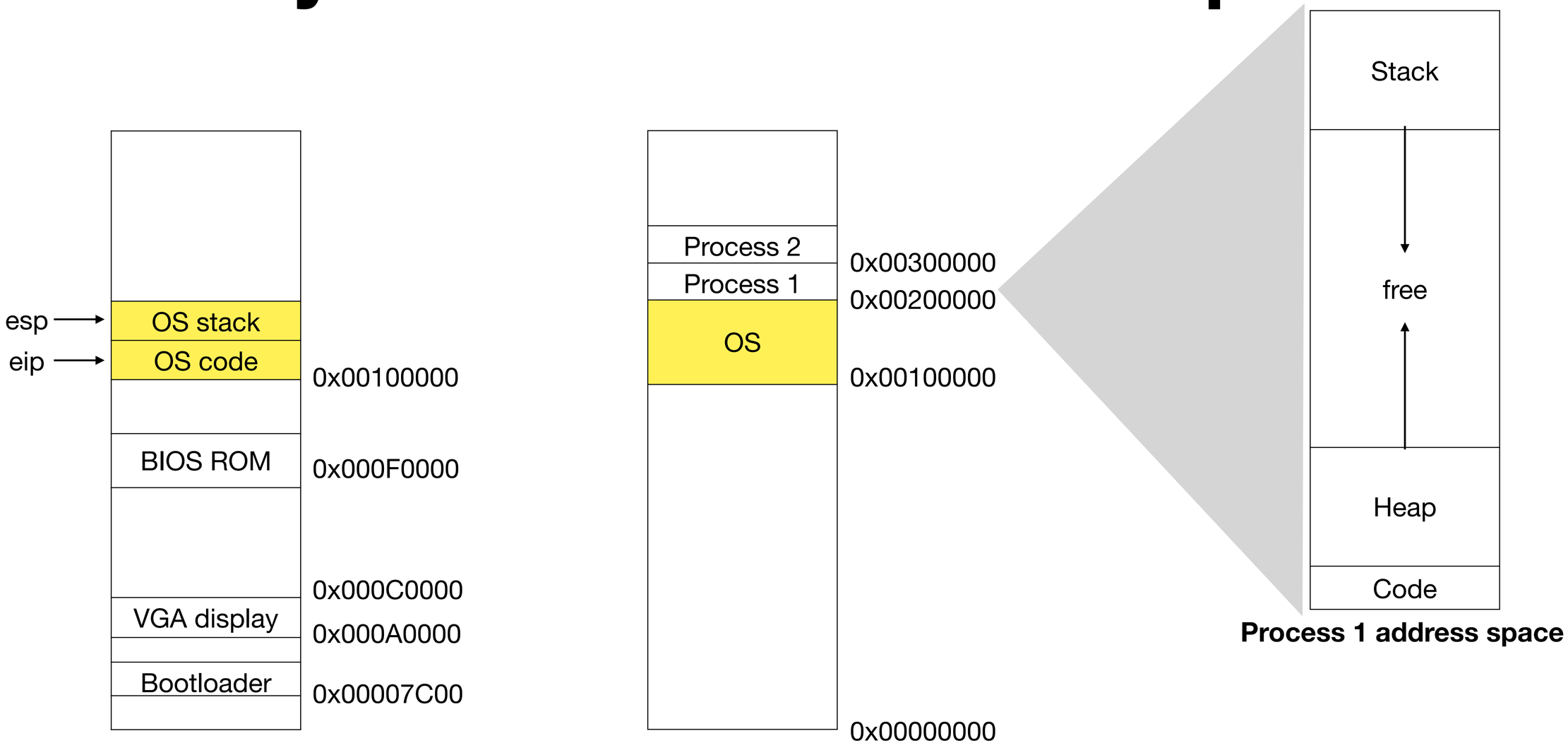


Memory isolation and address space





Memory isolation and address space



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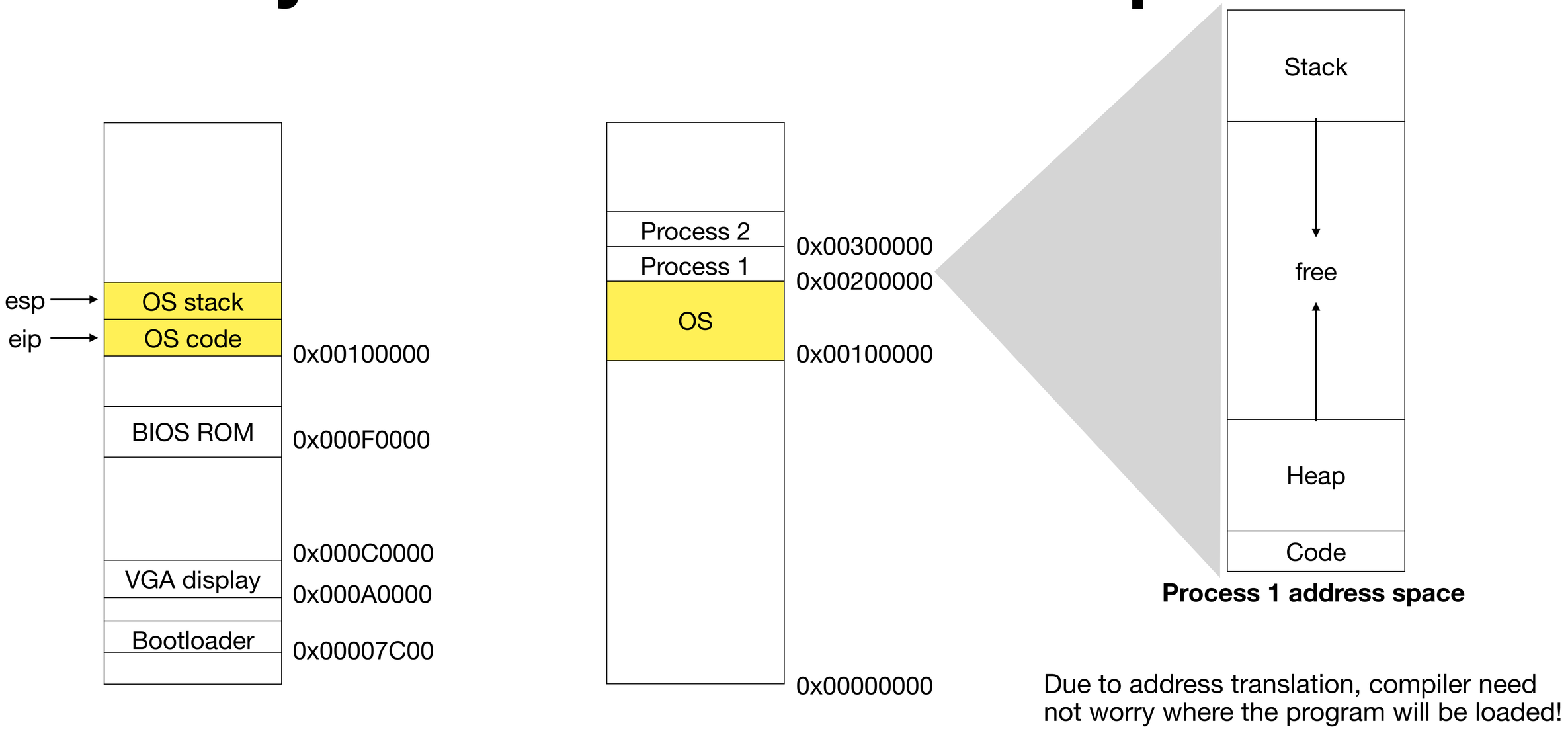
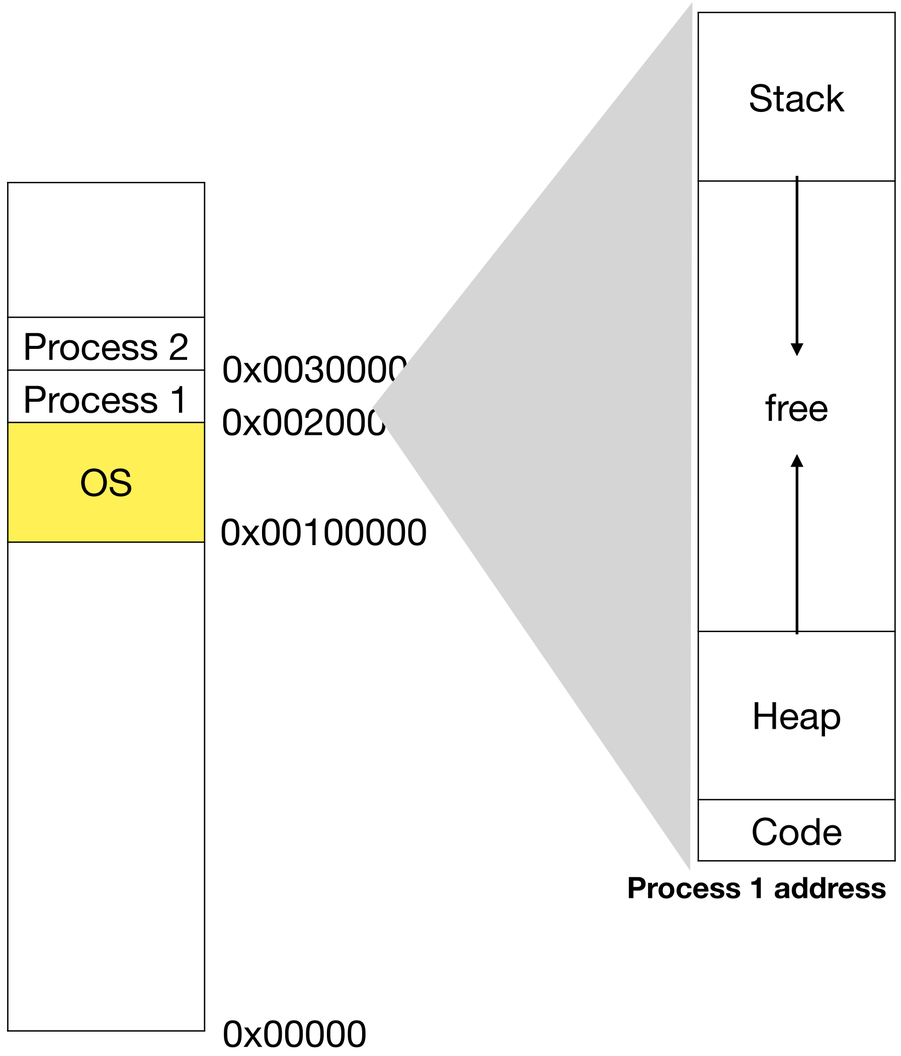
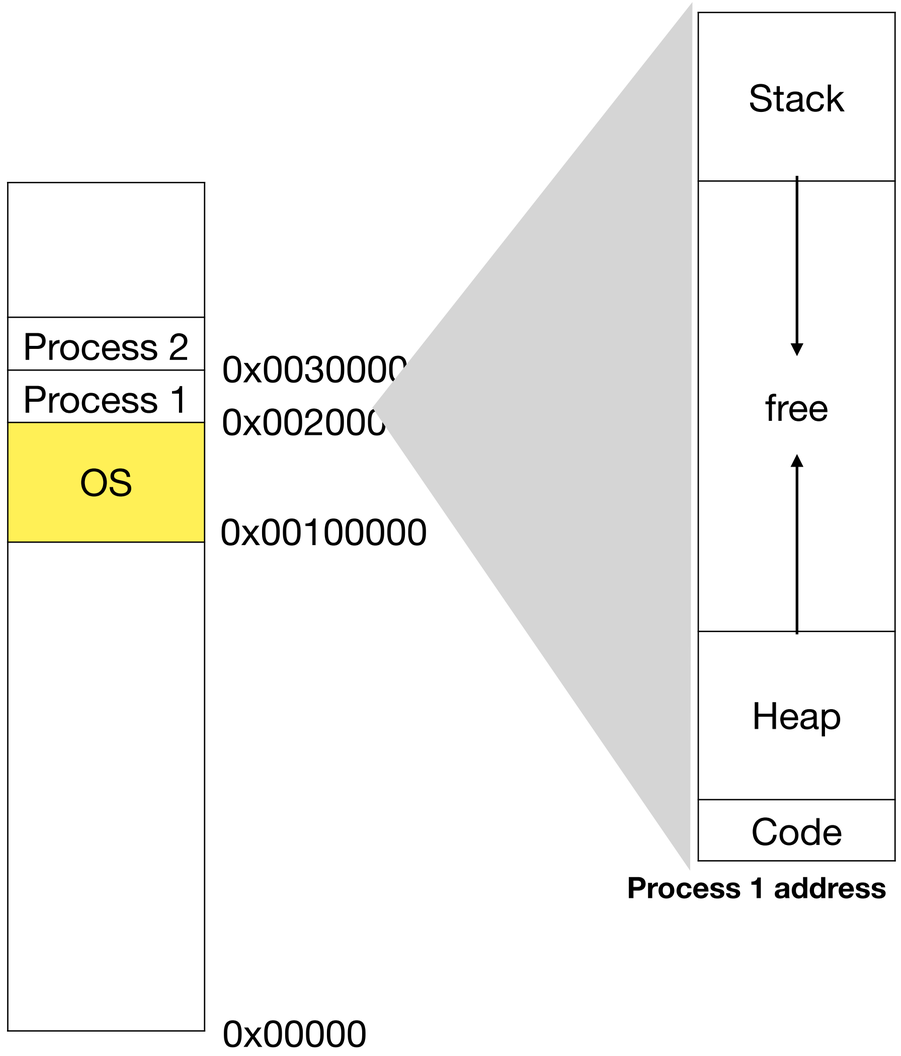


Due to address translation, compiler need not worry where the program will be loaded!

Segmentation

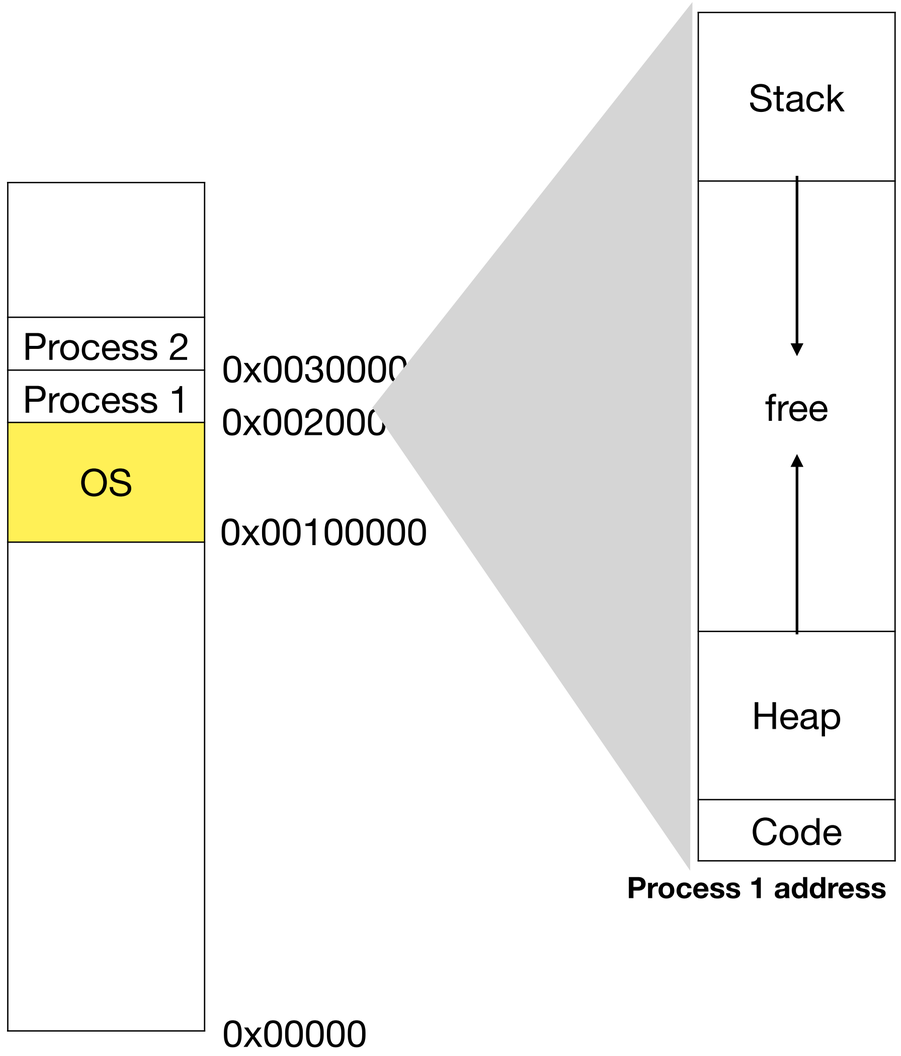


Segmentation



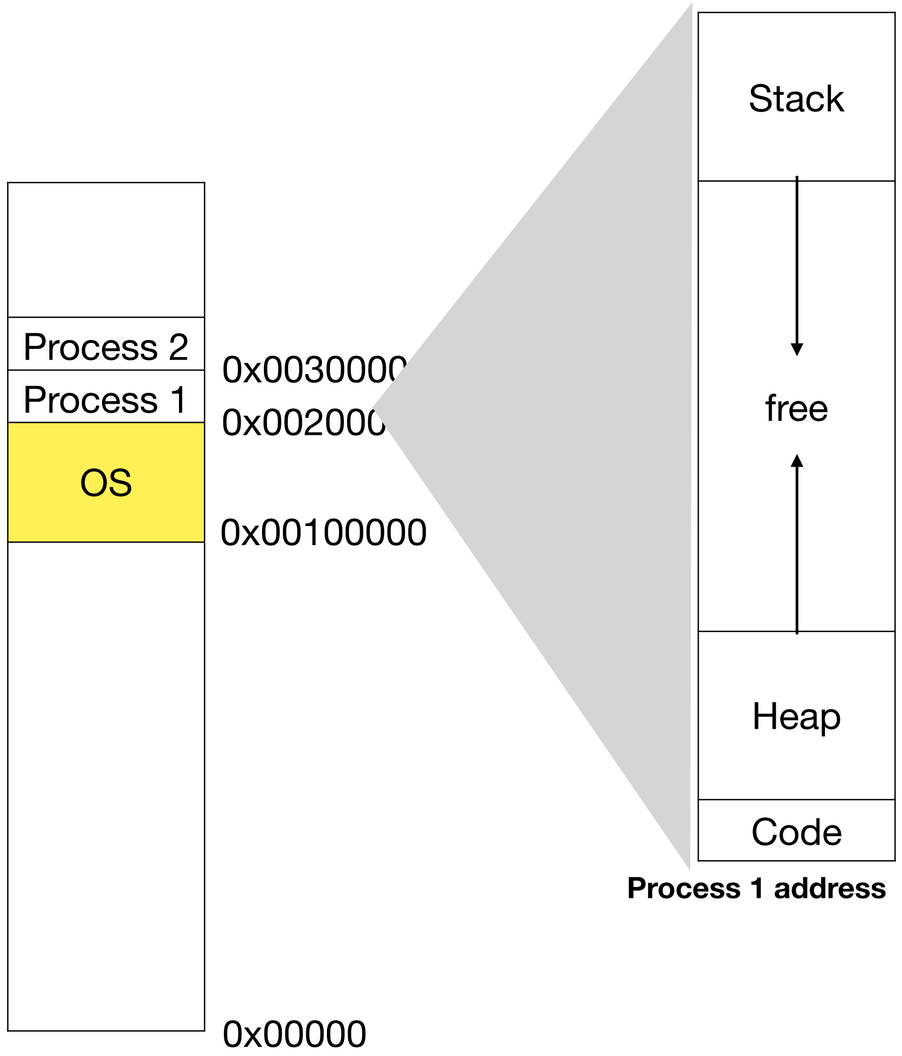
- Place each segment independently to not map free space

Segmentation



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

Segmentation



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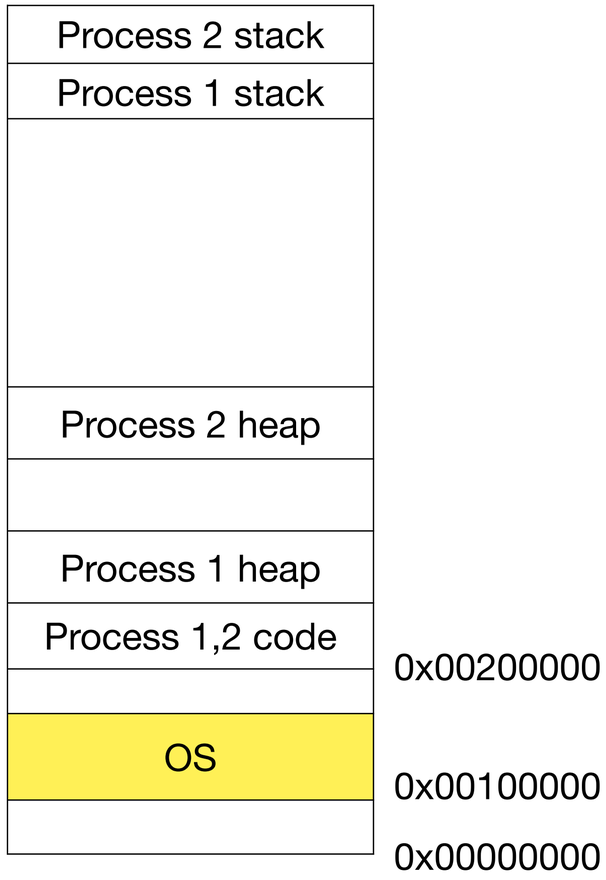
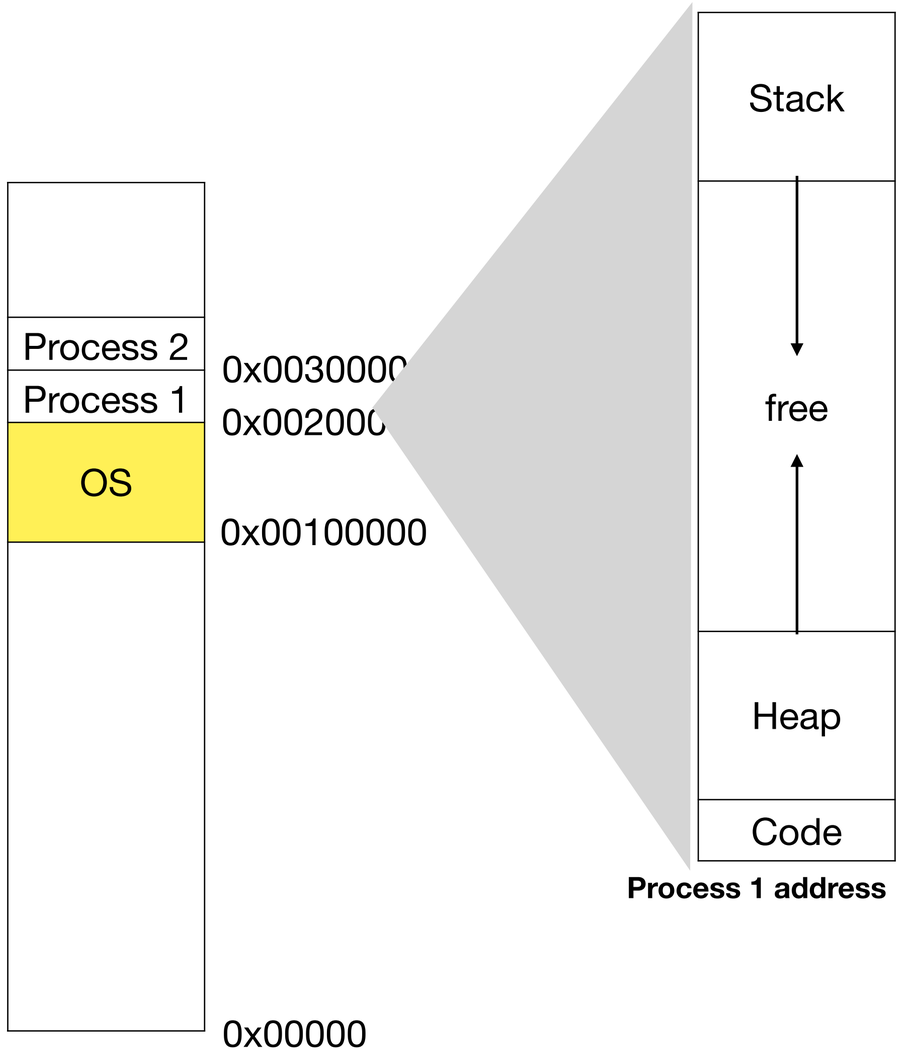
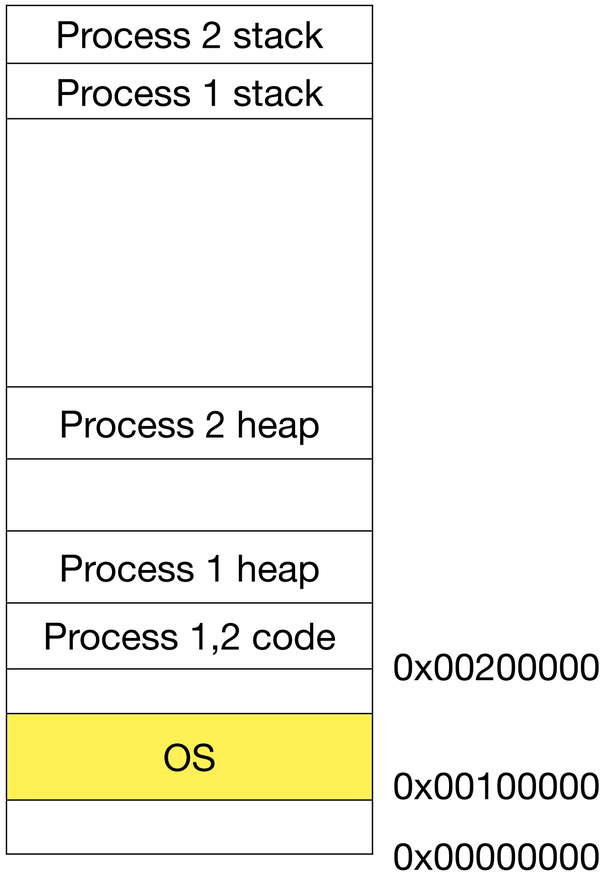


Segmentation



- 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

GDTR: Global descriptor table register

Global Descriptor Table

S.No.*	Permission	Base	Limit
0x01	WRITE		
0x02	EXECUTE	0x1F	0xFF
…	…	…	…

cs: top 13 bits
0b…10xxx

*: S.No. added only for illustration

Address translation

cs: top 13 bits
0b…10xxx

Global Descriptor Table

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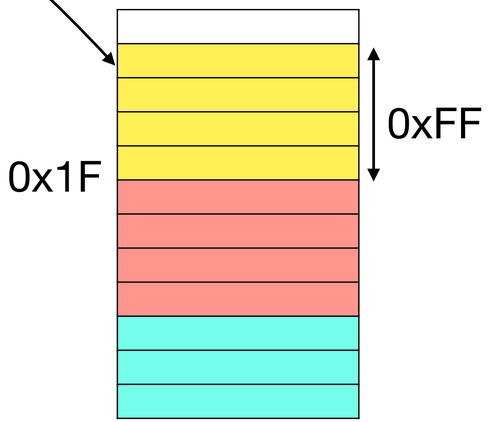

Address translation

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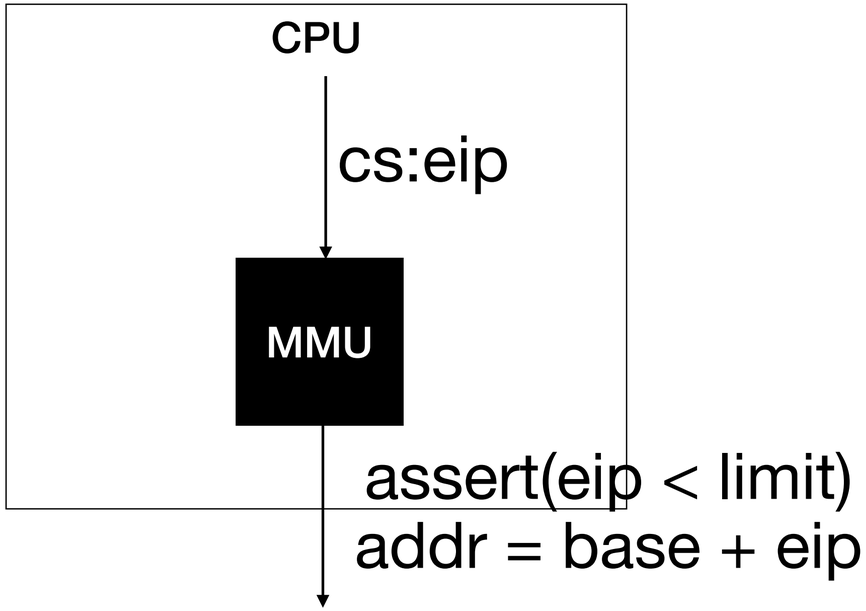
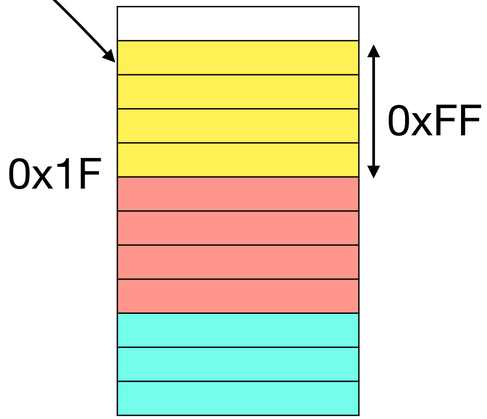
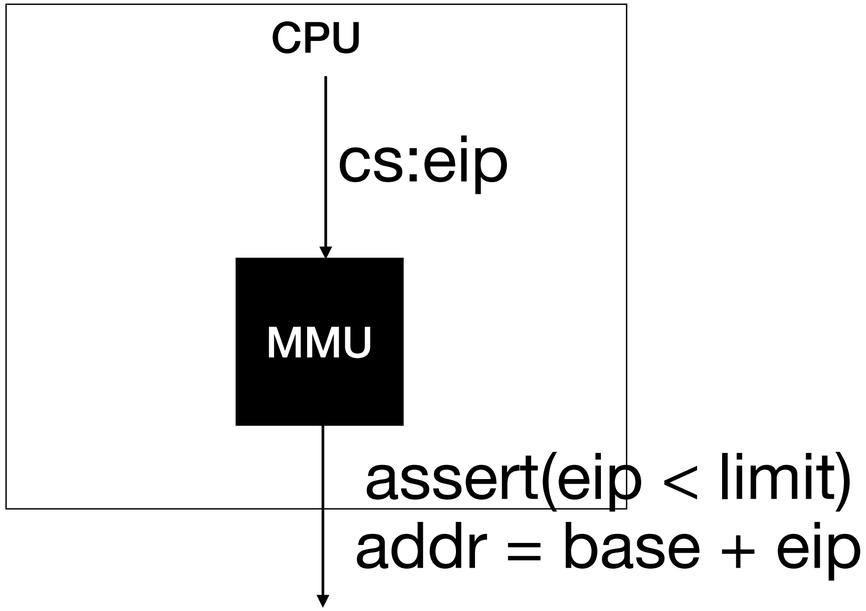




Address translation



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0b…10xxx

Global Descriptor Table

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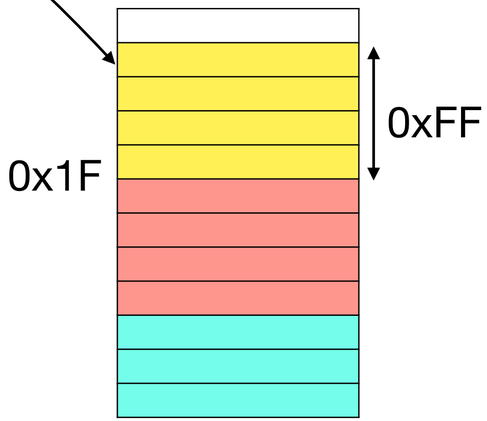
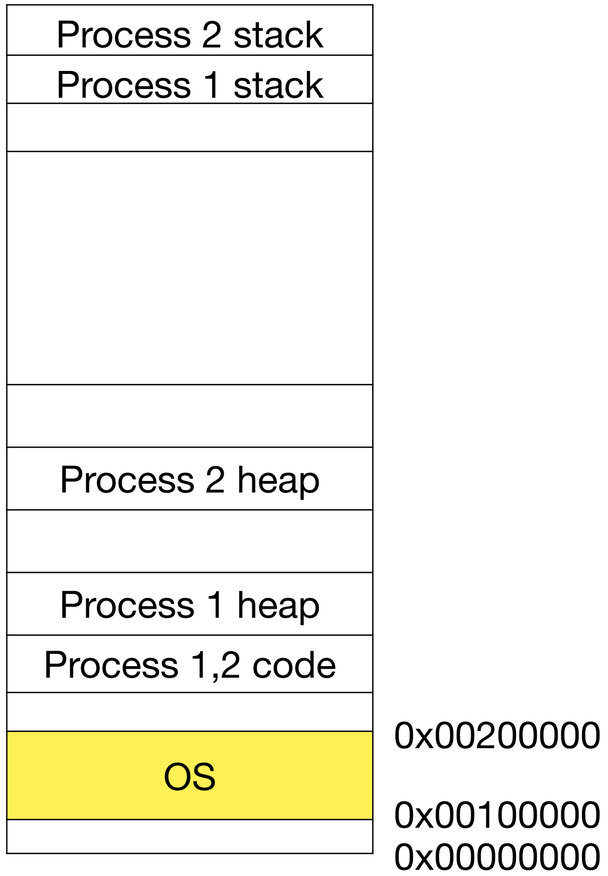


- Can “protect” different segments from each other

Allocating memory to a new process

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



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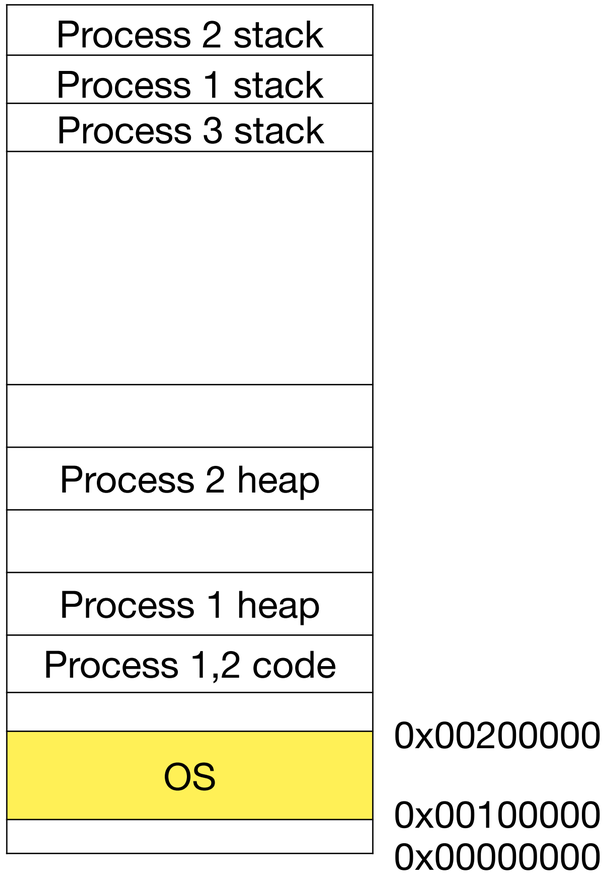

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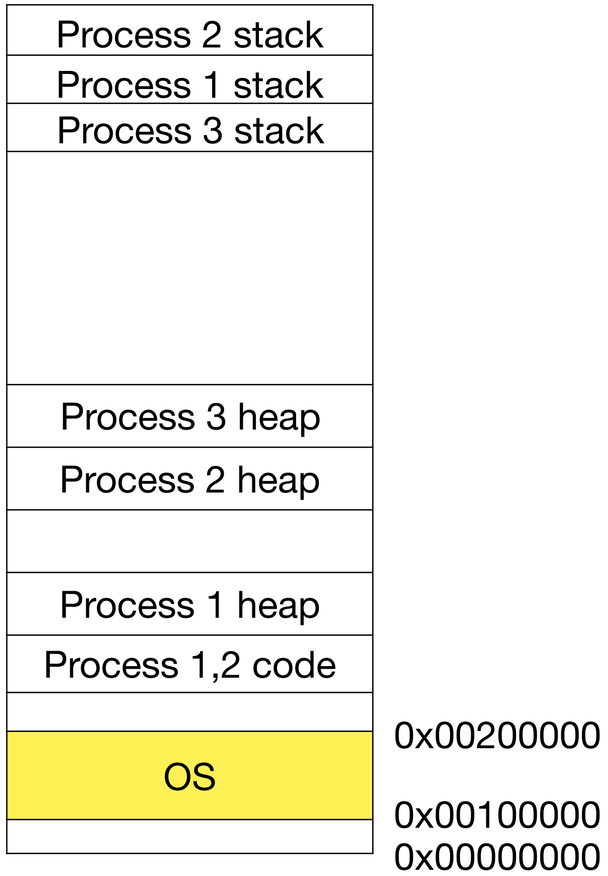

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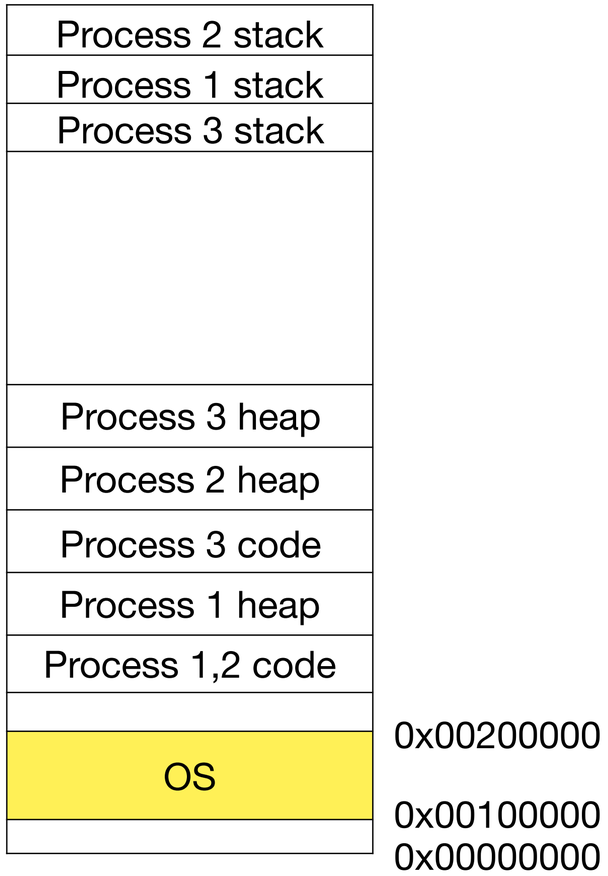
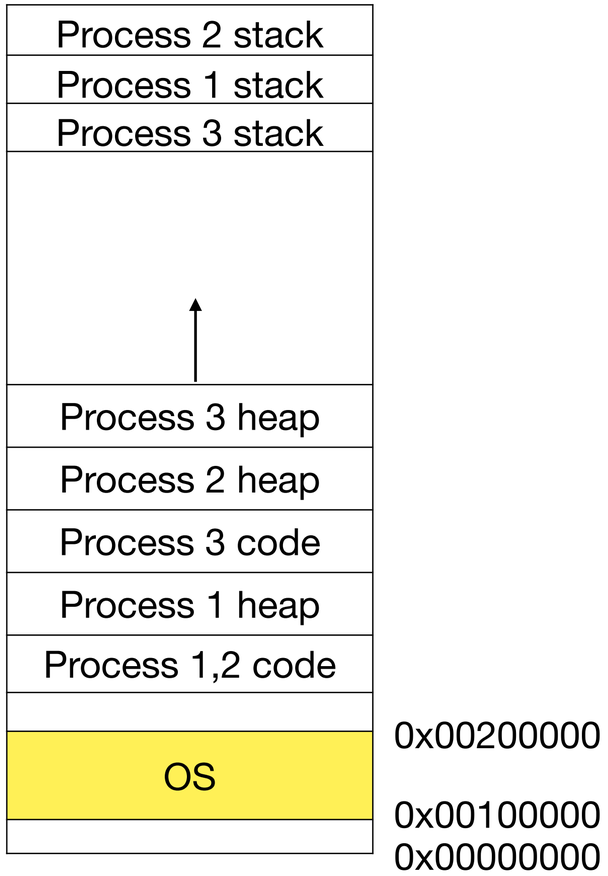


Growing heap

- sbrk can grow heap segment



External fragmentation

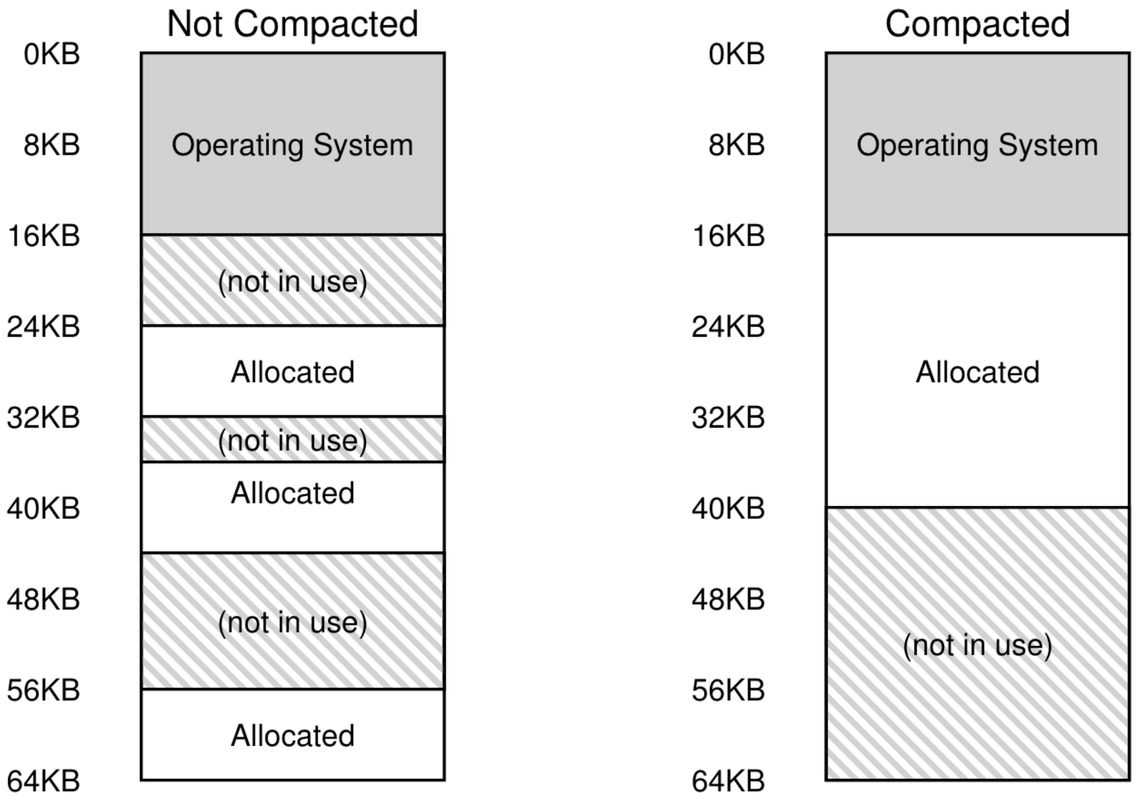


Figure 16.6: **Non-compacted and Compacted Memory**

External fragmentation

- After many processes start and exit, memory might become "fragmented" (similar to disk)
  - Example: cannot allocate 20 KB segment

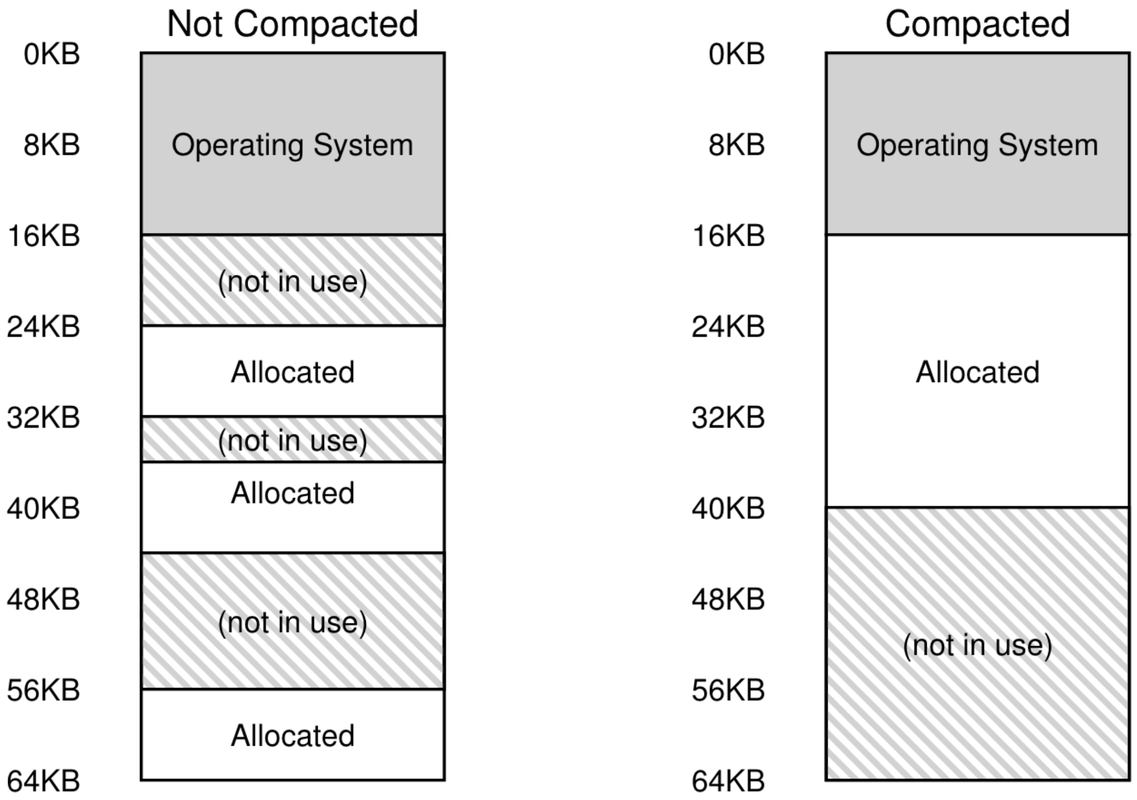


Figure 16.6: **Non-compacted and Compacted Memory**

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

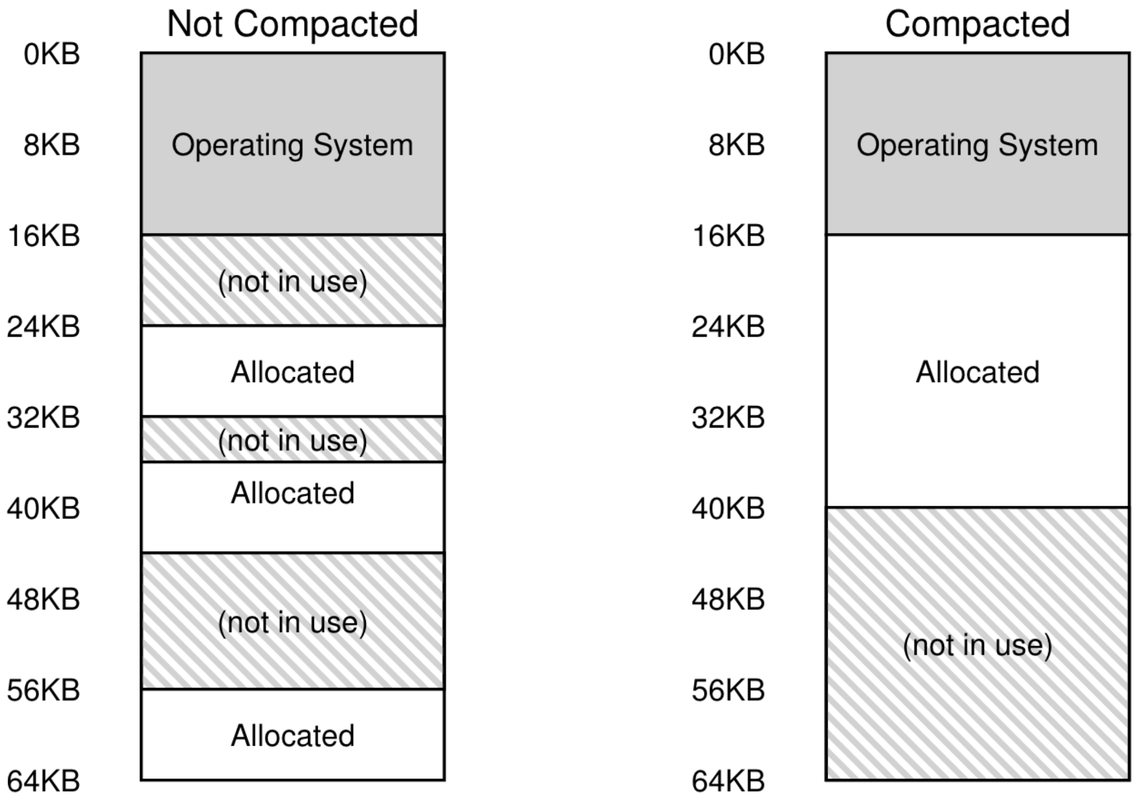
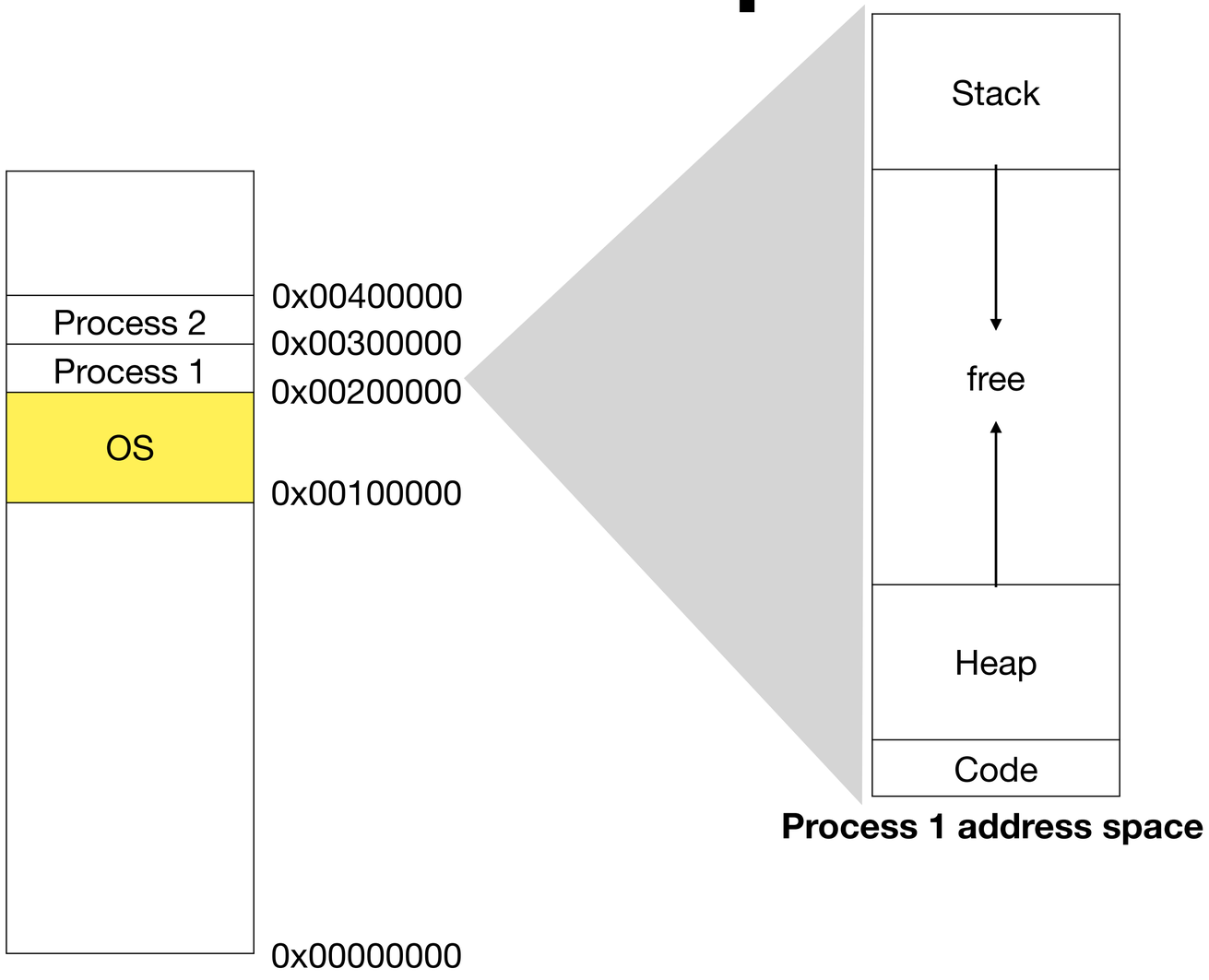


Figure 16.6: **Non-compacted and Compacted Memory**

Processes in action

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

Memory isolation and address space



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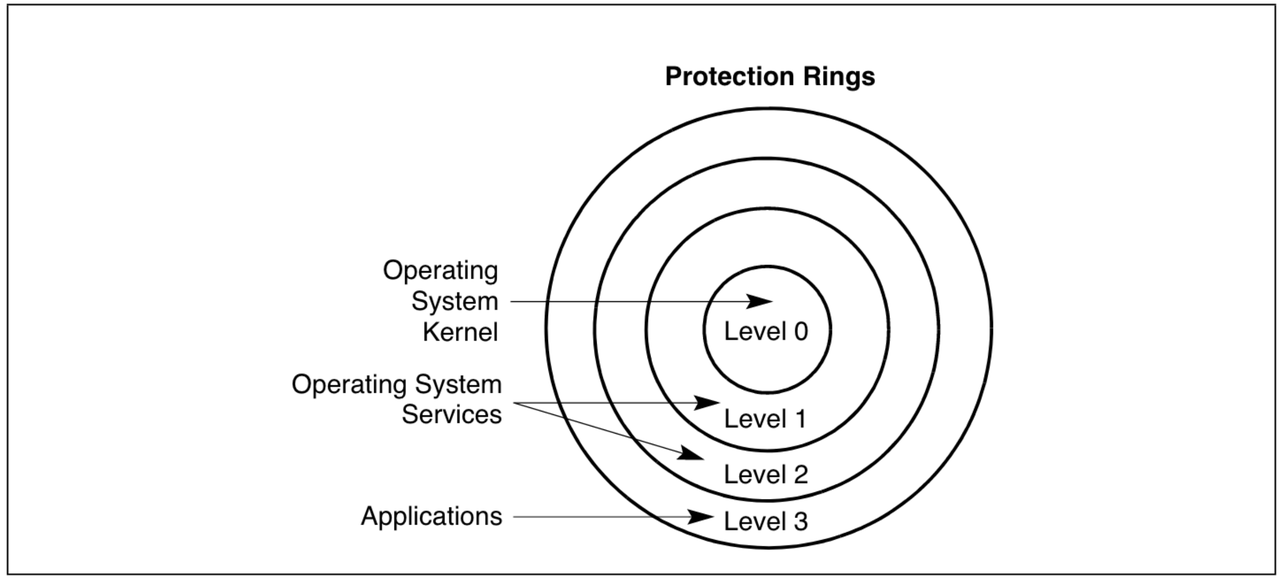

Figure 5-3. Protection Rings

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- Process cannot modify OS code since it is not in process' *address space*
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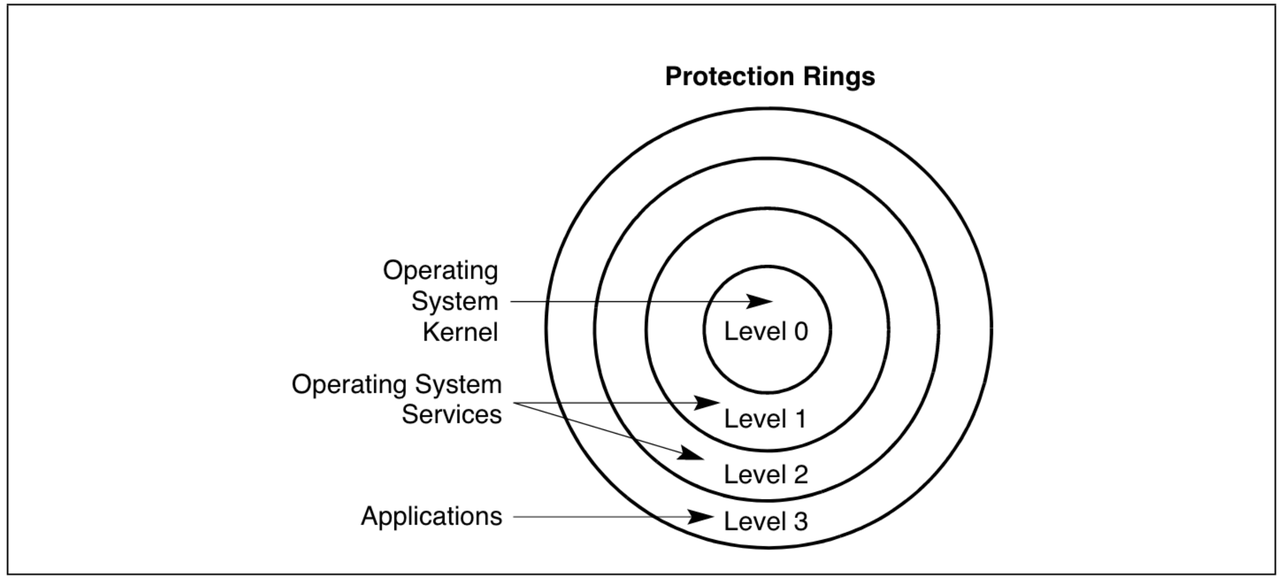
  - Ring 0: kernel mode. Ring 3: user mode



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- 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"

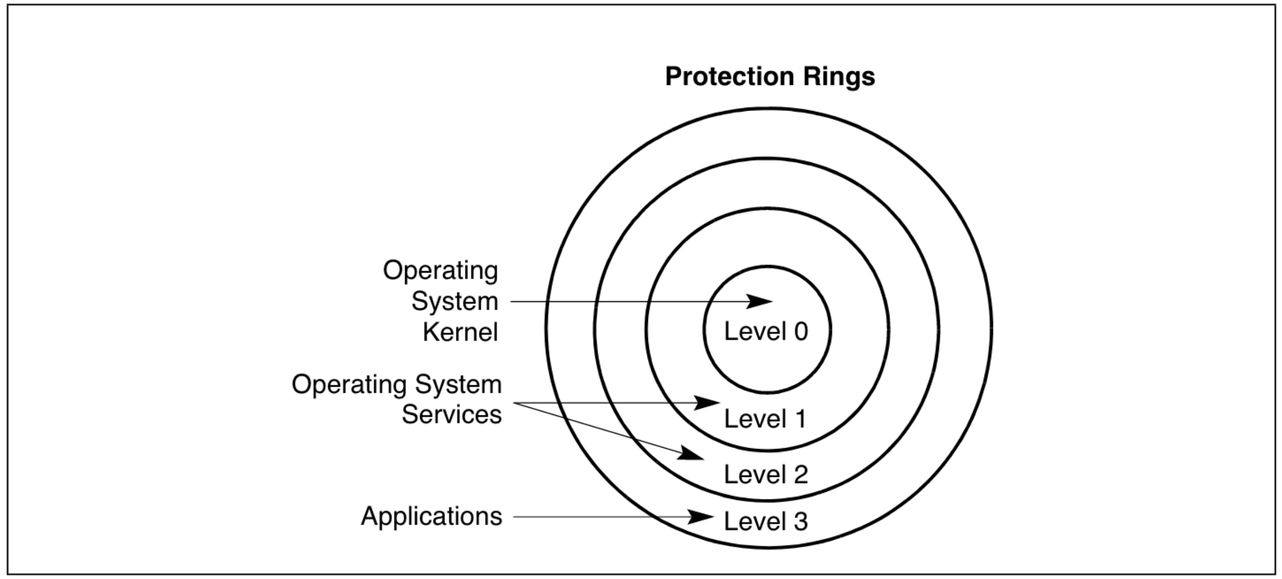

Figure 5-3. Protection Rings

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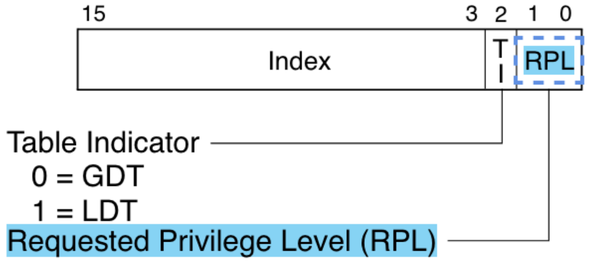

Figure 3-6. Segment Selector

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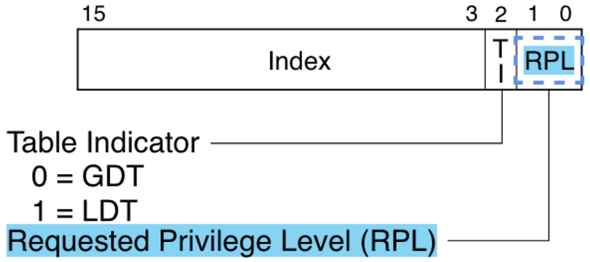
- Segment descriptor specifies "descriptor privilege level" (DPL)



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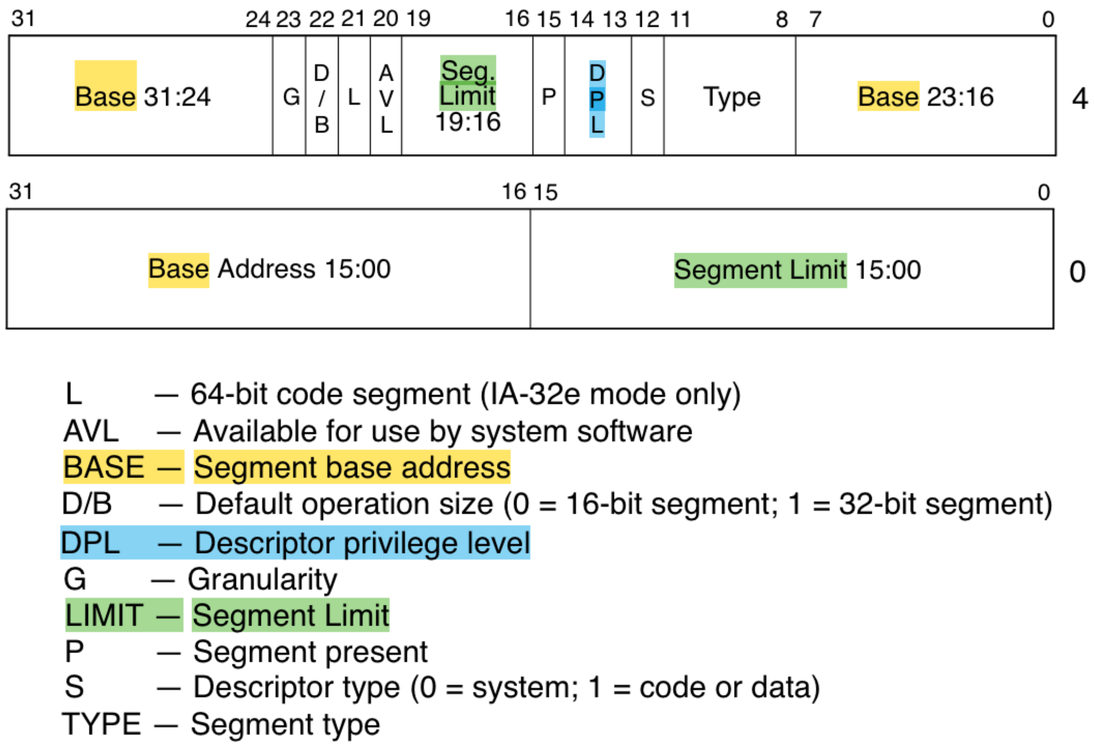

Figure 3-8. Segment Descriptor

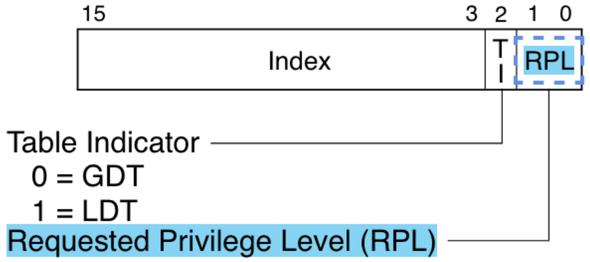

Figure 3-6. Segment Selector

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  - Programs cannot lower their CPL directly

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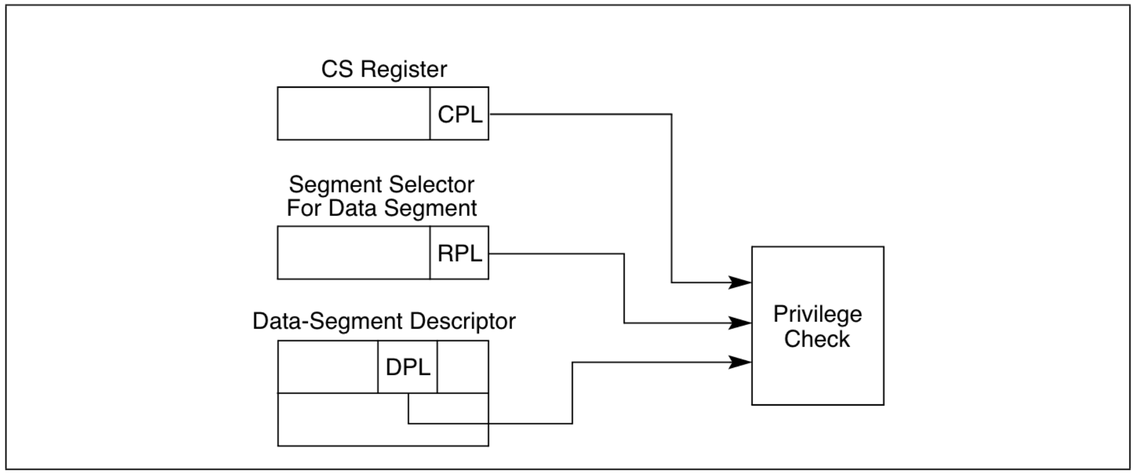

Figure 5-4. Privilege Check for Data Access

How does hardware enforce the current privilege level?

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- Programs can change their segment selectors
  - Programs cannot lower their CPL directly
  - INT instruction causes a software interrupt to set ring = 0
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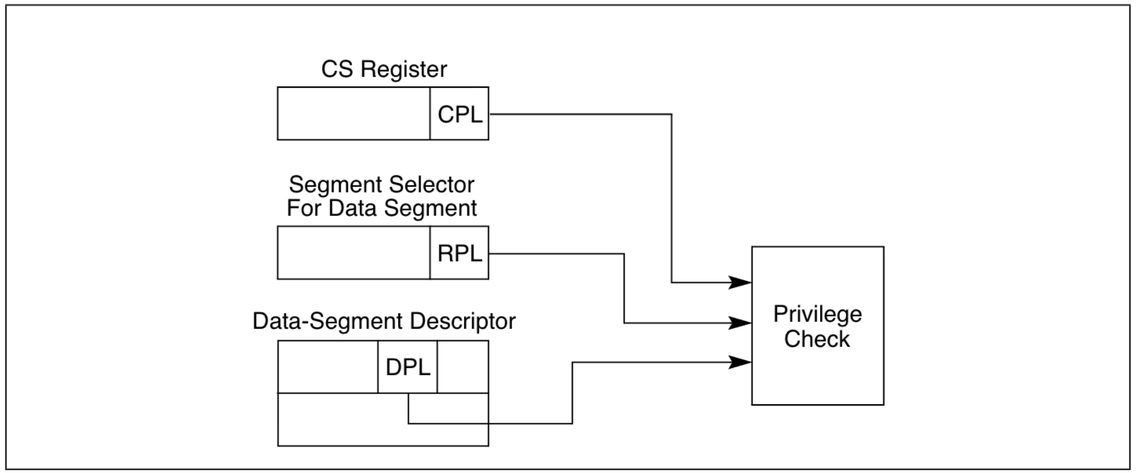


Figure 5-4. Privilege Check for Data Access

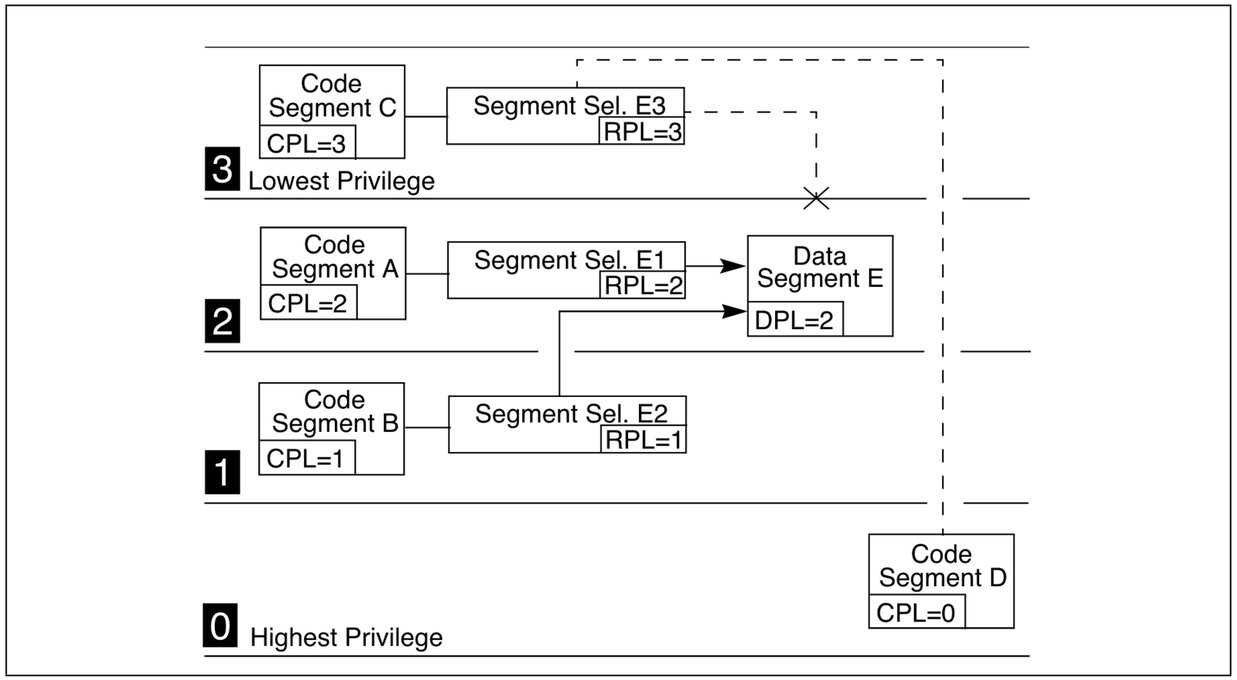
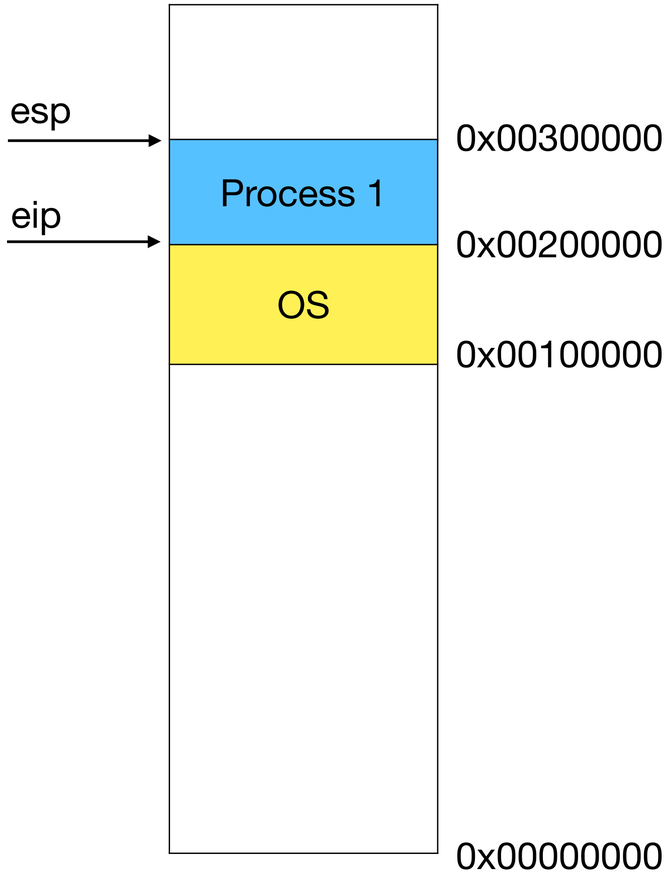


Figure 5-5. Examples of Accessing Data Segments From Various Privilege Levels

Setting up our first process in xv6!

p15-initproc

- 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;
}

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;
}
```

eip

```
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
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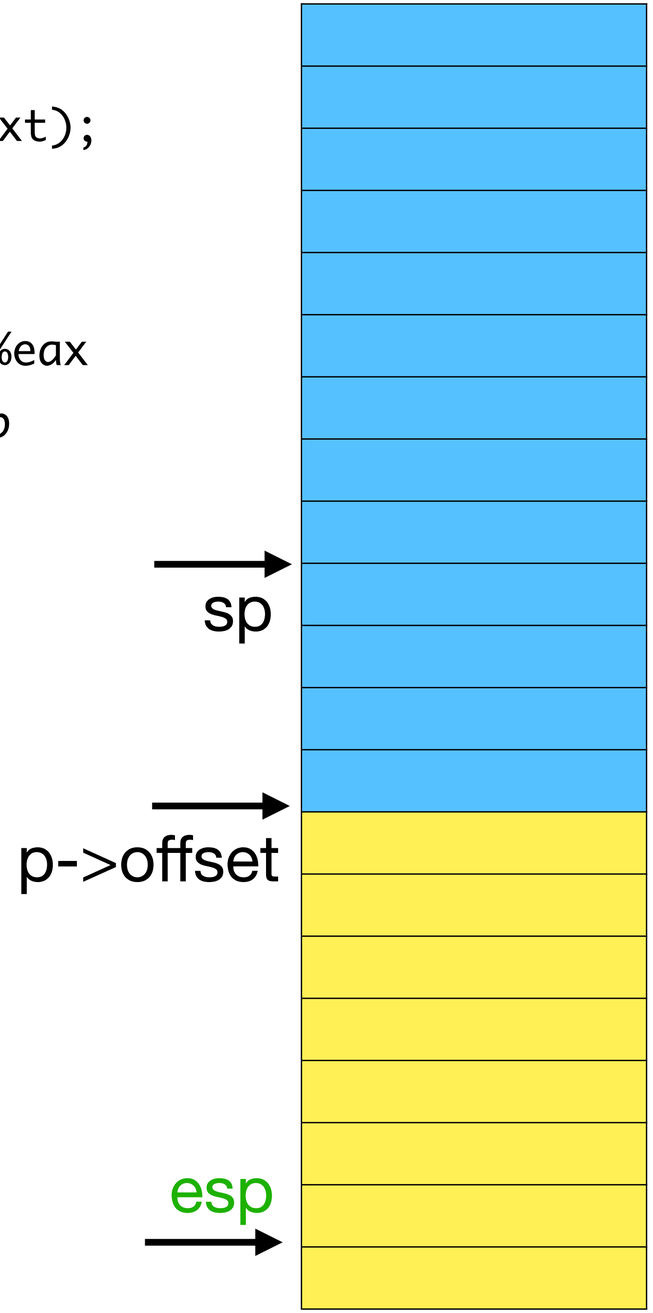

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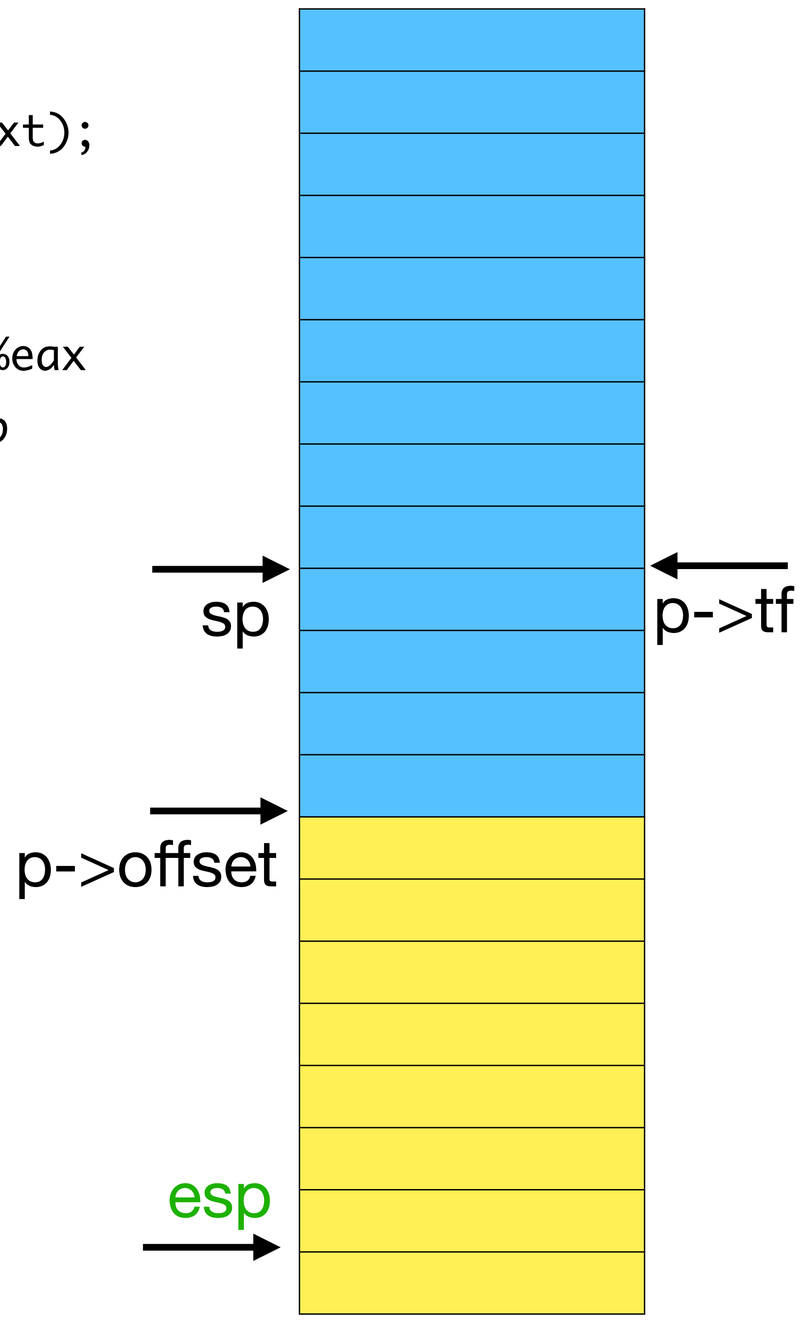

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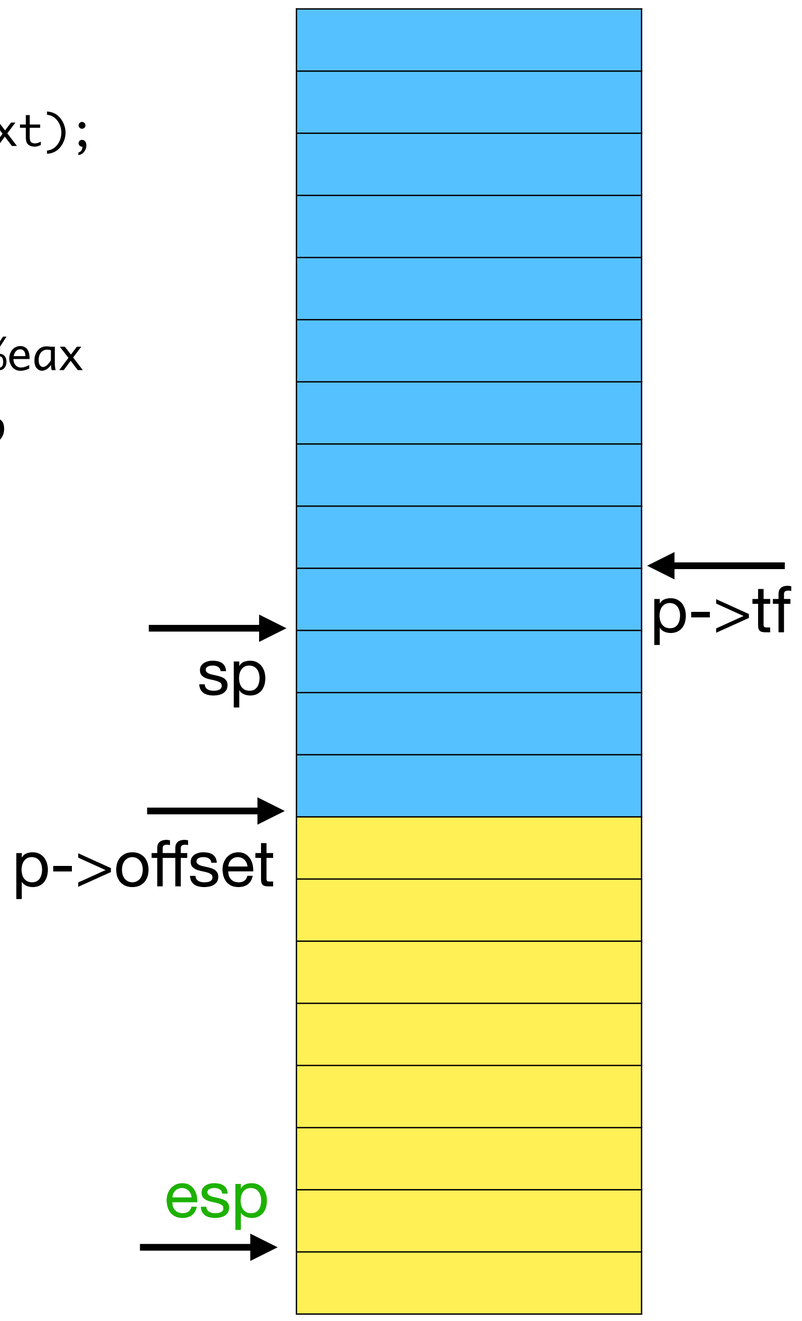

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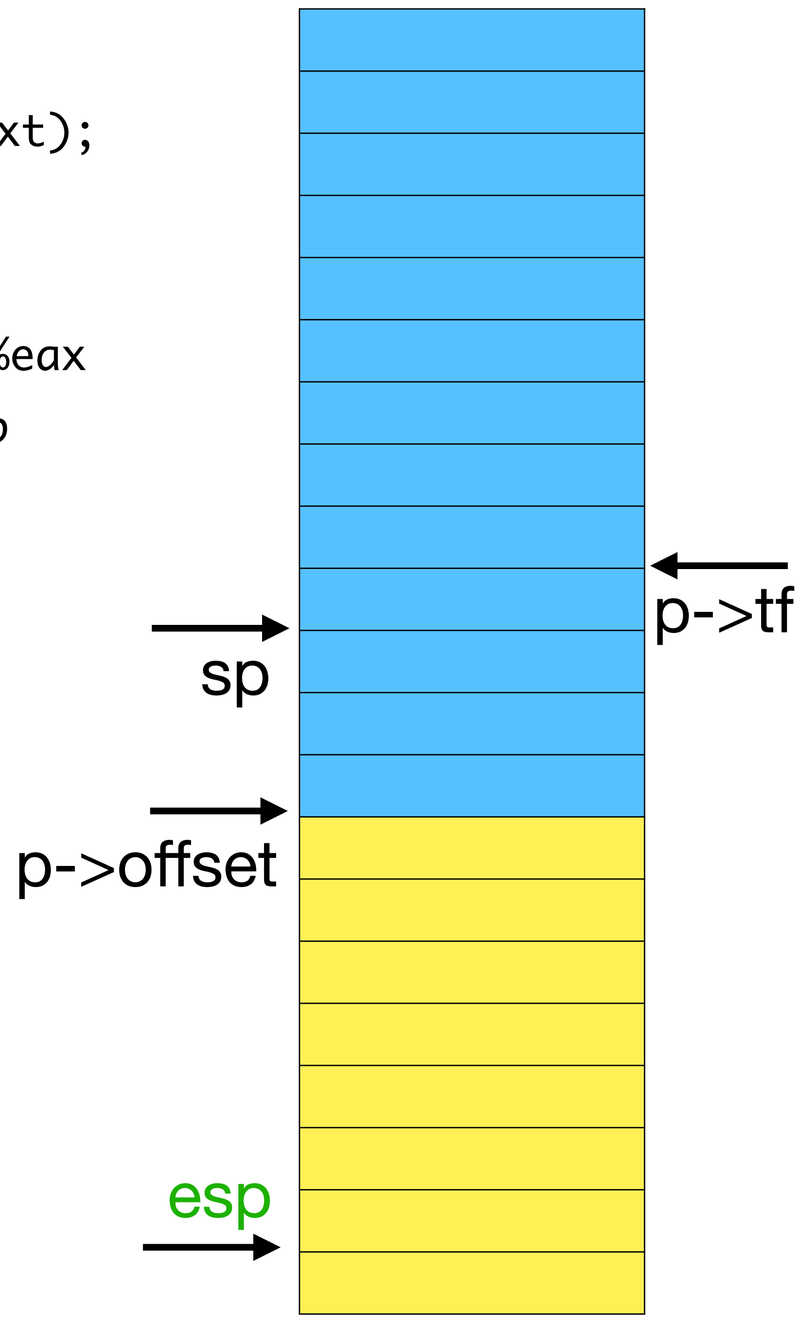

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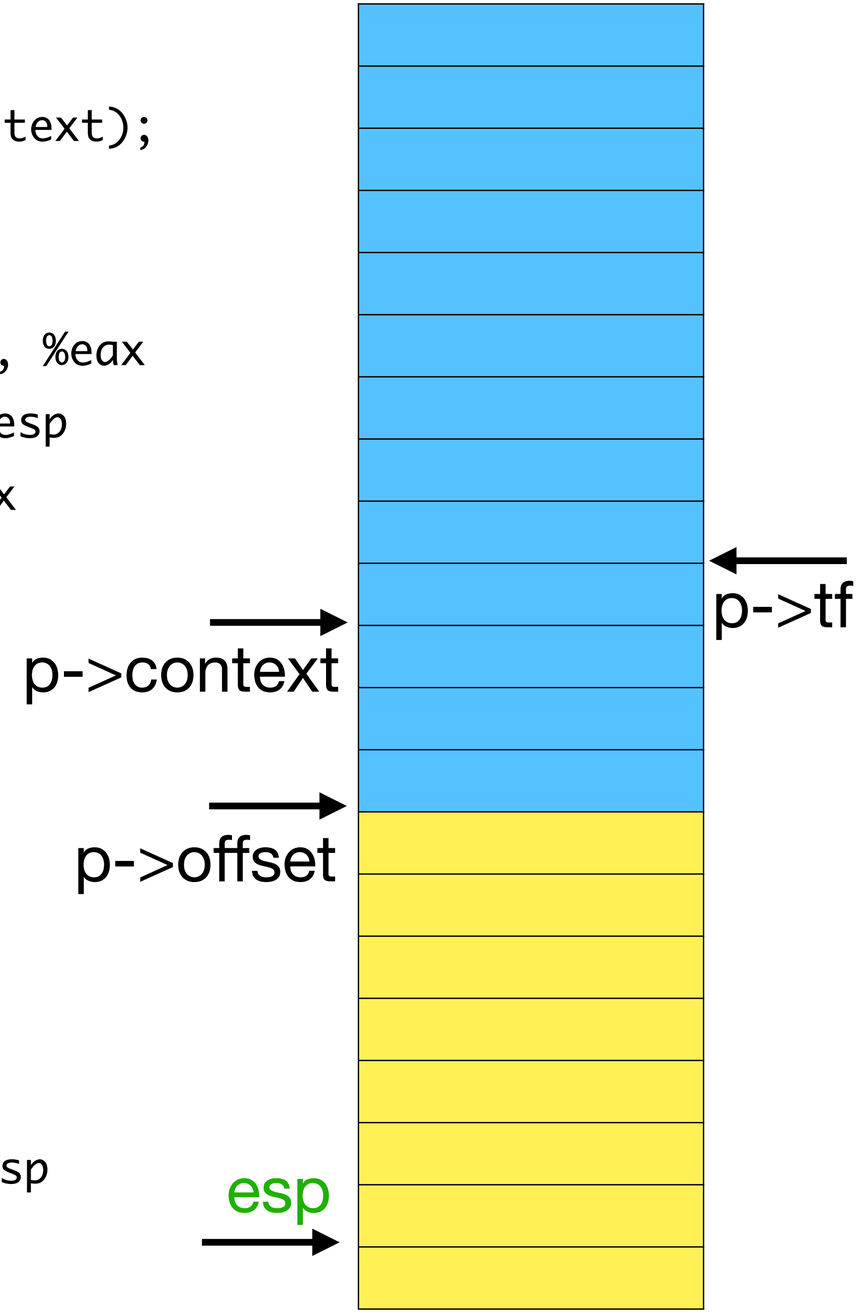

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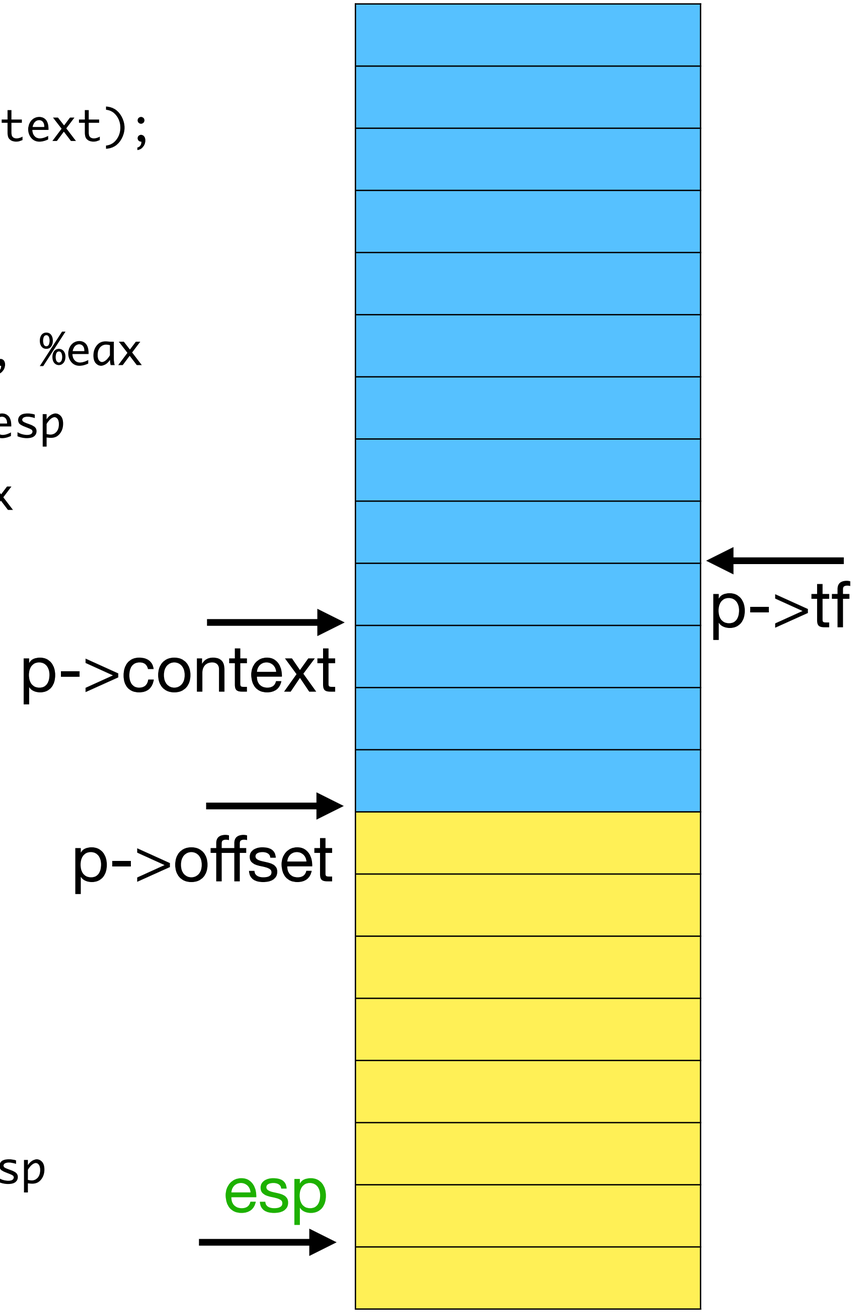

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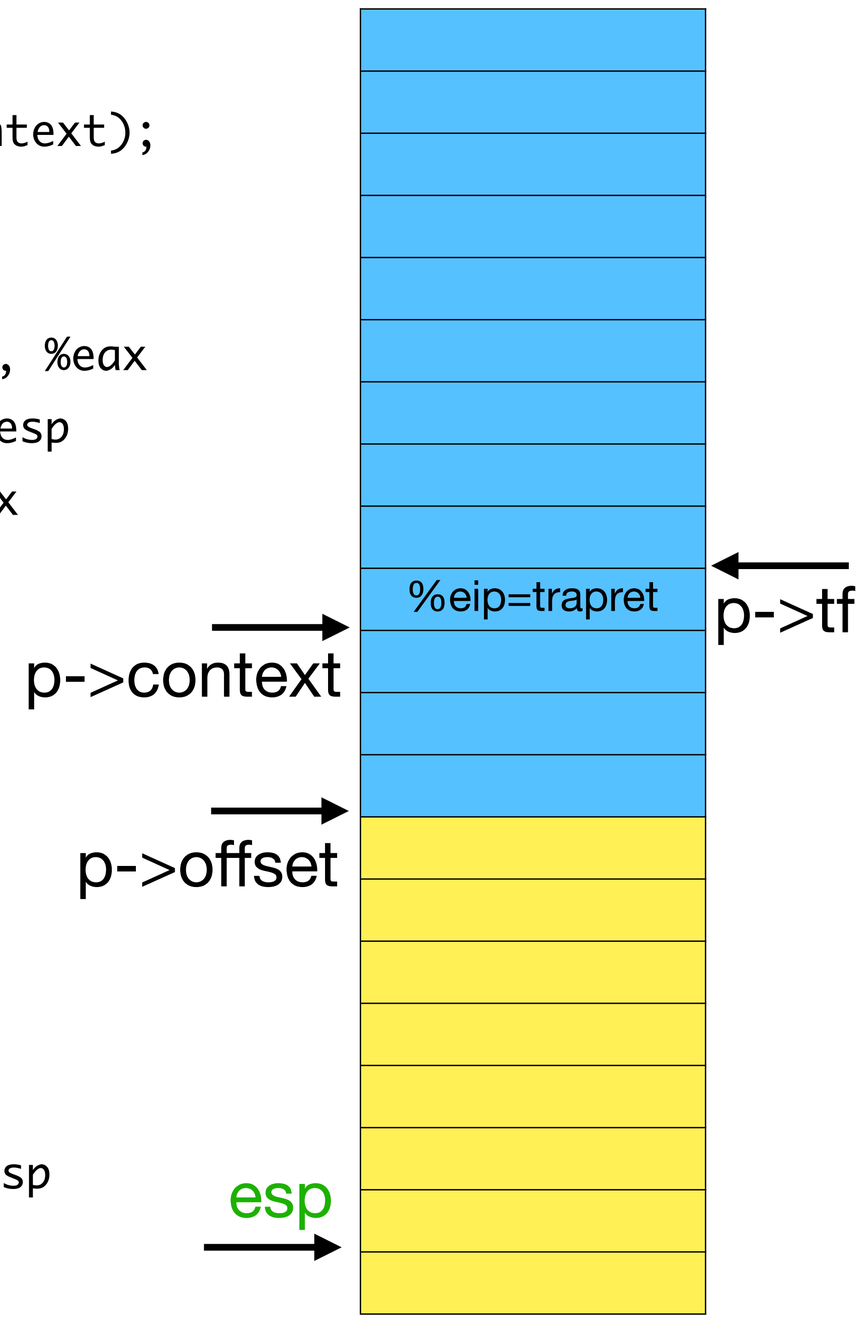

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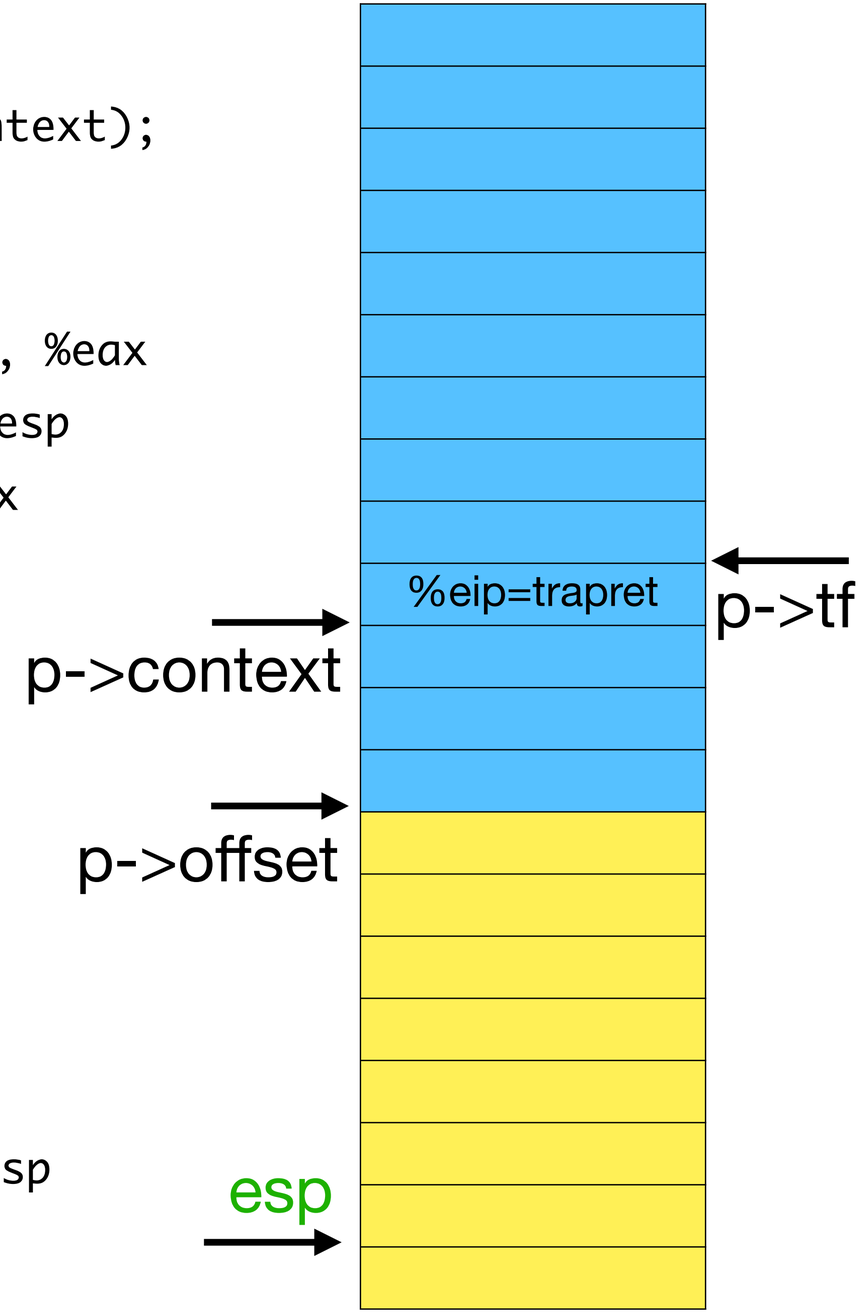
  addl $0x8, %esp
  iret
```



Understanding swtch

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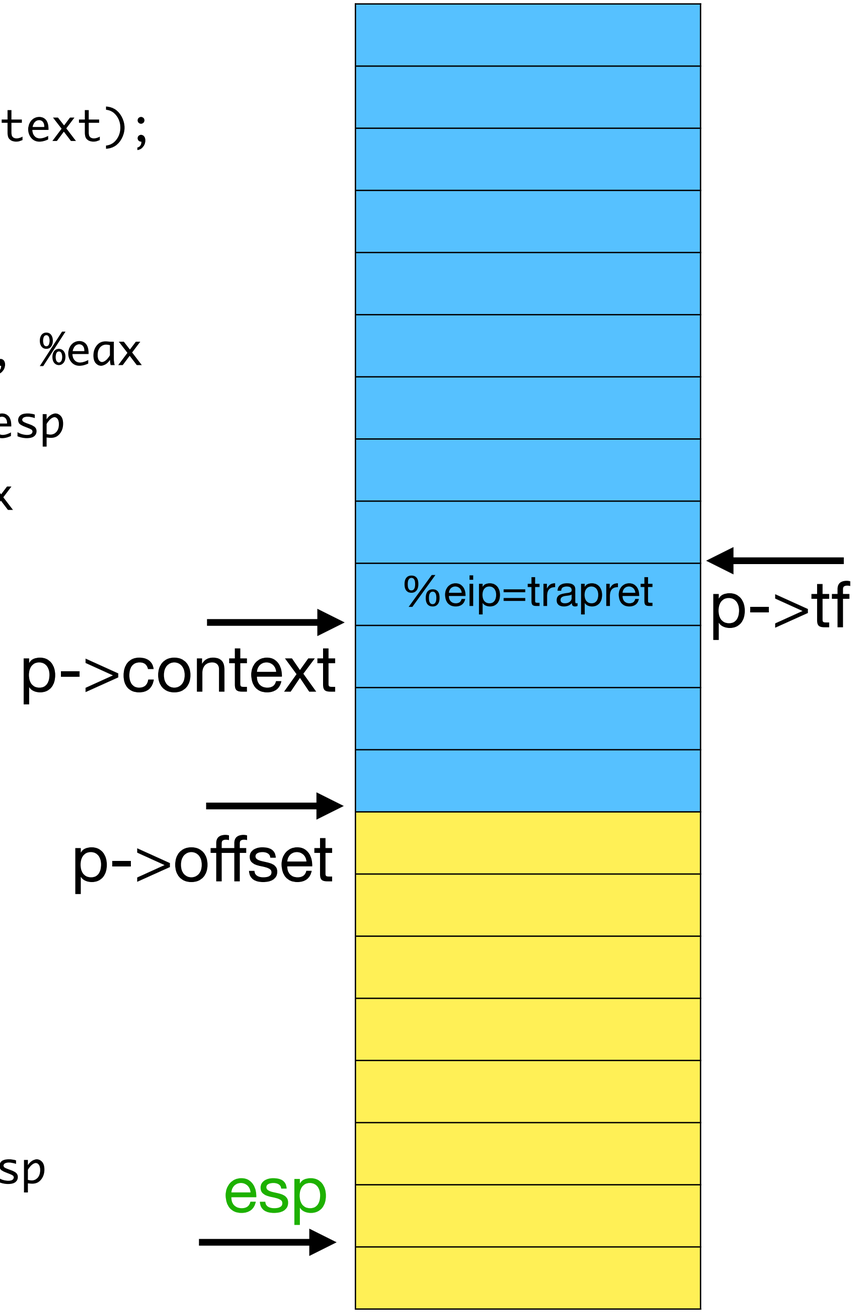
  p->tf->cs = (SEG_UCODE<<3) | DPL_USR;
  p->tf->eflags = FL_IF;
  p->tf->eip = 0;
}

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;
}
```

eip

```
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
```



Understanding swtch

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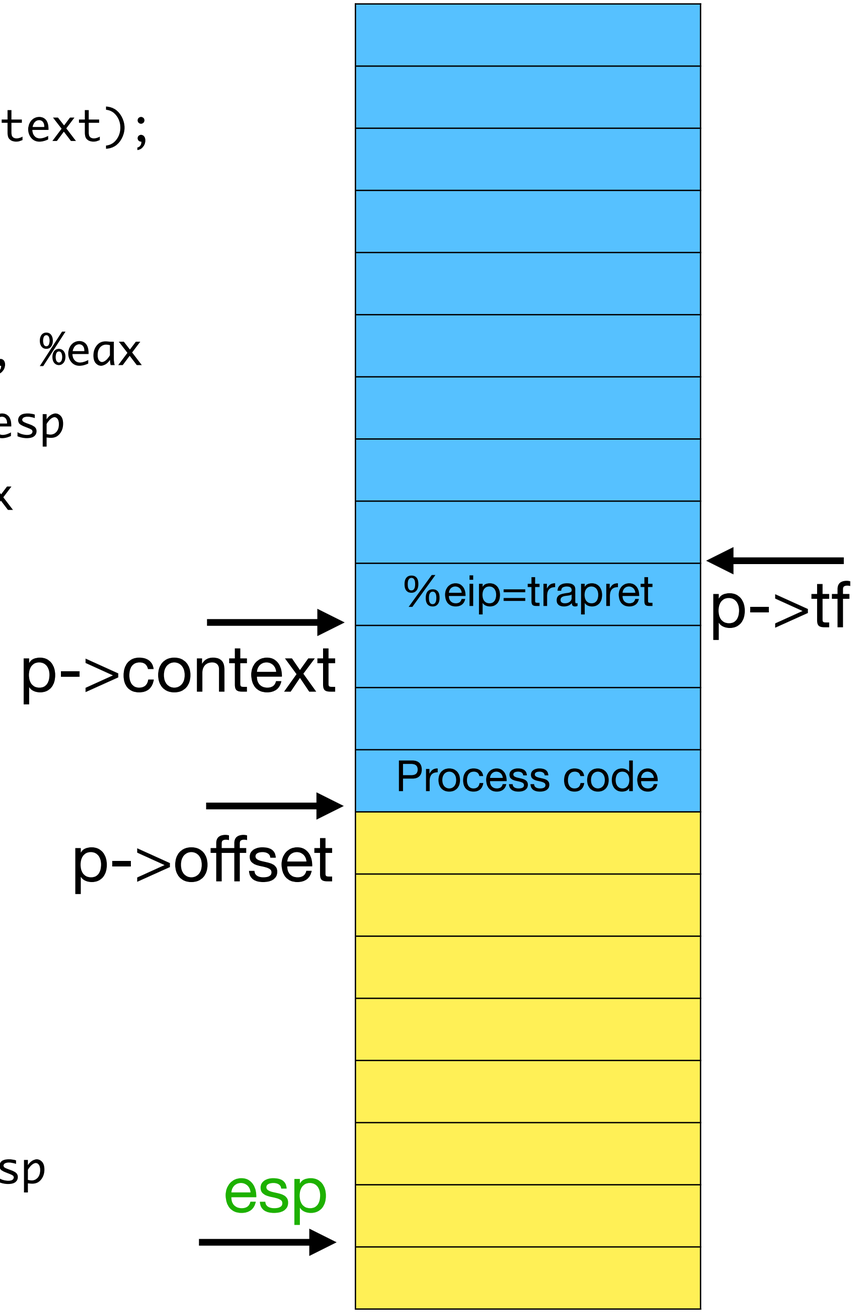

Understanding swtch

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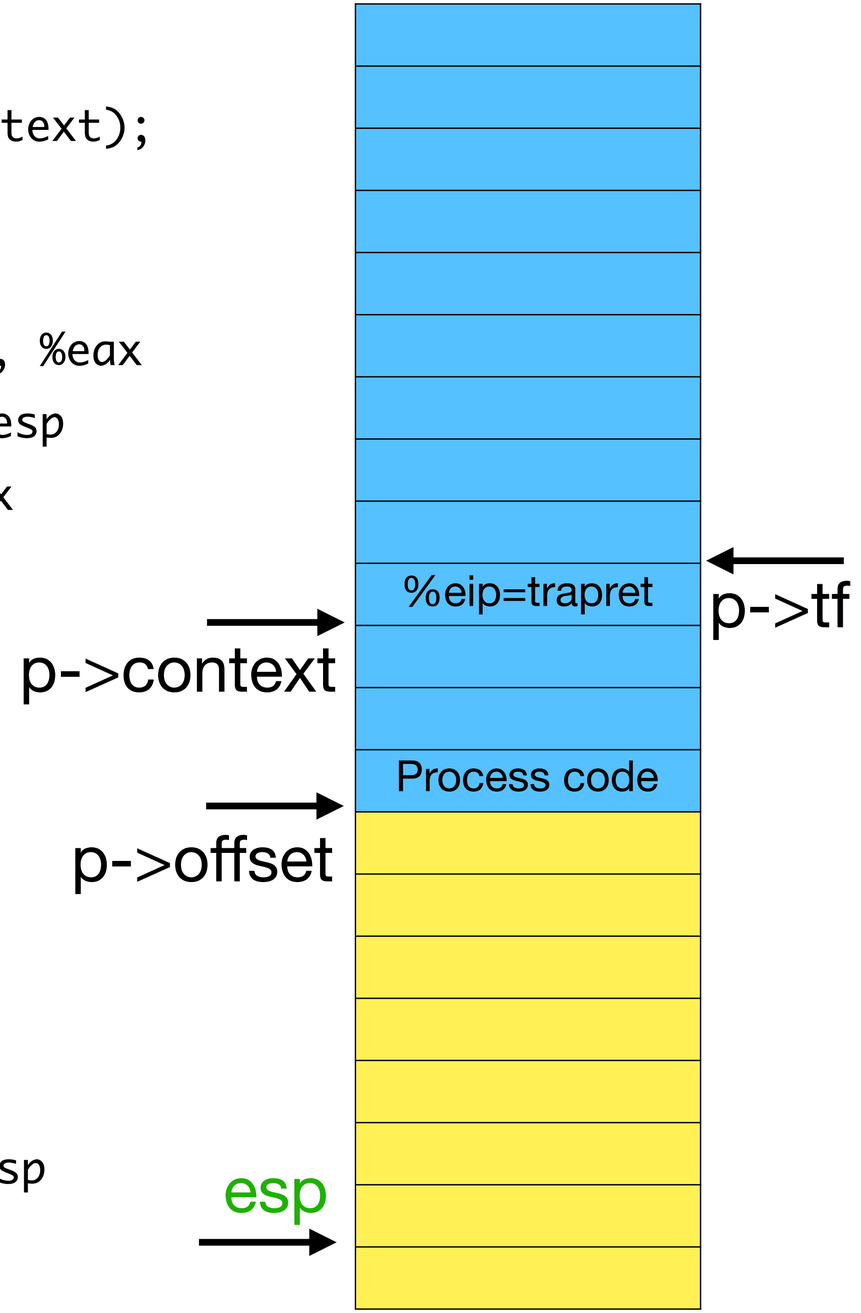

Understanding swtch

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  popl %es
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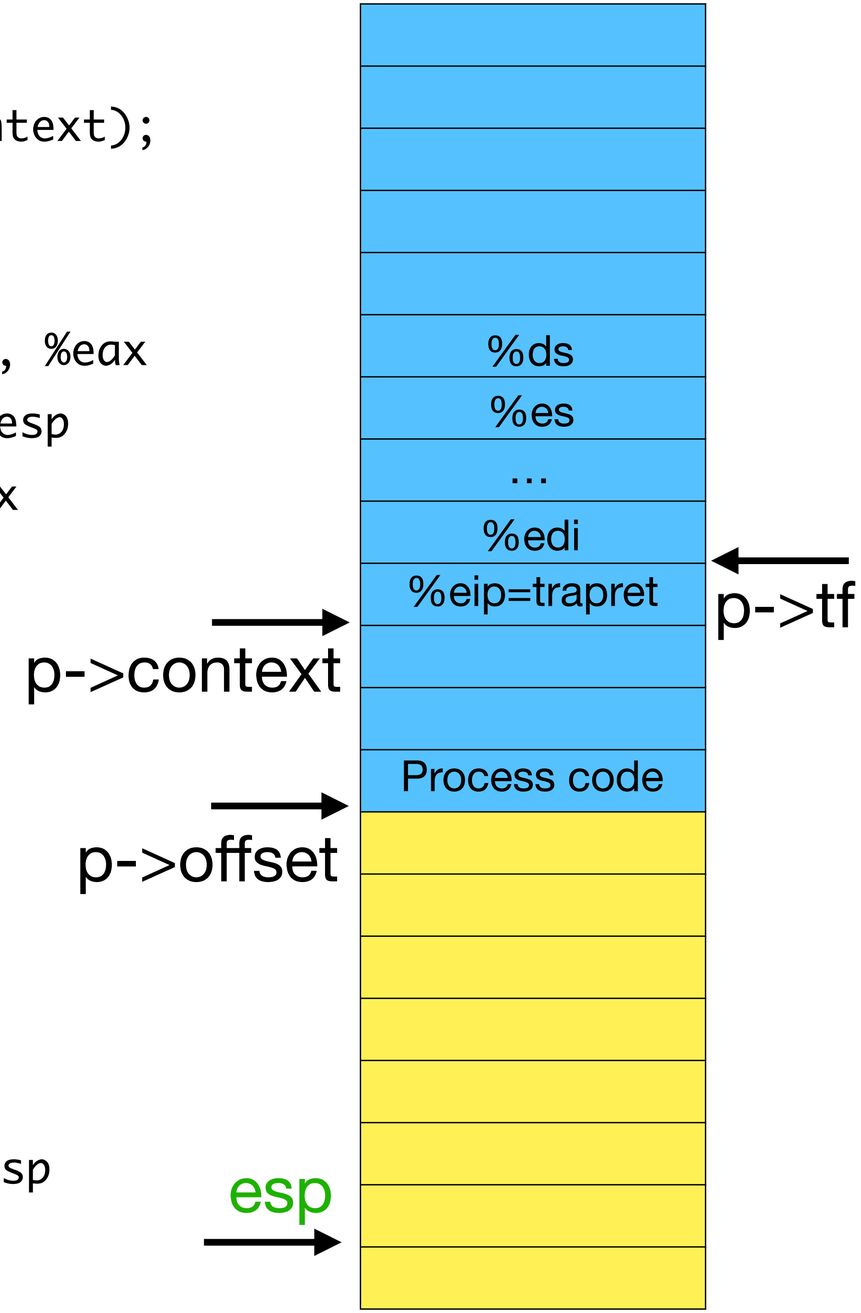

Understanding swtch

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  popl %fs
  popl %es
  popl %ds
  addl $0x8, %esp
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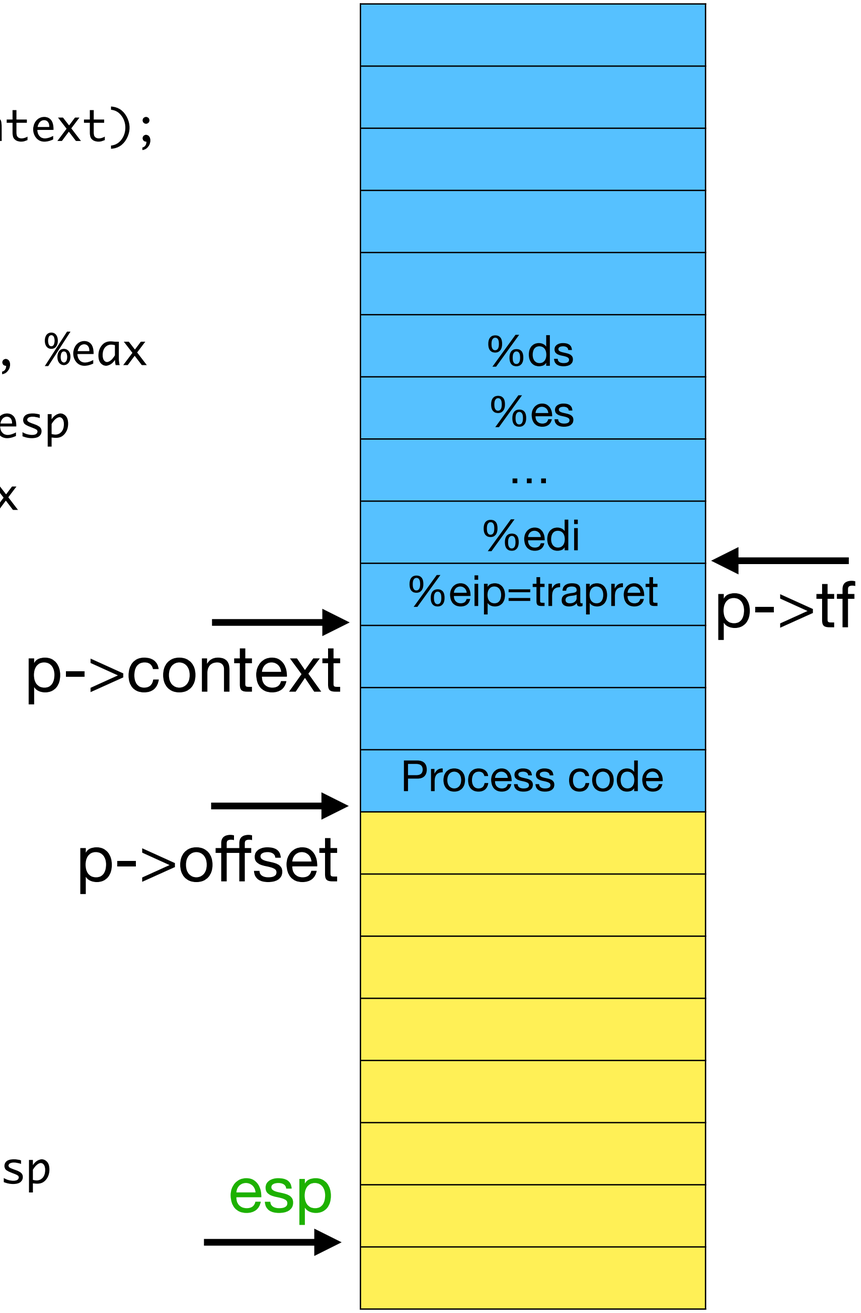

Understanding swtch

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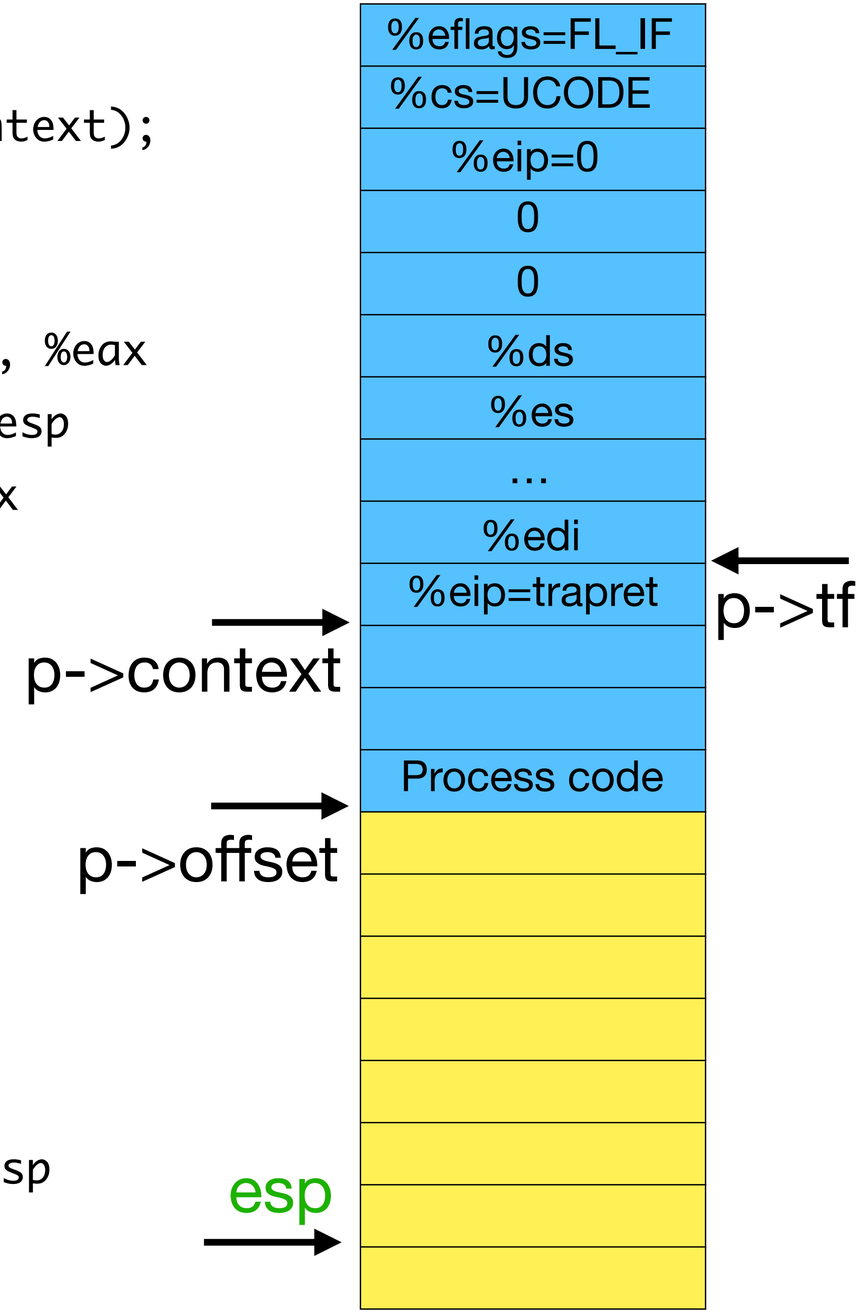

Understanding swtch

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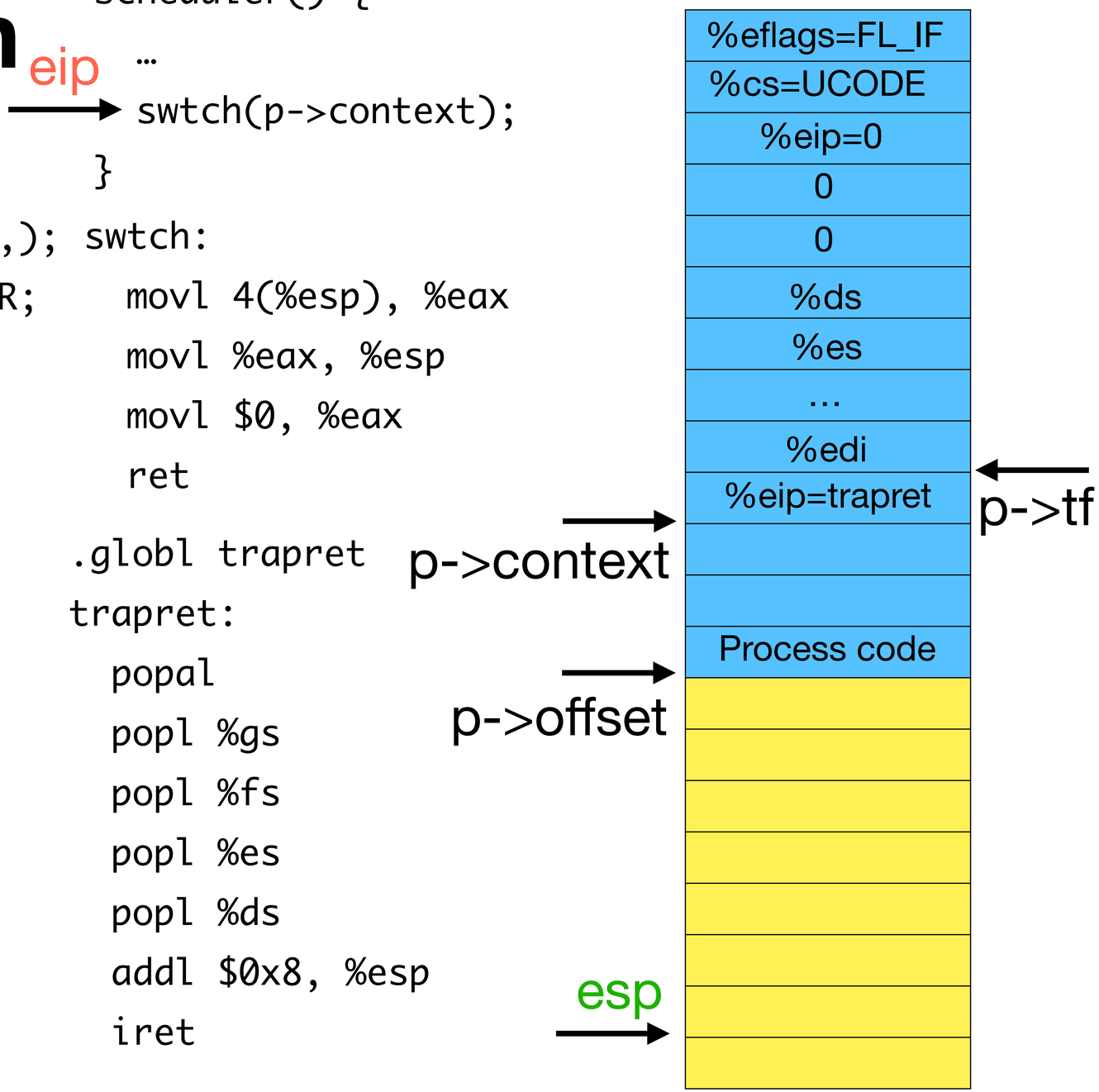

Understanding swtch

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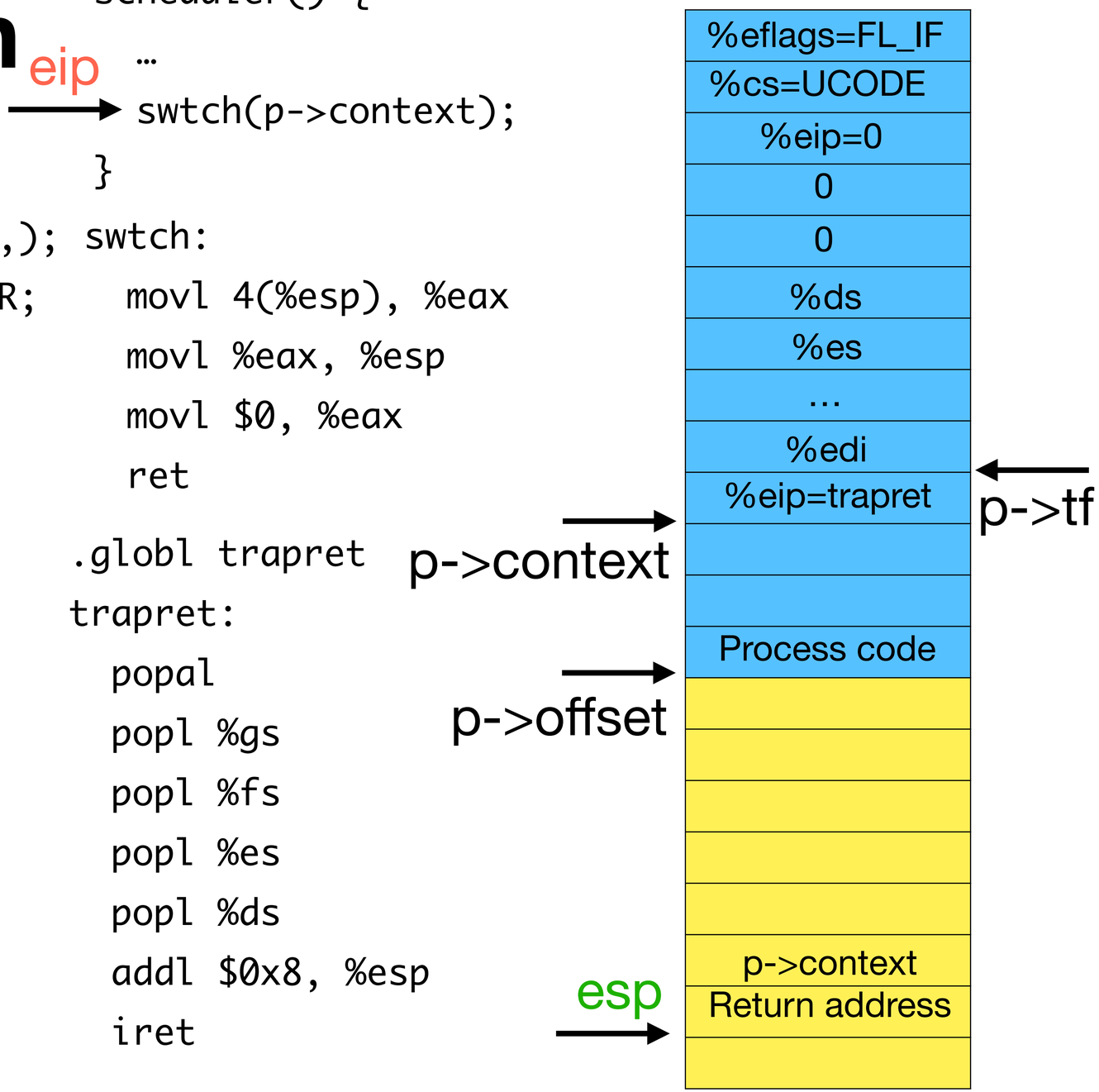

Understanding swtch

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  popl %fs
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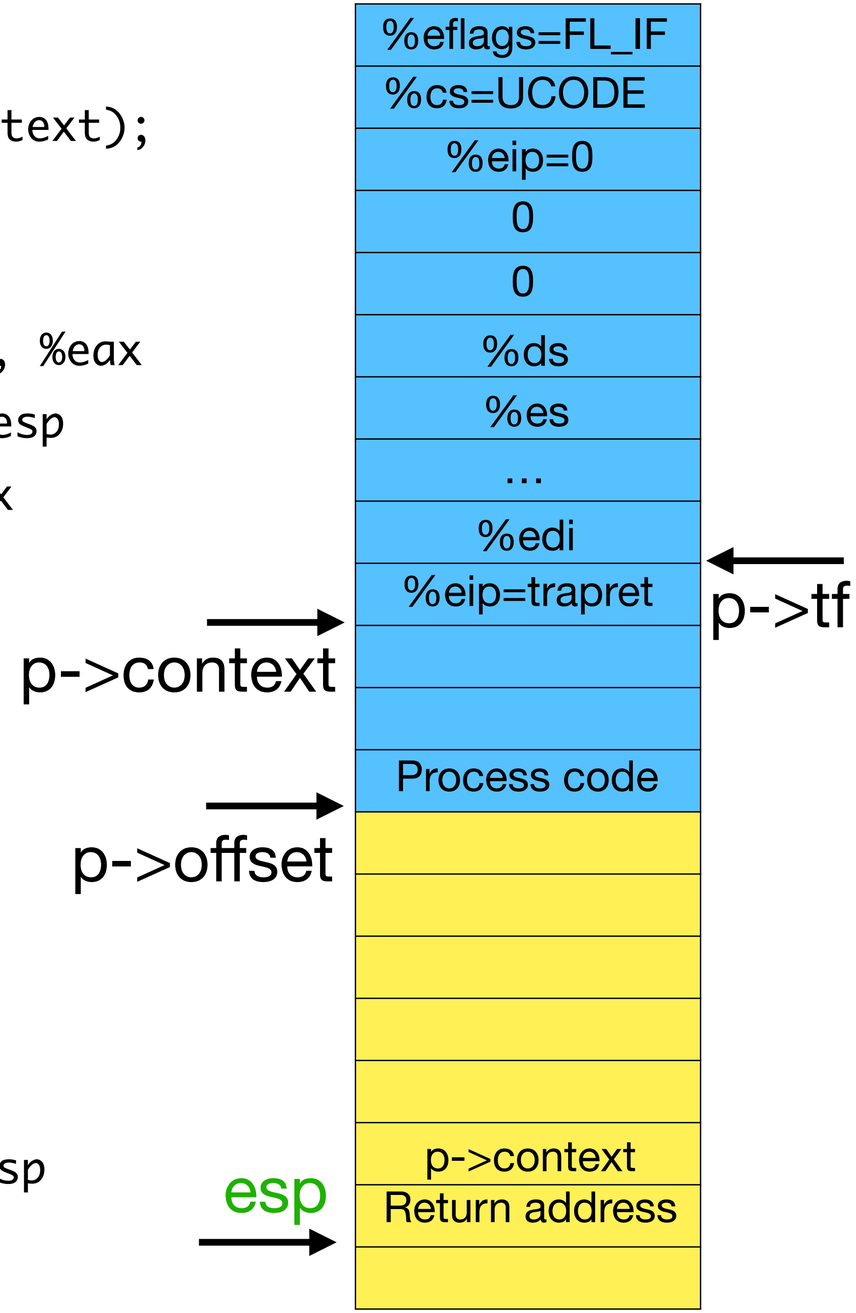

Understanding swtch

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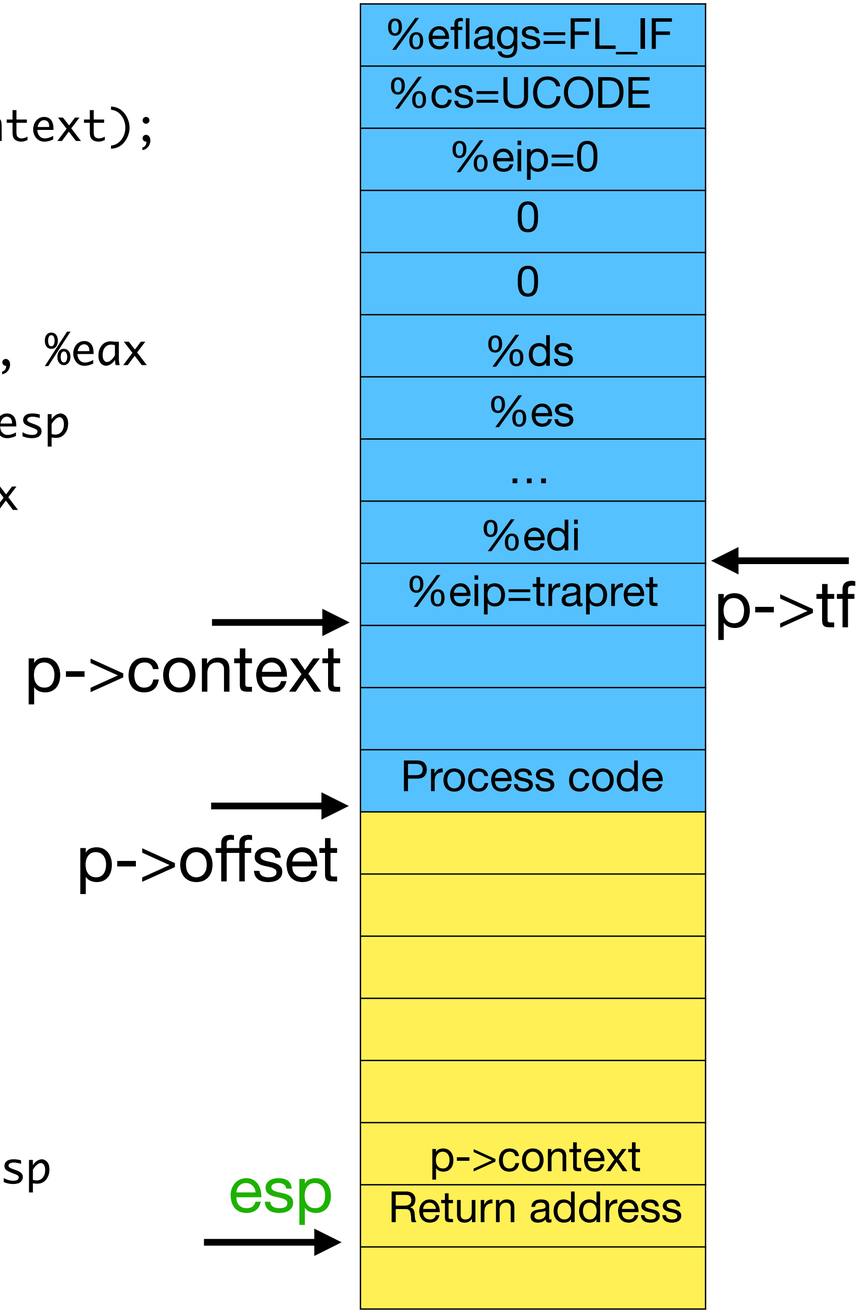
```

eip



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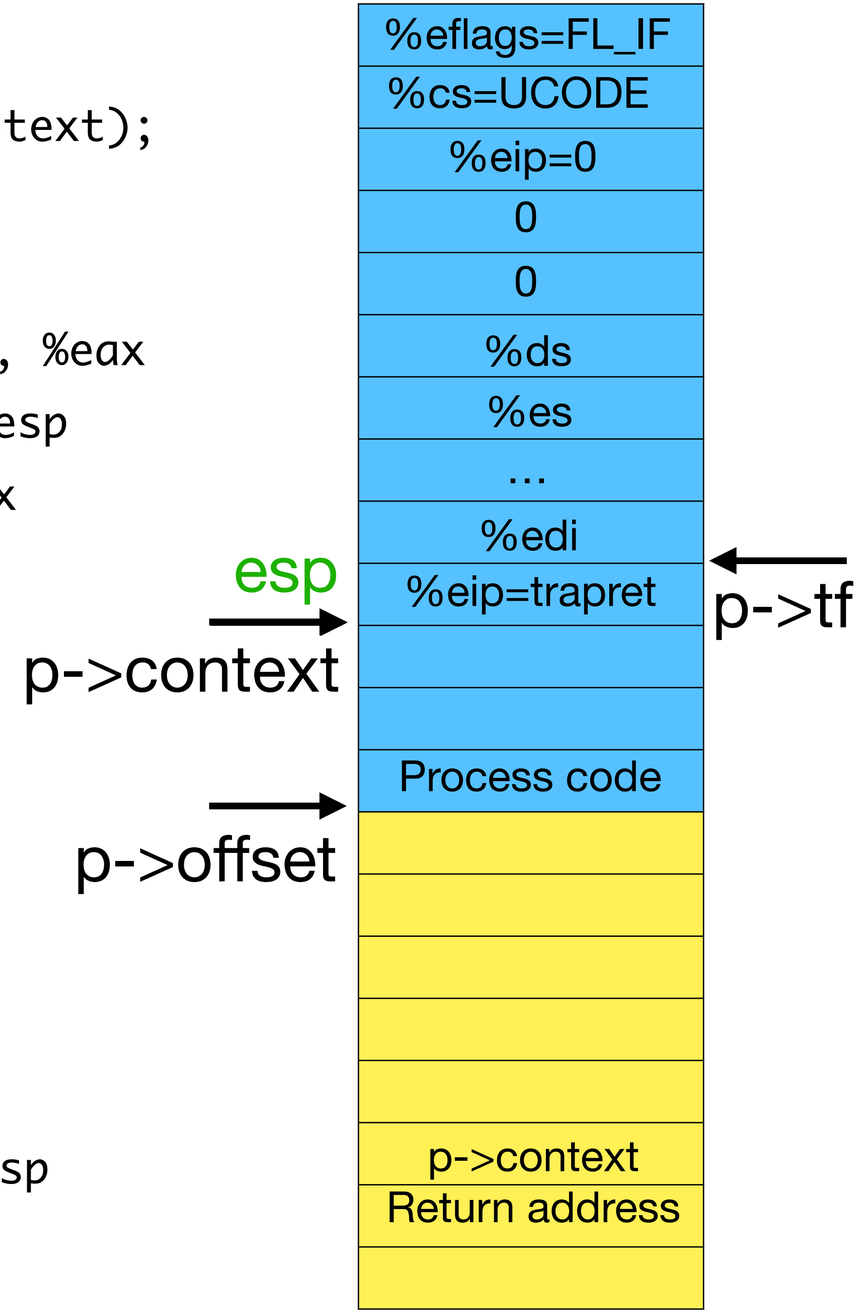
eip



Understanding swtch

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  popl %es
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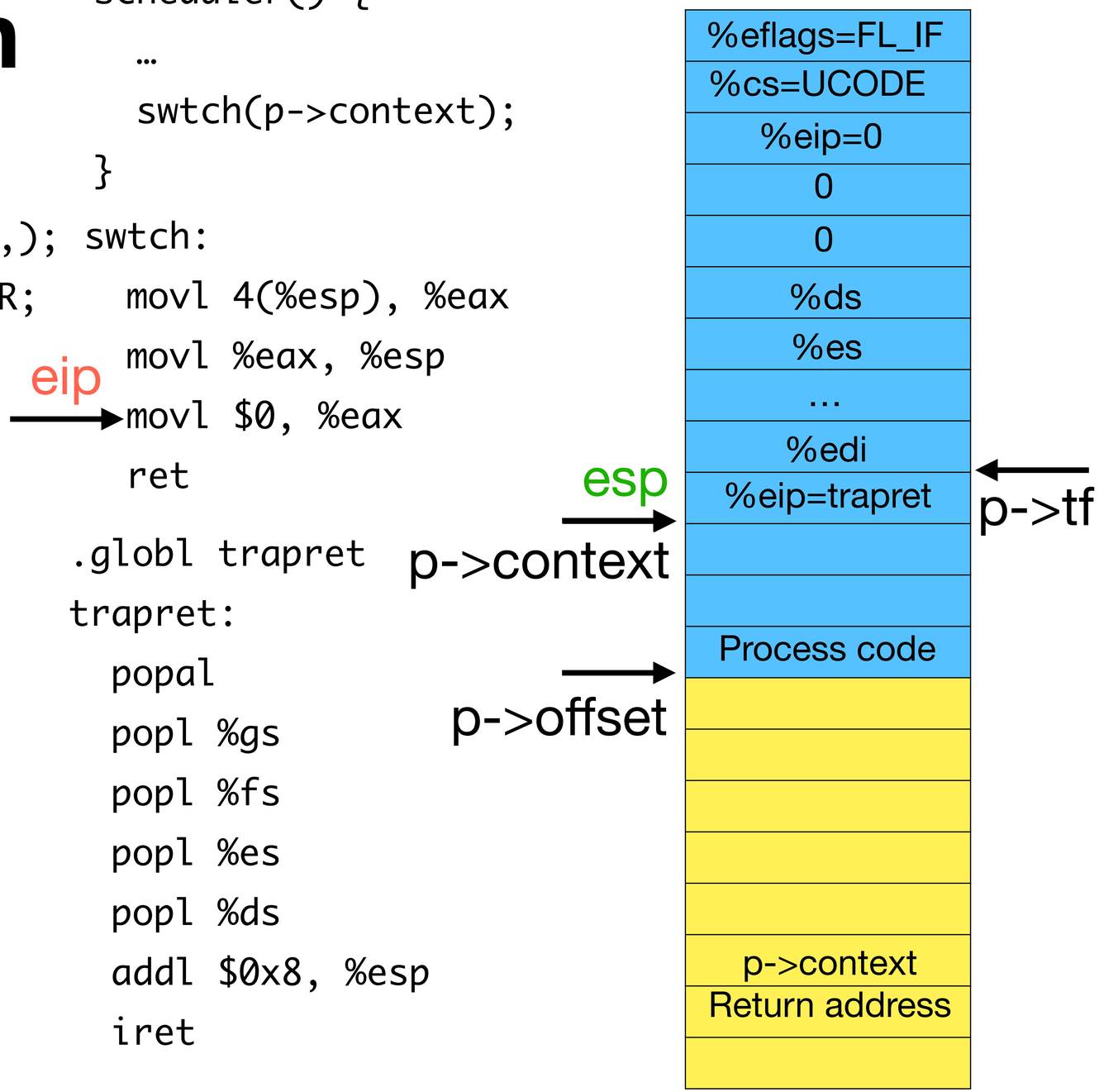

Understanding swtch

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  popl %ds
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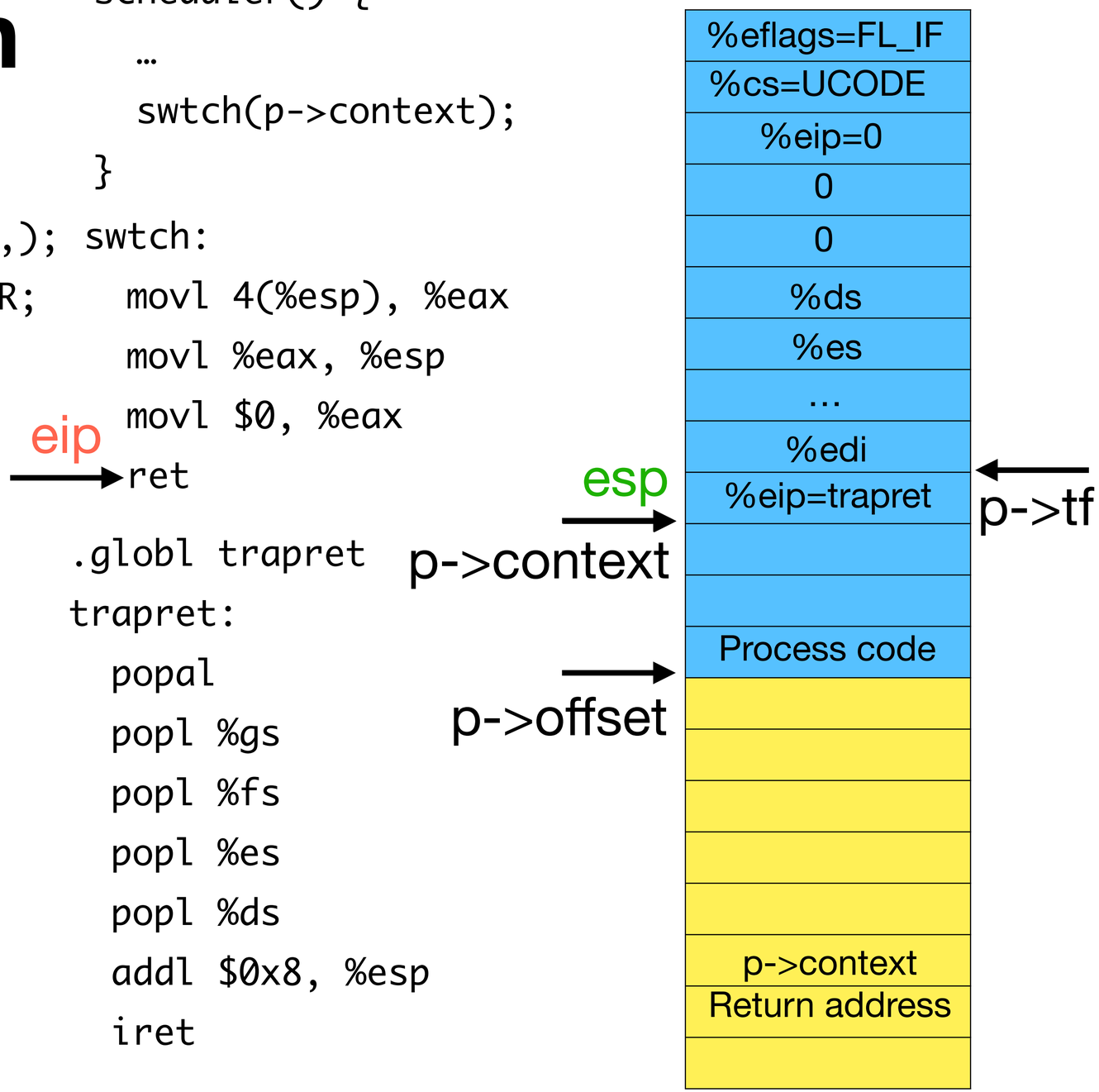

Understanding swtch

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  popl %es
  popl %ds
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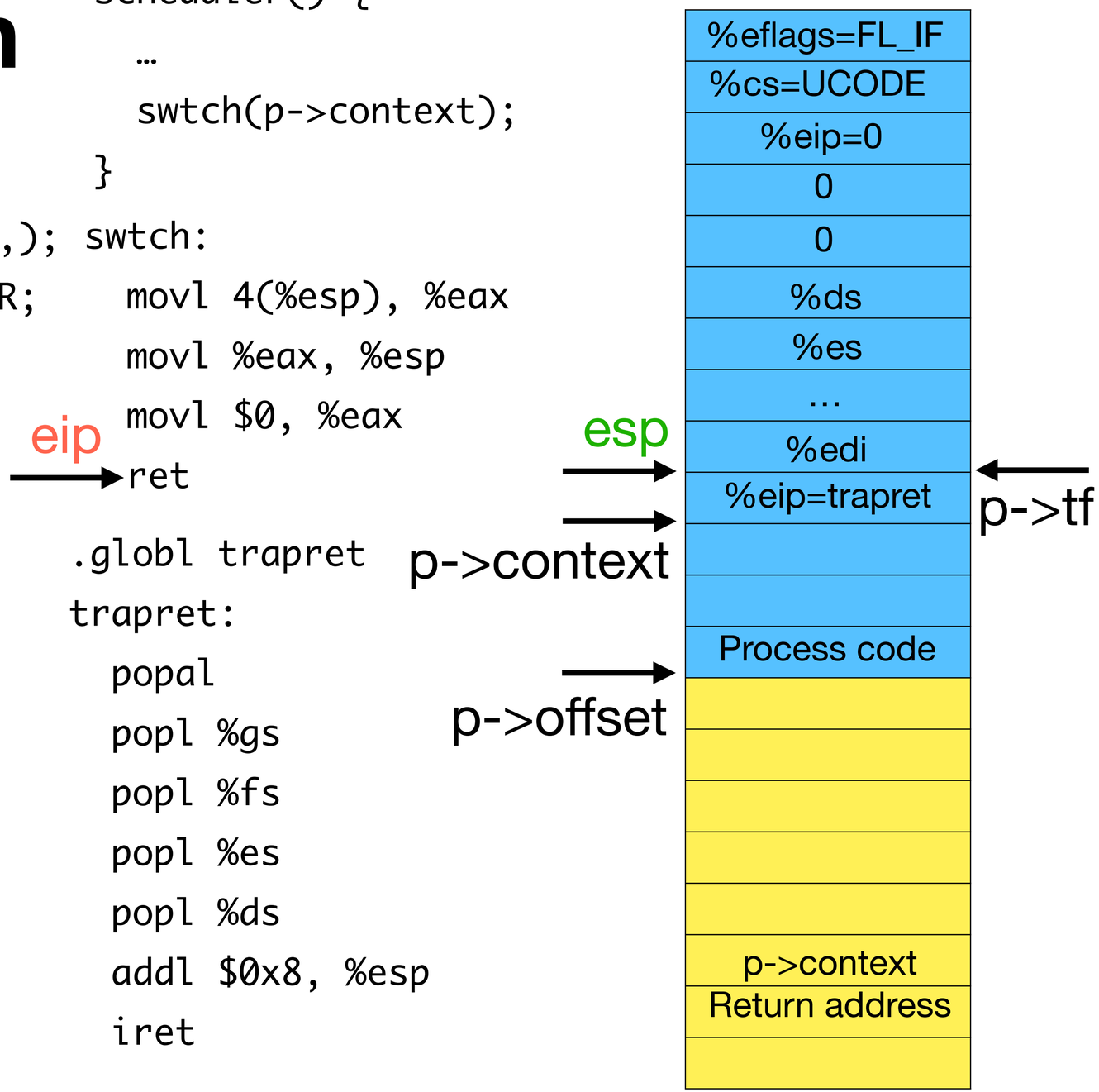

Understanding swtch

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  popl %es
  popl %ds
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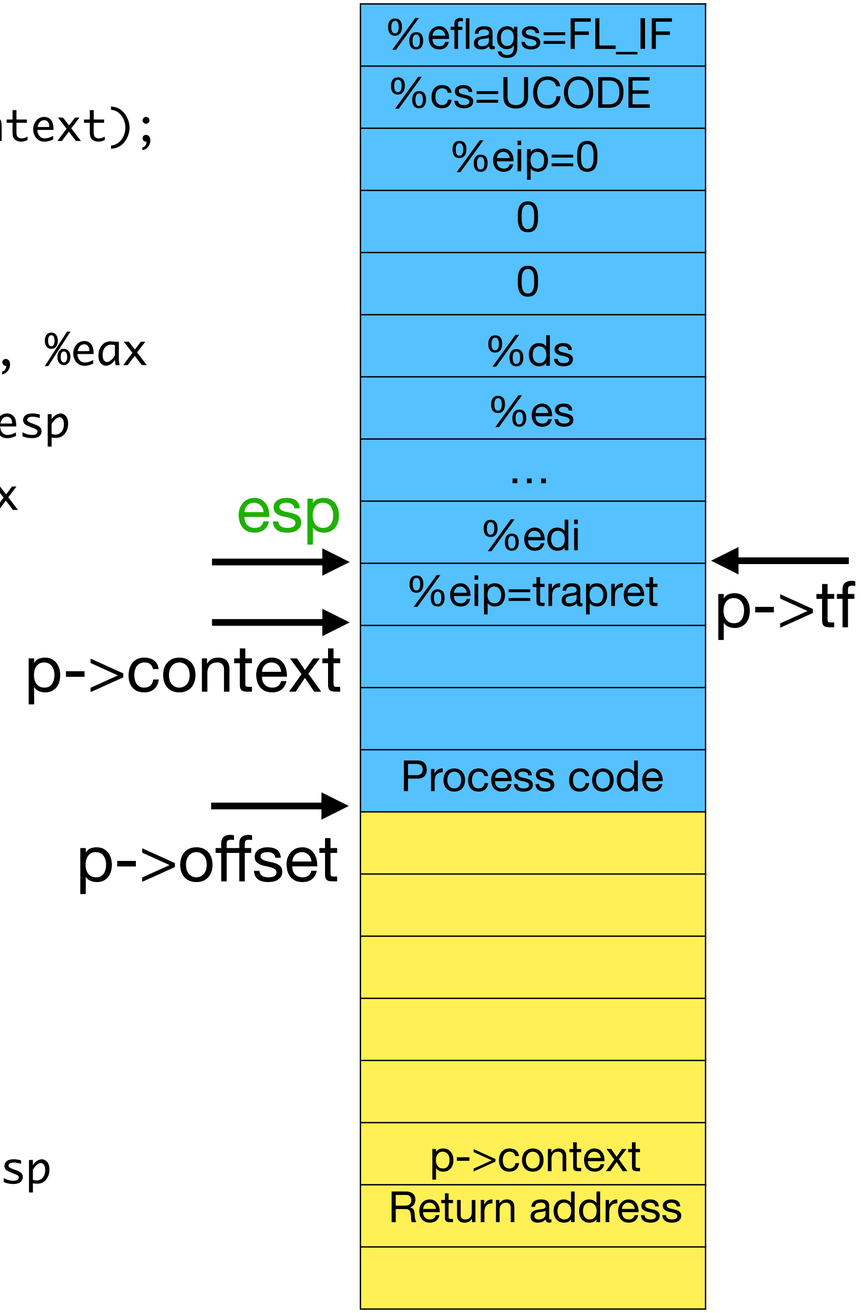
```

eip



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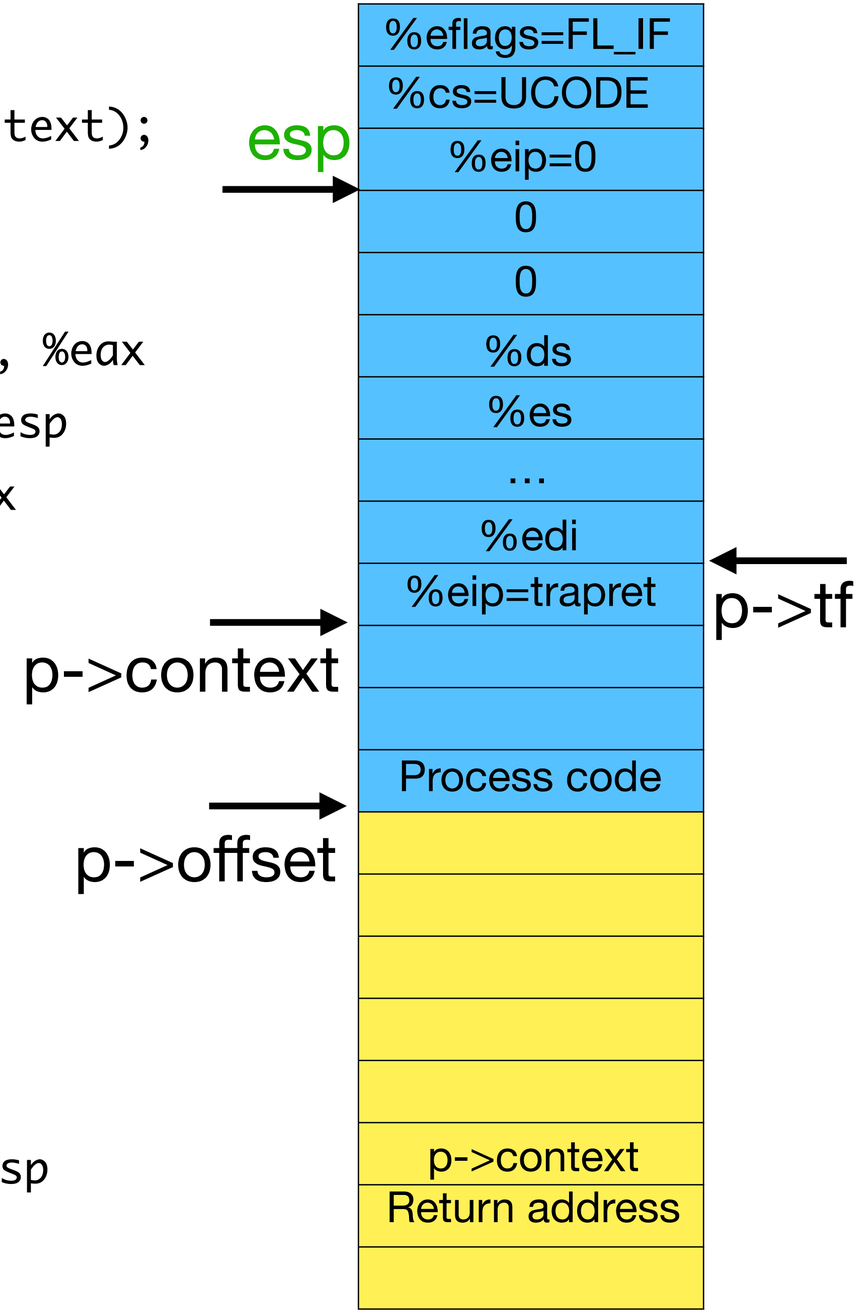
```

eip



Understanding swtch

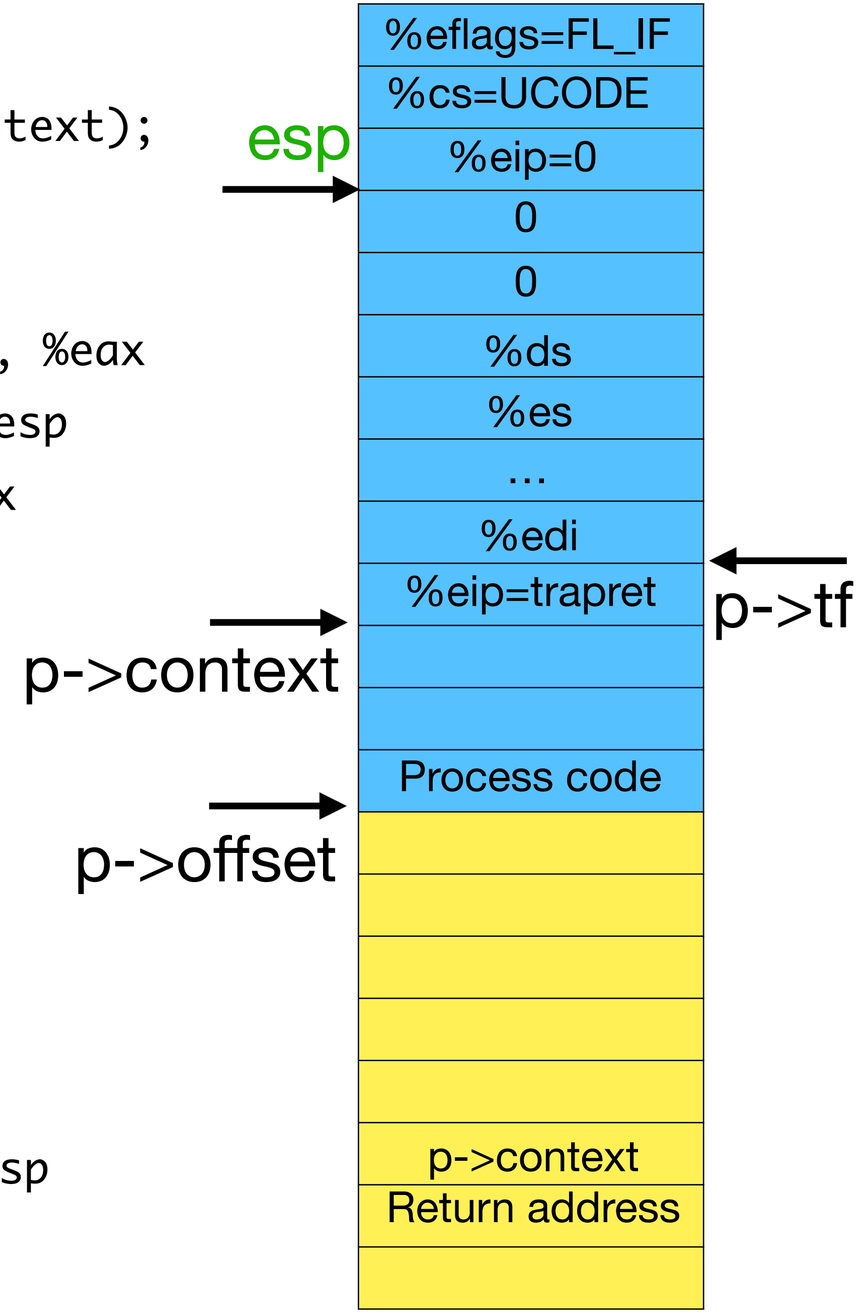
```
pinit(){
  p = allocproc();
  memmove(p->offset, _binary_initcode_start,);
  p->tf->ds,es,ss = (SEG_UDATA<<3) | DPL_USR;
  p->tf->cs = (SEG_UCODE<<3) | DPL_USR;
  p->tf->eflags = FL_IF;
  p->tf->eip = 0;
}

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
```

eip



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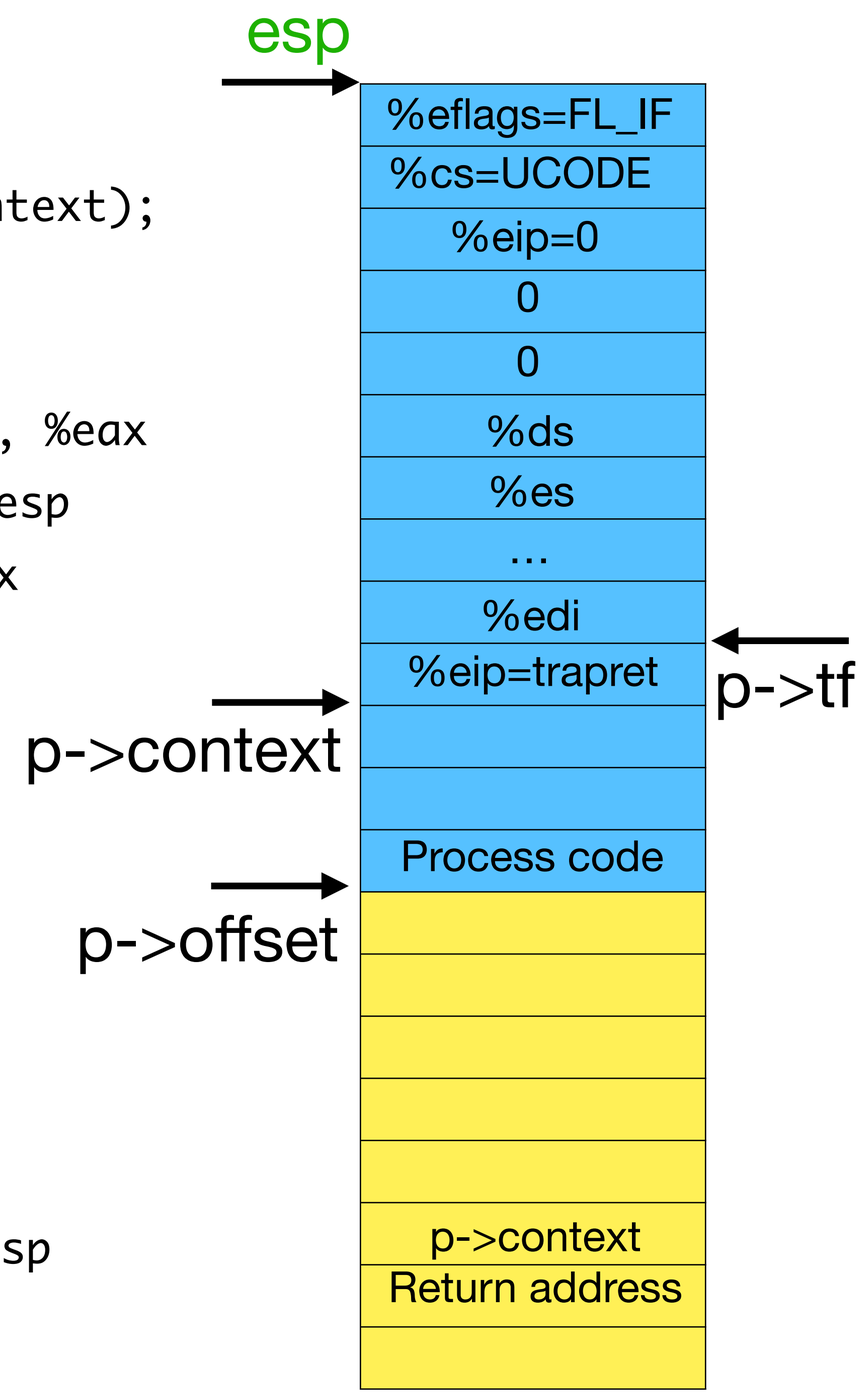
eip



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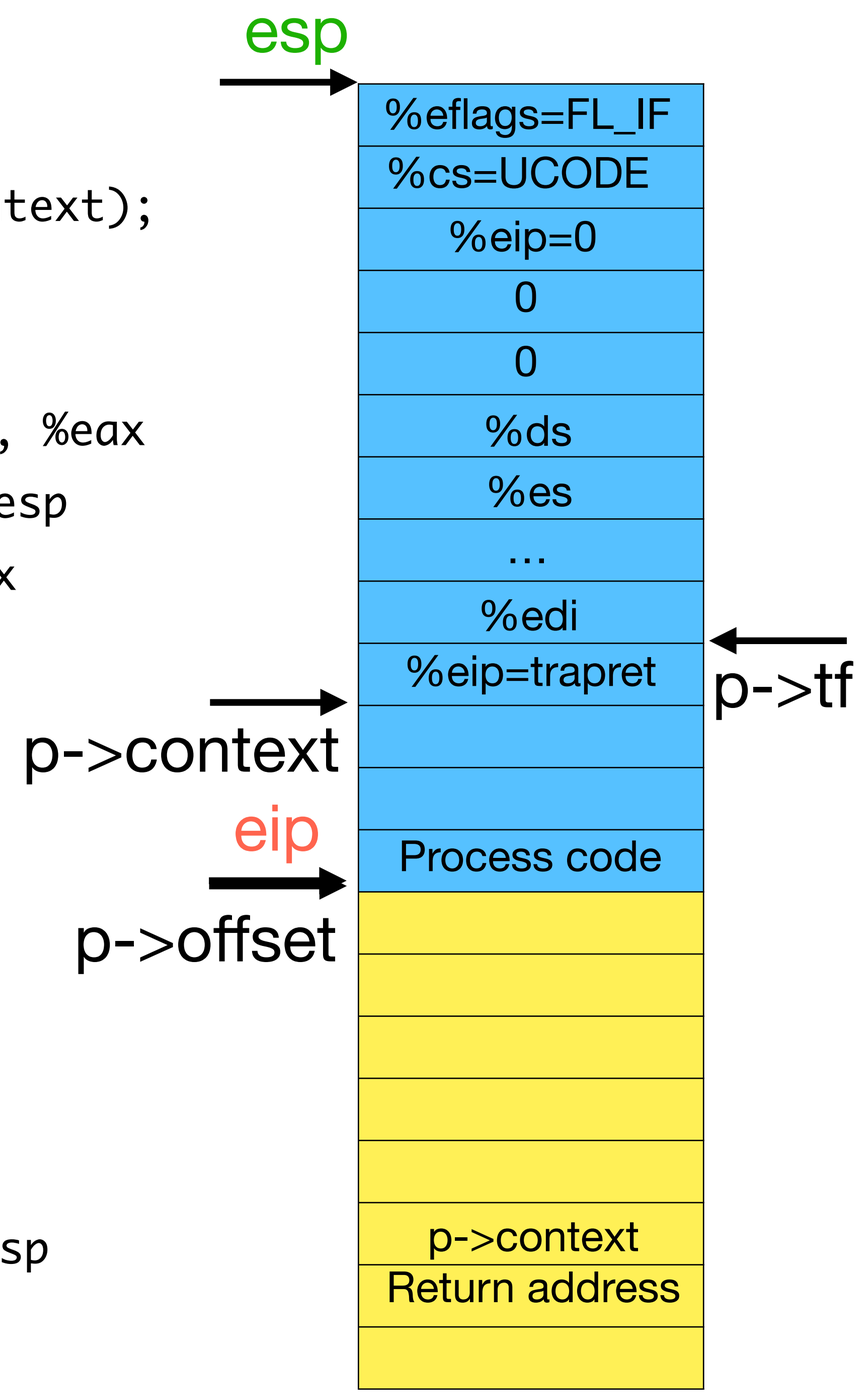

Interrupt handling revisited

eip

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vectors.S

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trapasm.S

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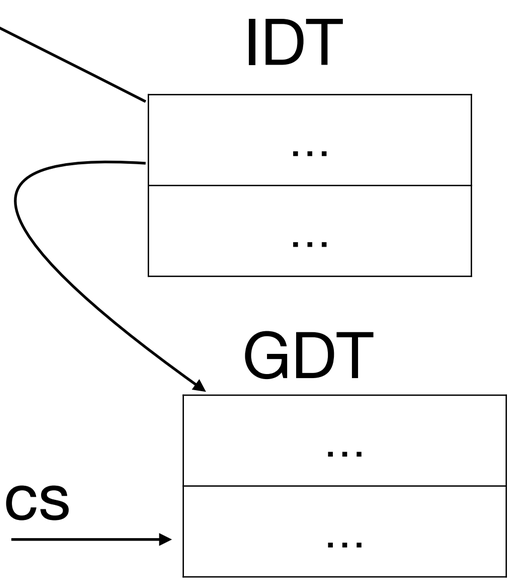

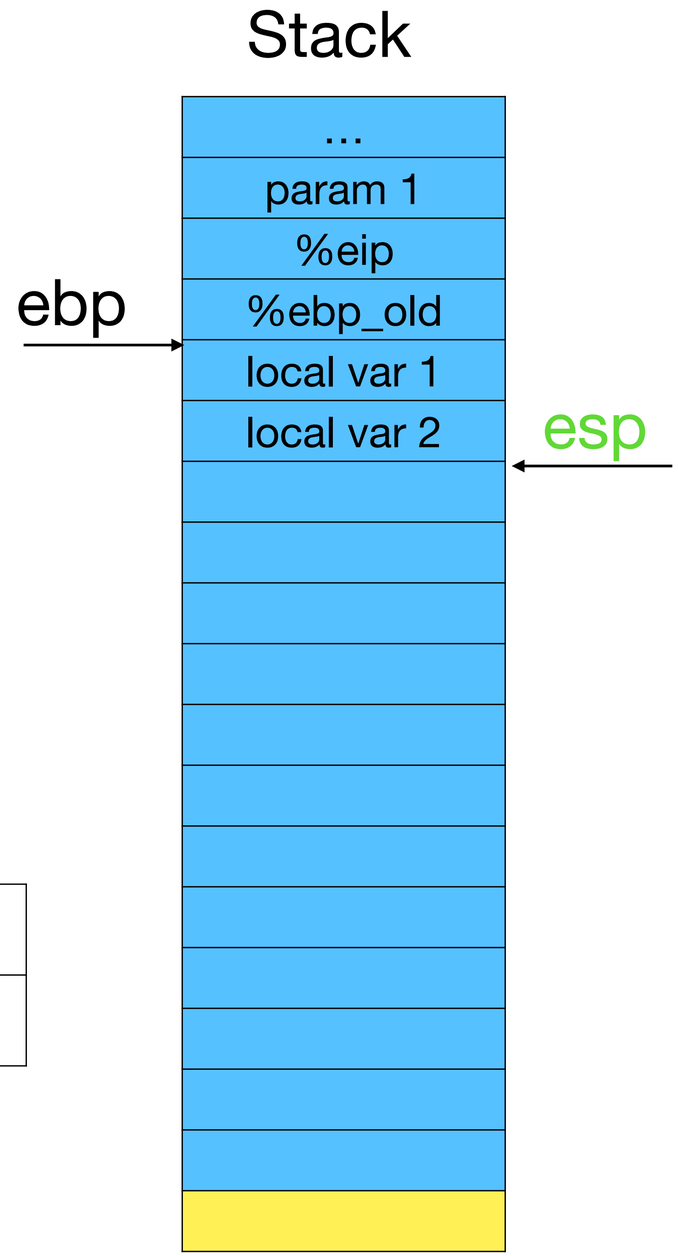

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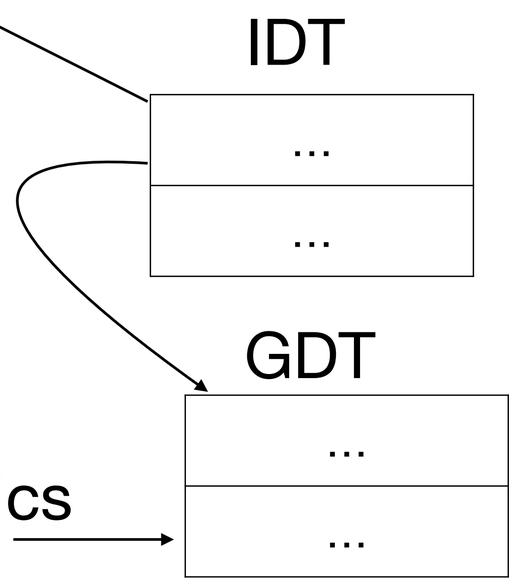

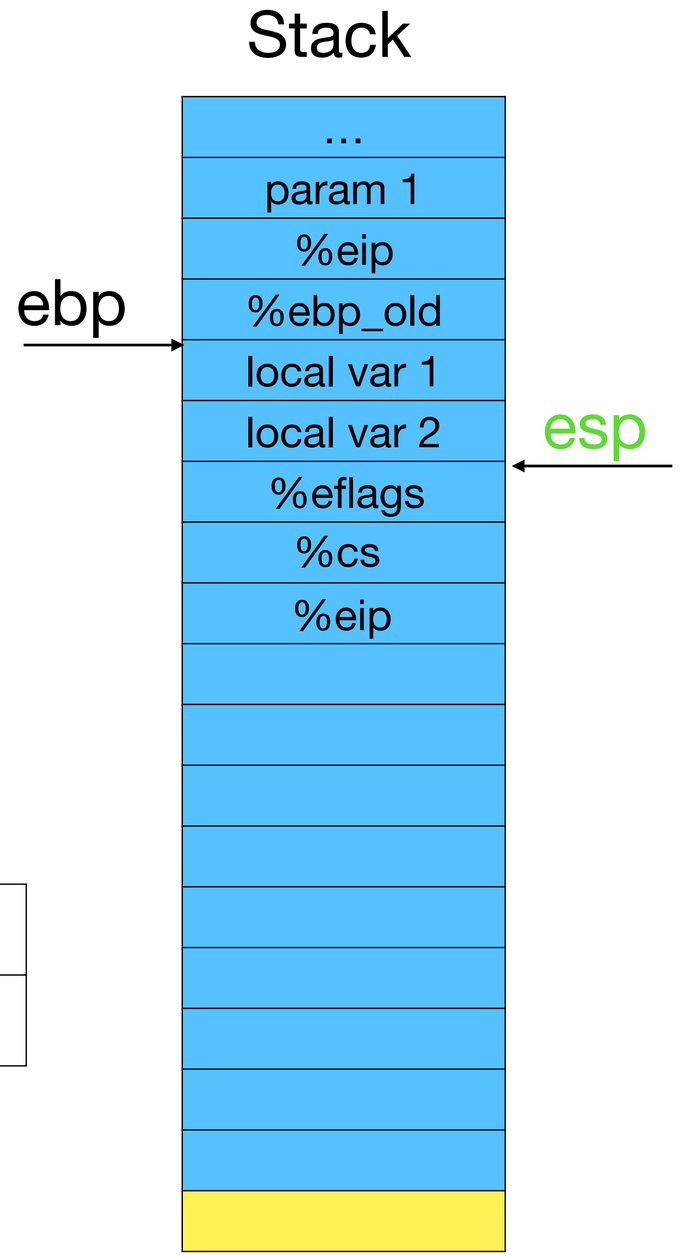

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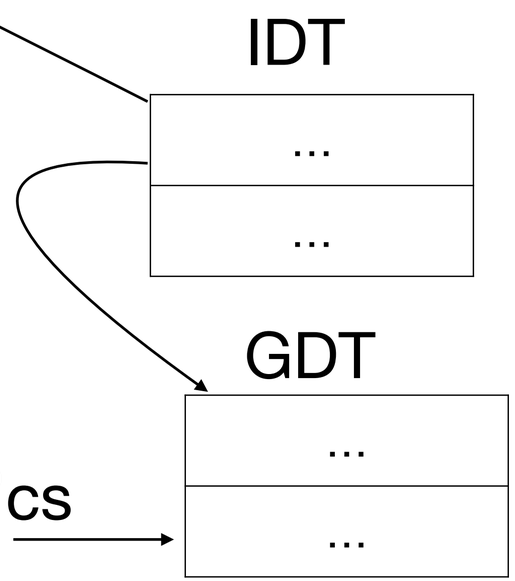

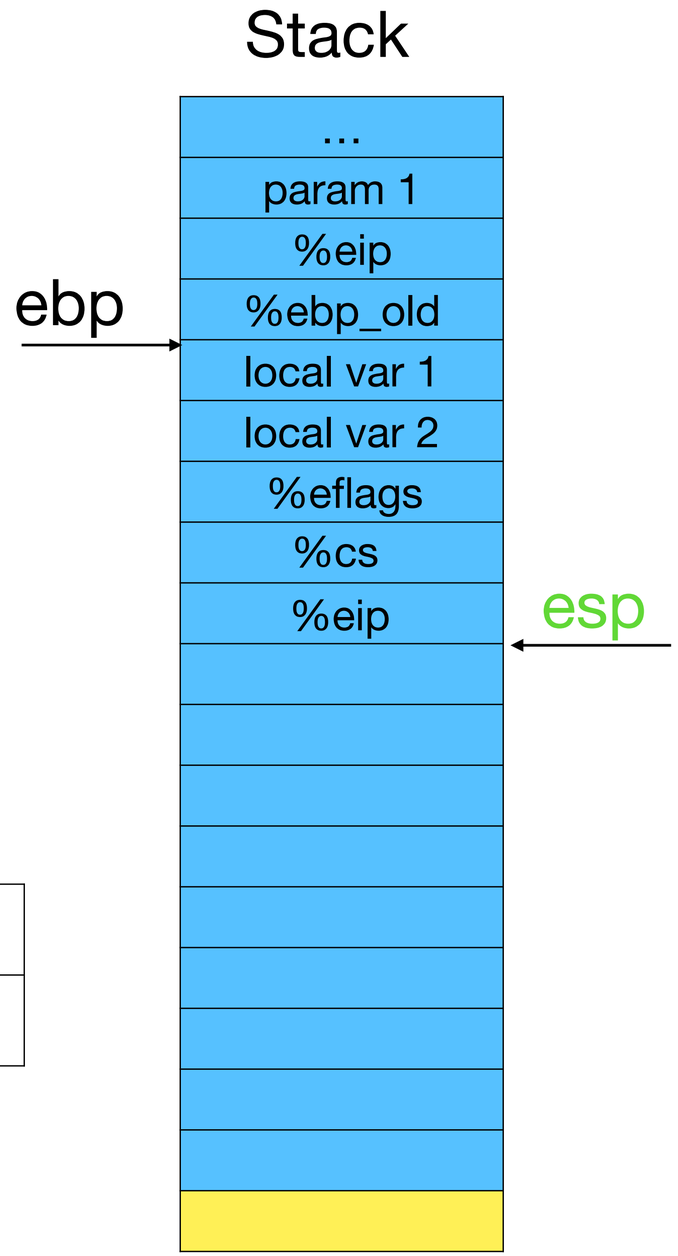

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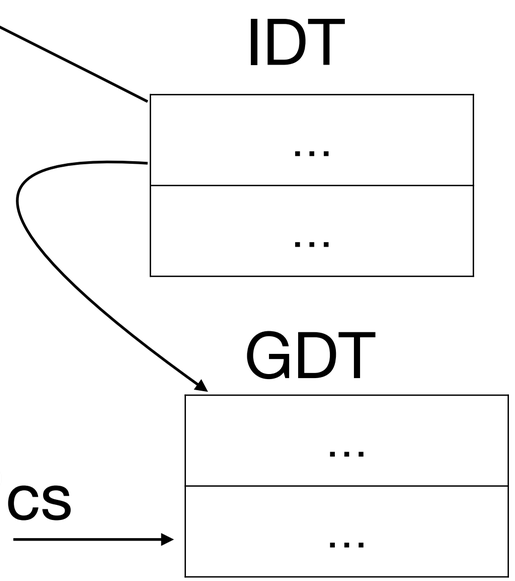

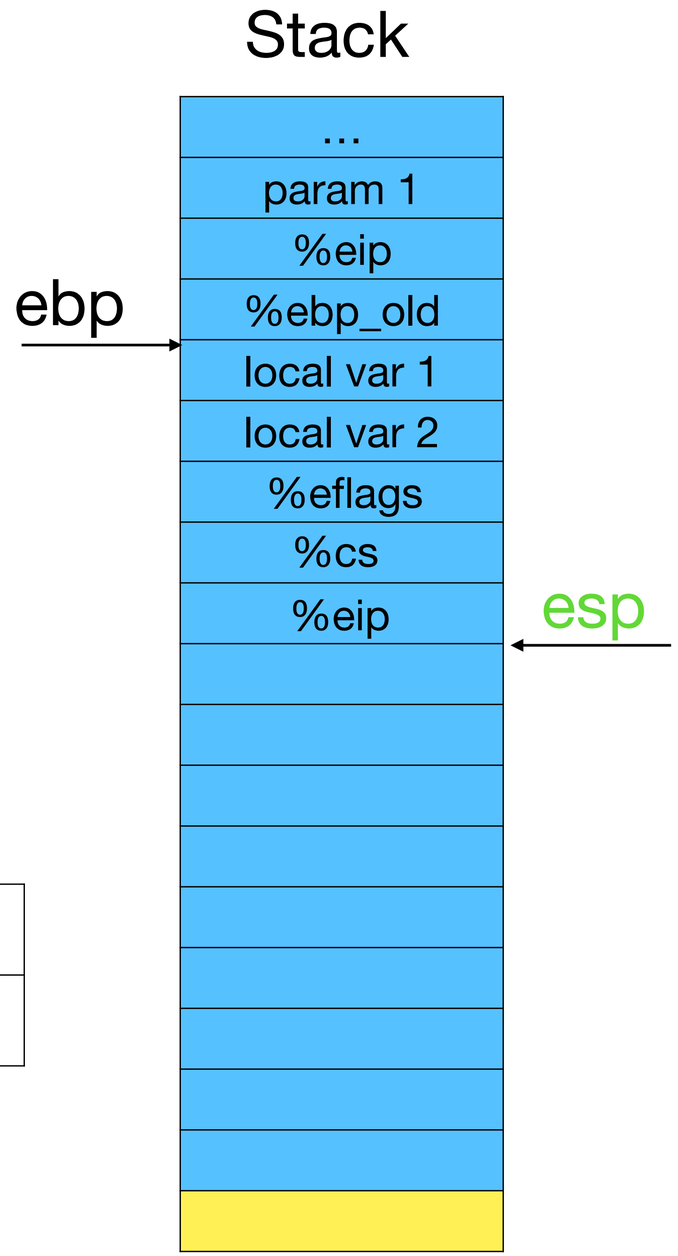

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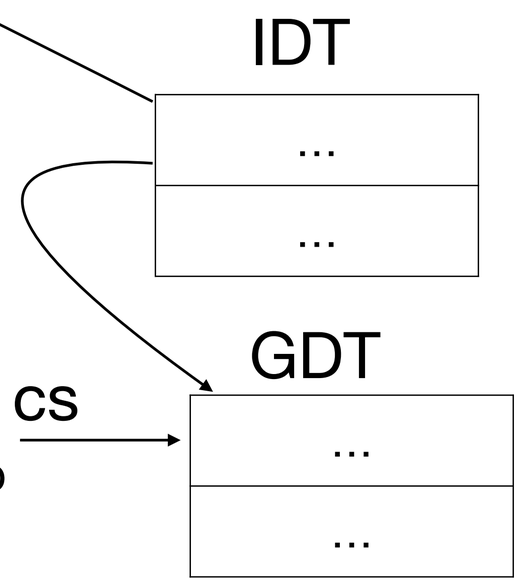

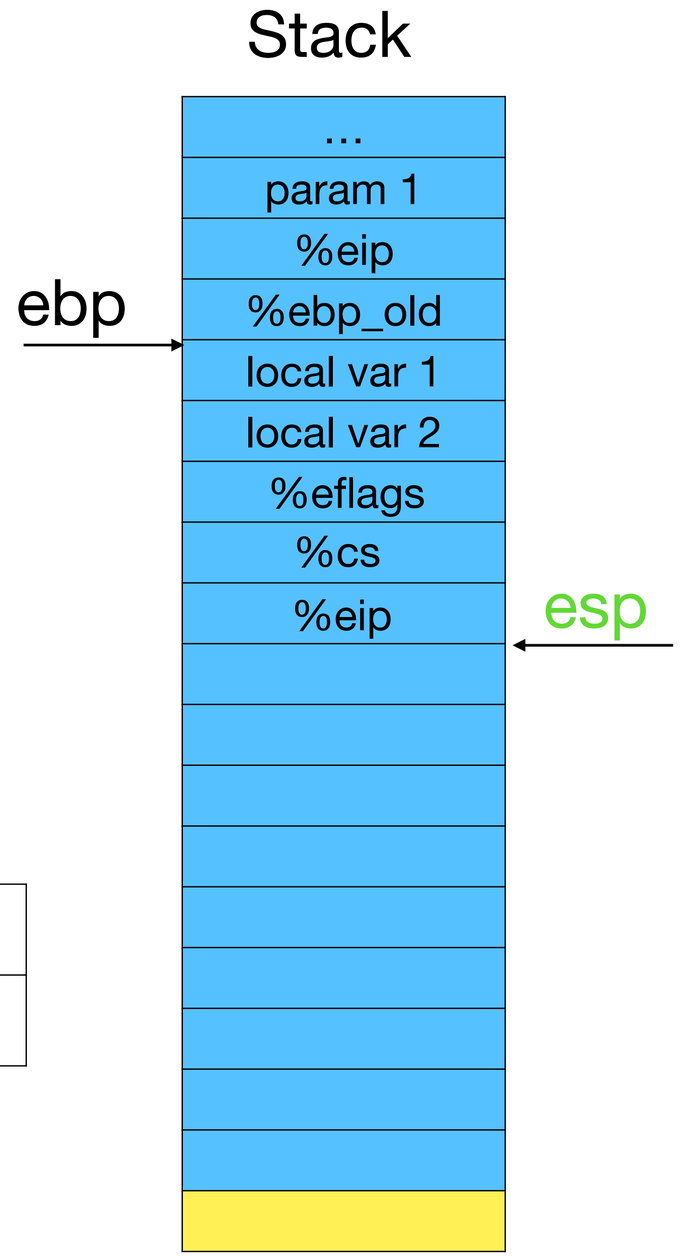

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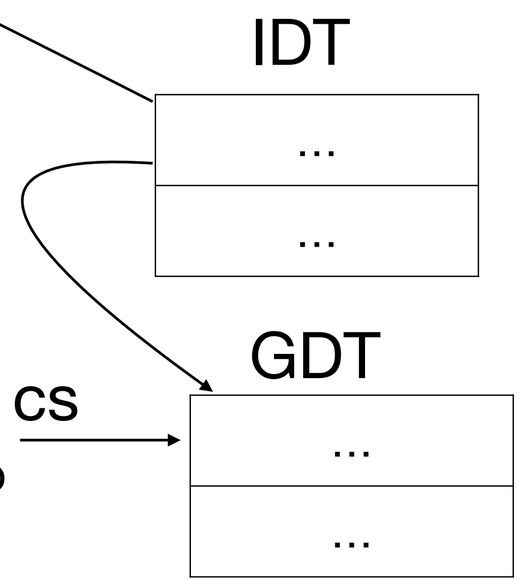

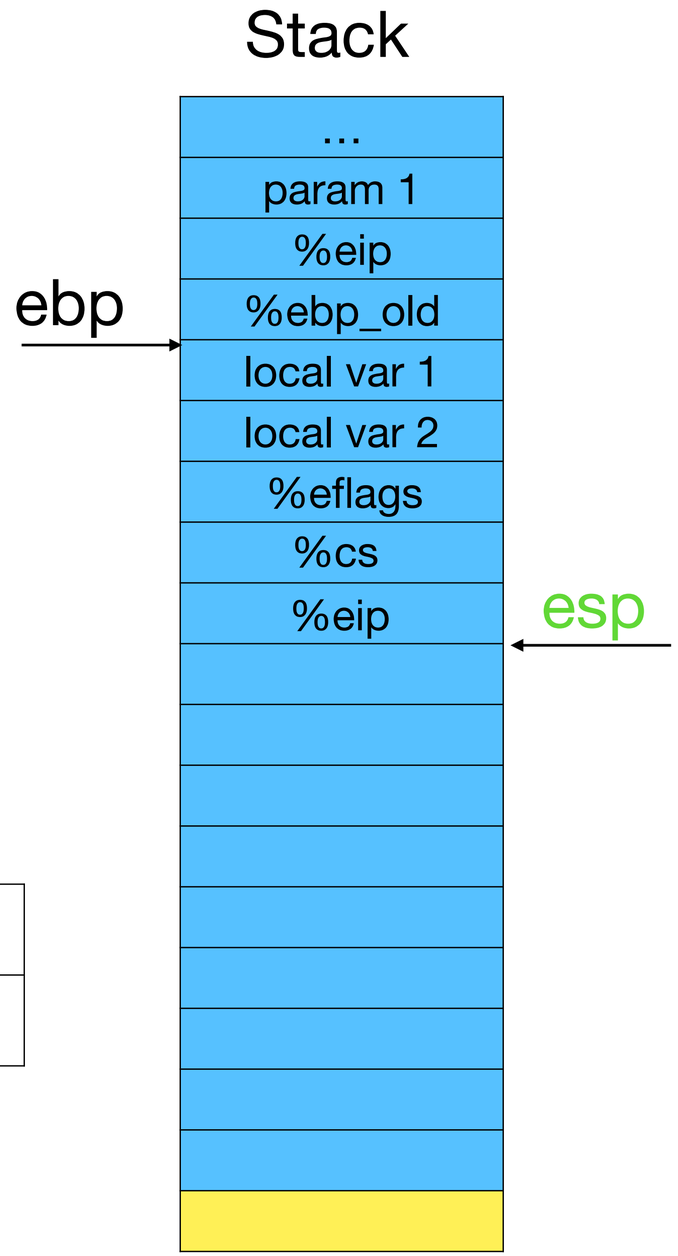

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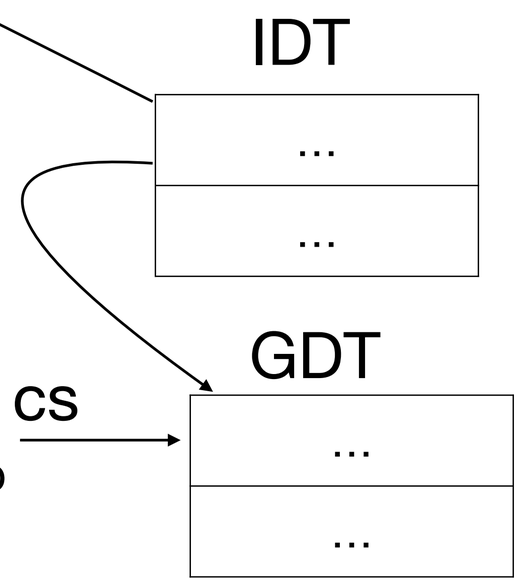

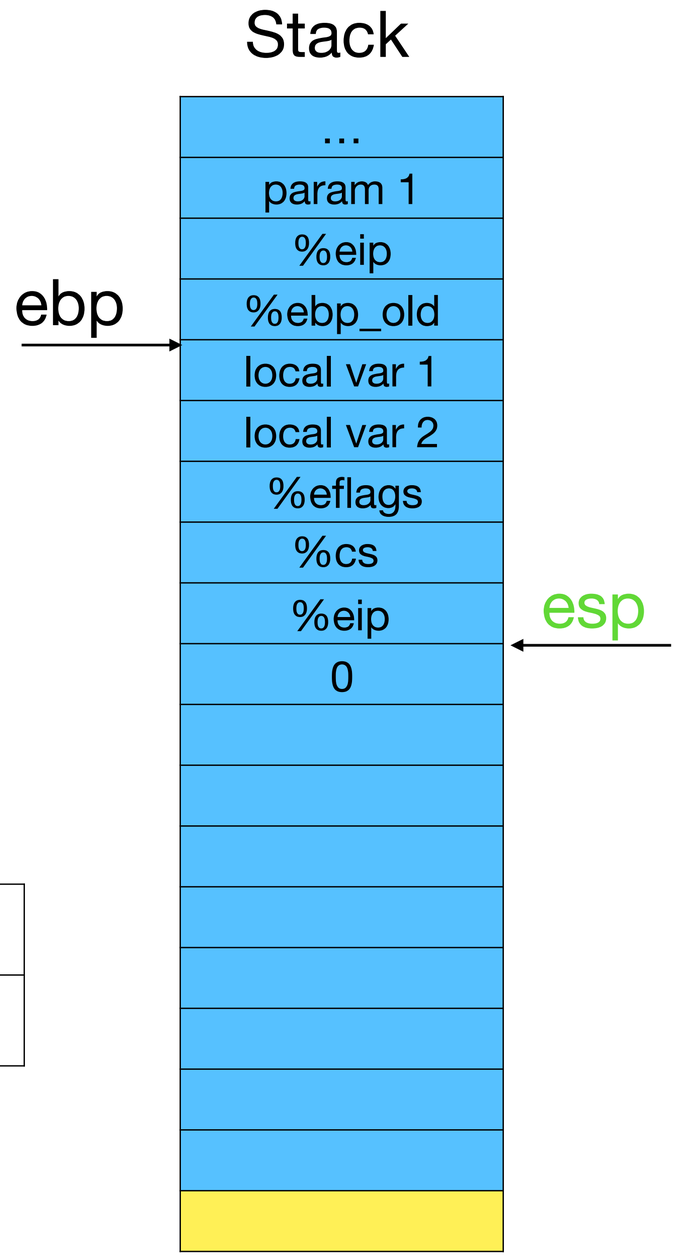

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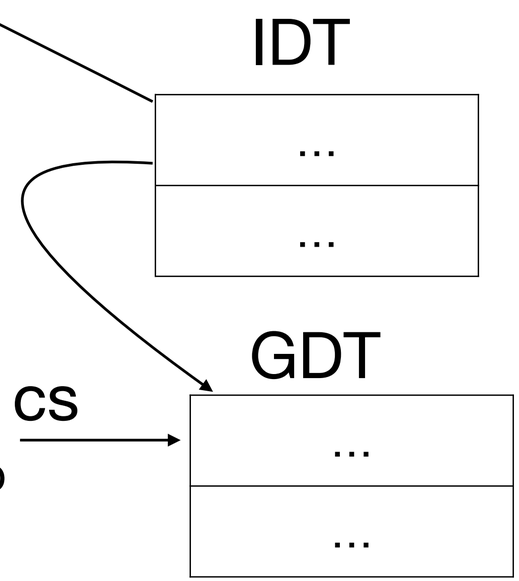

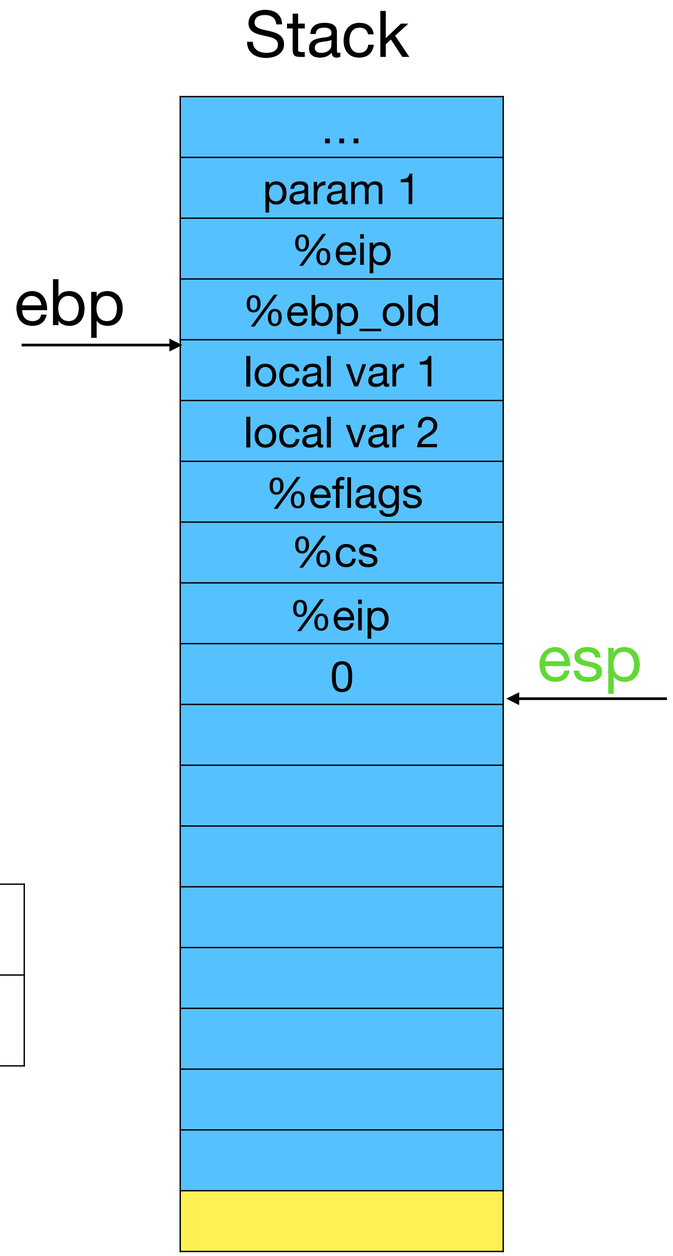

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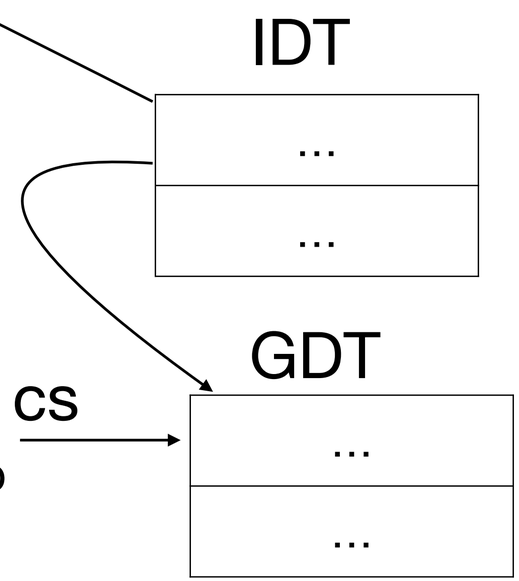

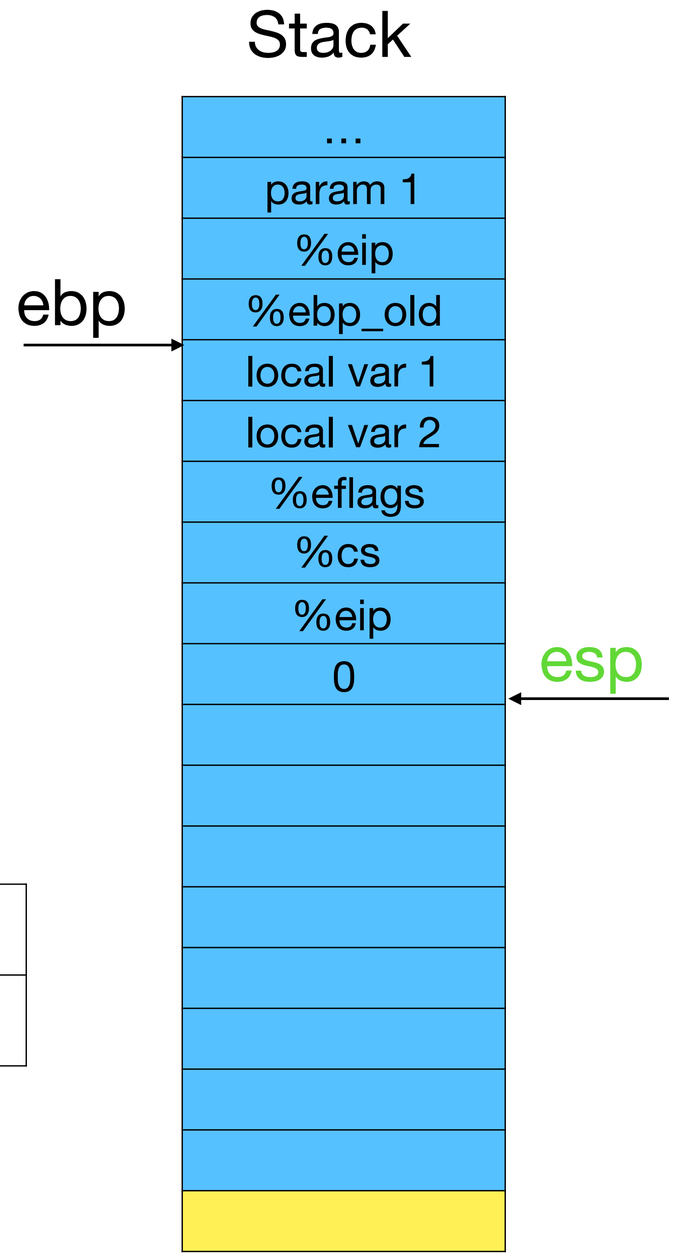

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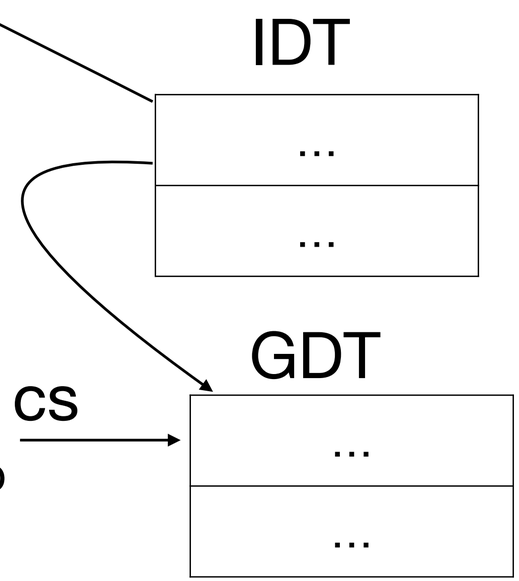

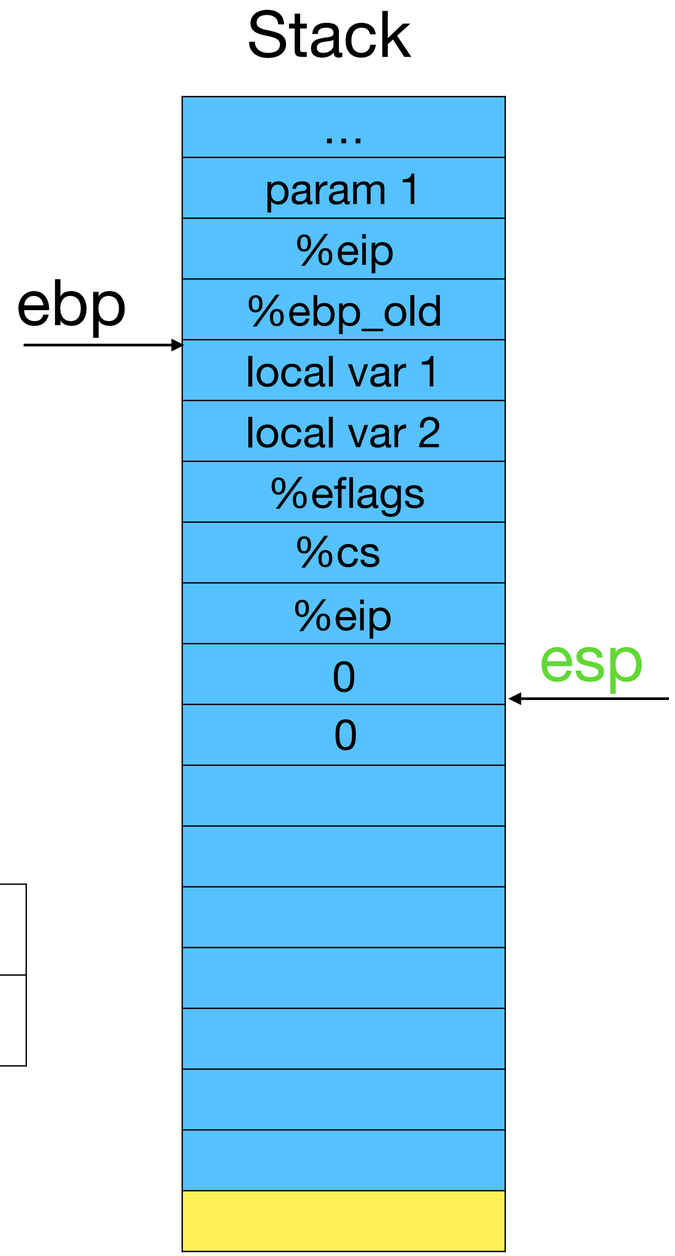

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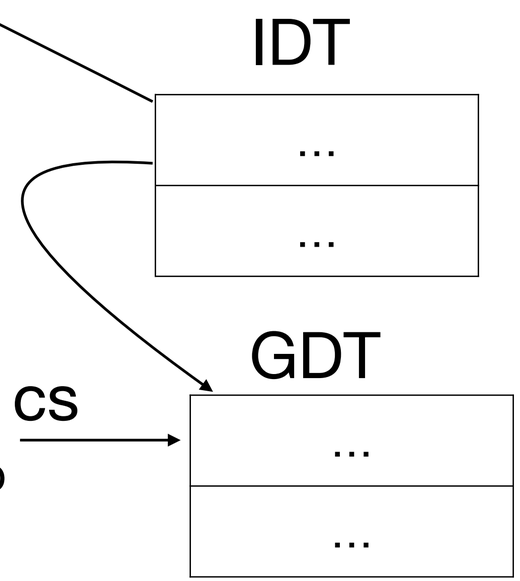

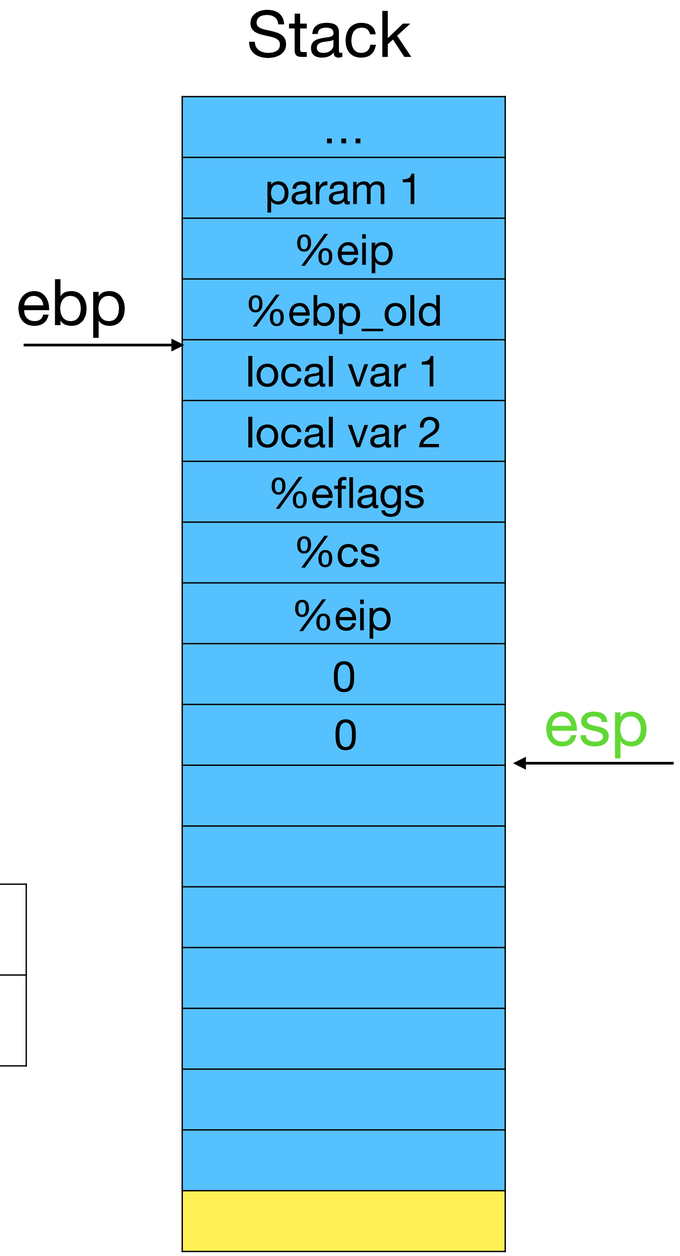

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IDT

...
...

GDT

...
...

CS

Stack

...
param 1
%eip
%ebp_old
local var 1
local var 2
%eflags
%cs
%eip
0
0

ebp

esp

Interrupt handling revisited

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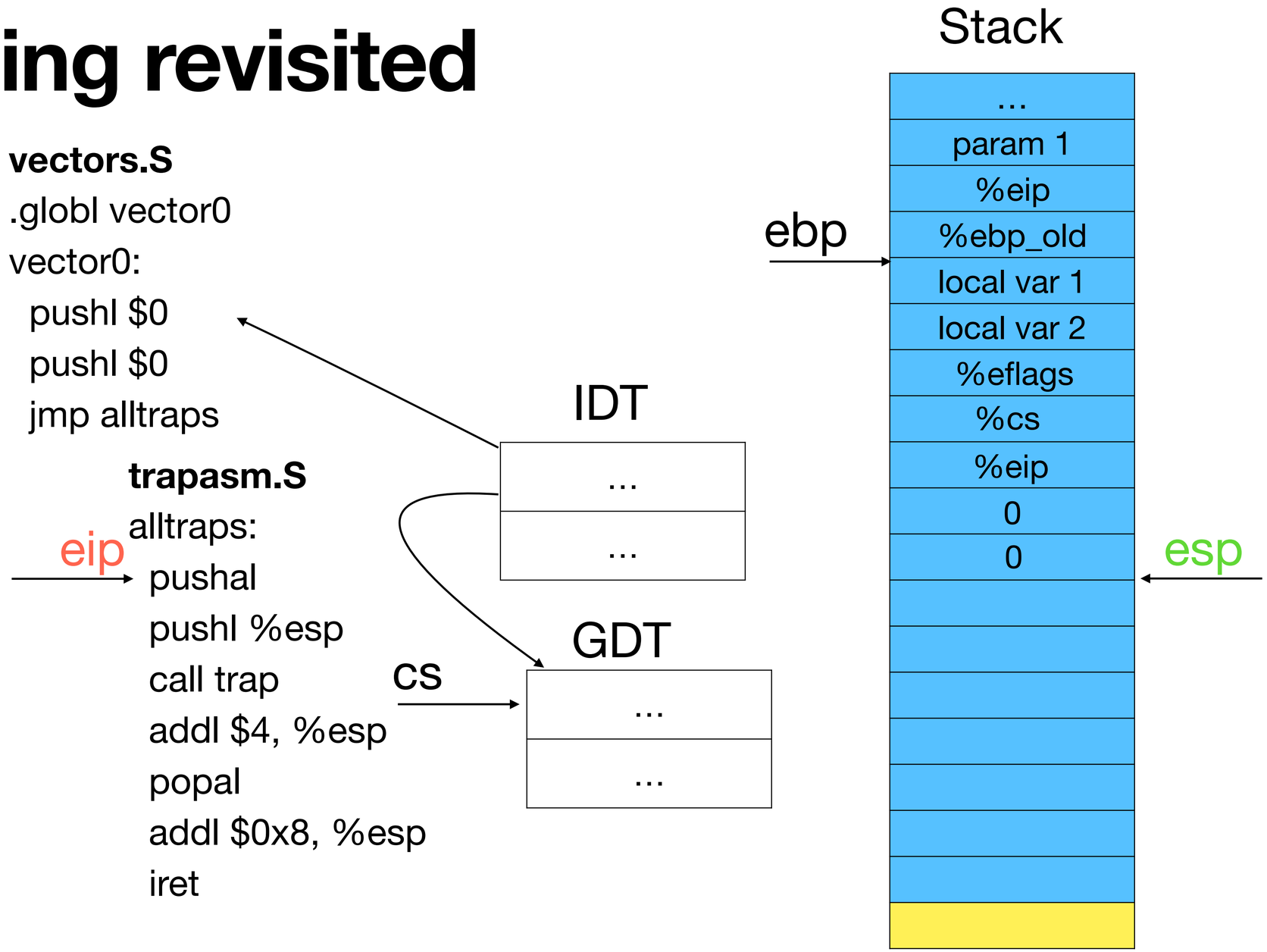

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  addl $4, %esp
  popal
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  iret
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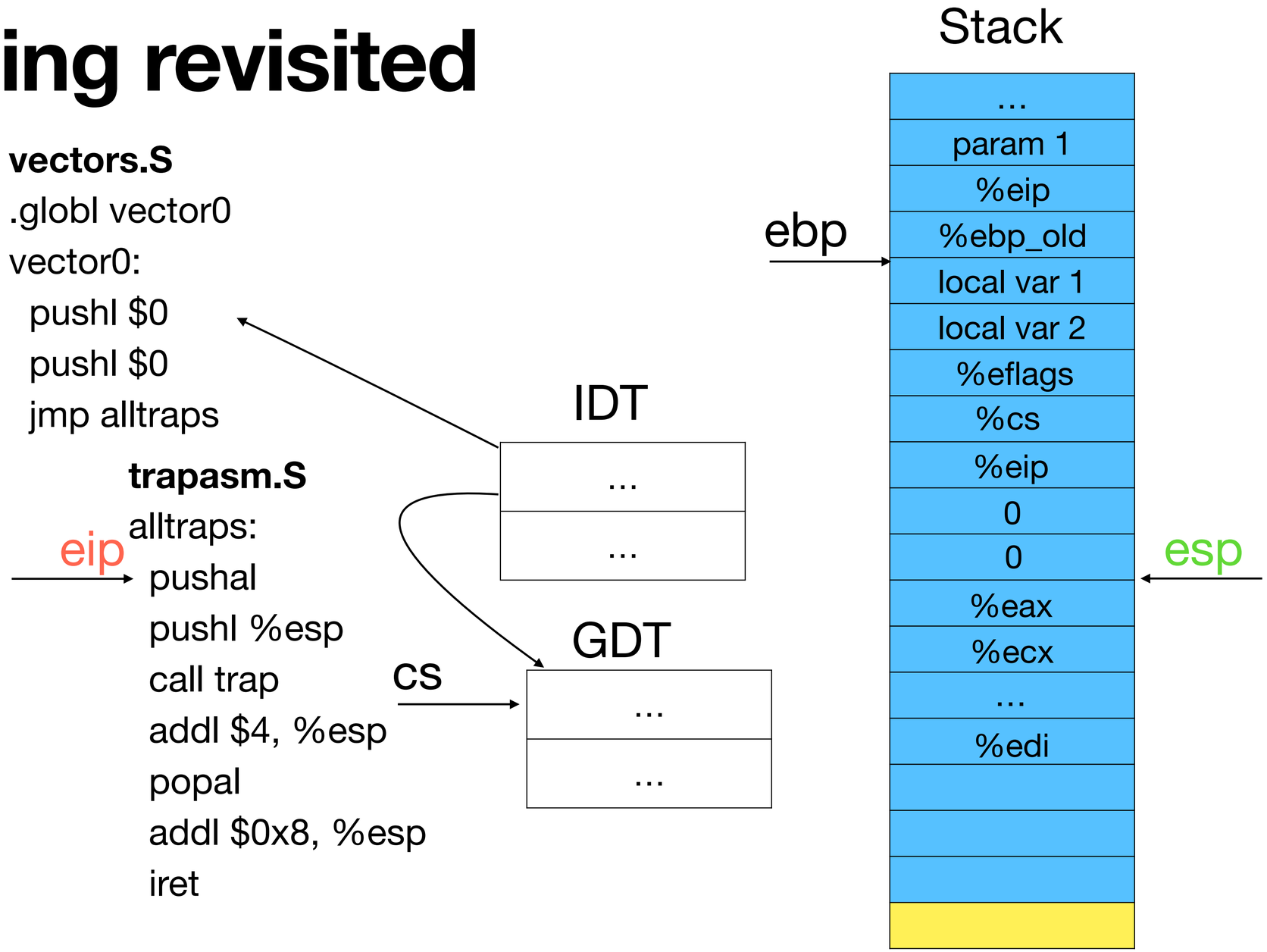

Interrupt handling revisited

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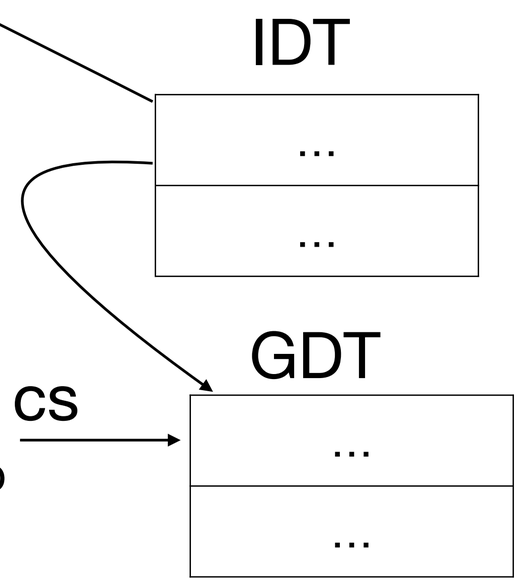

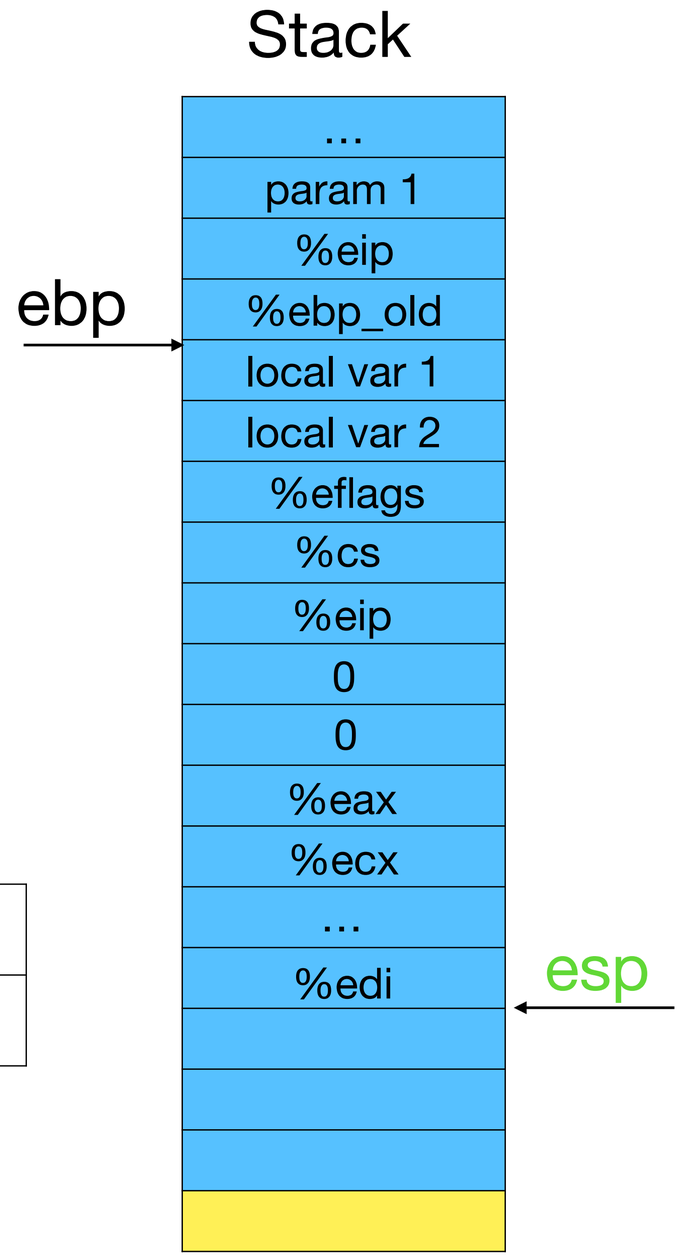

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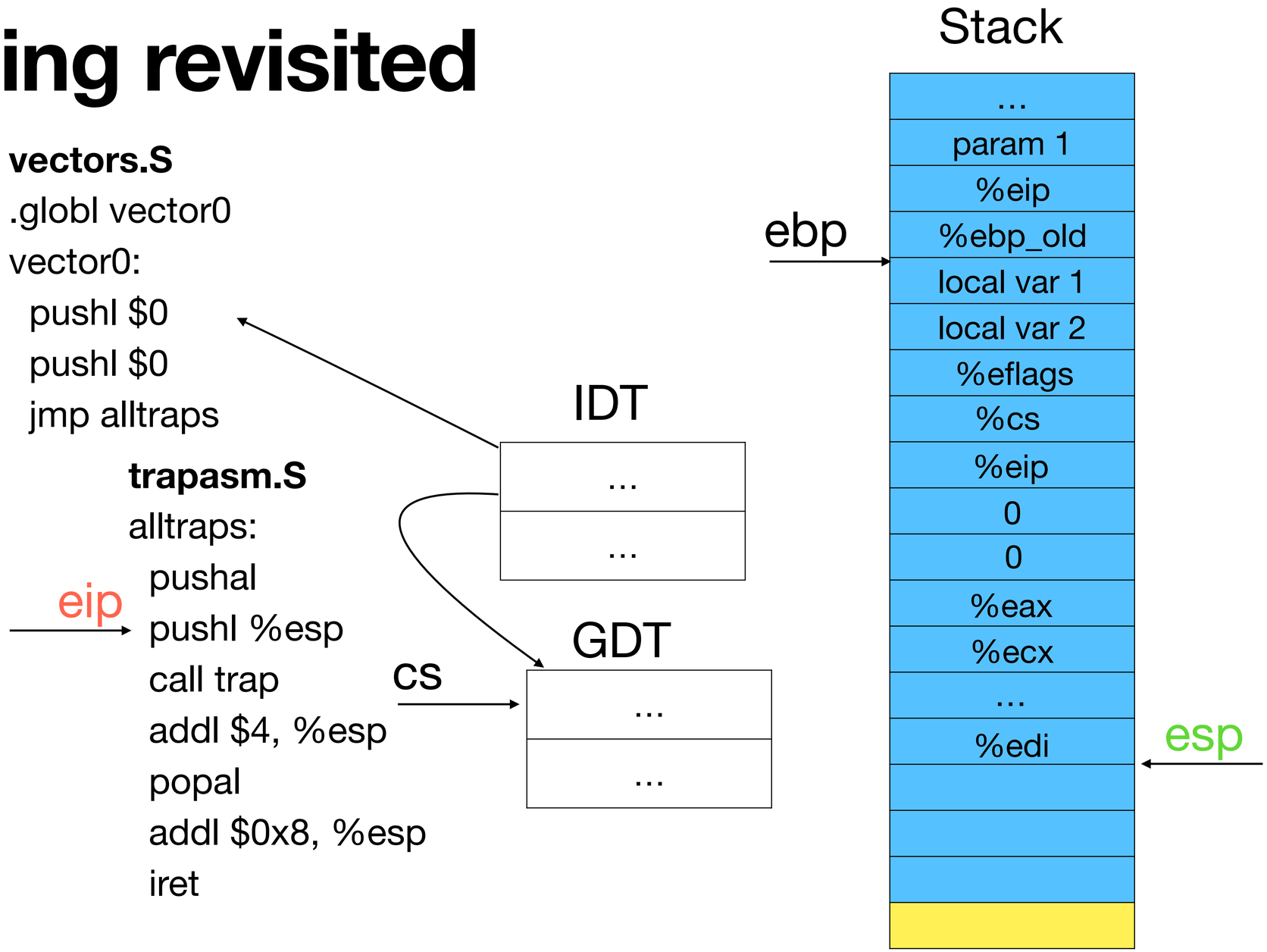

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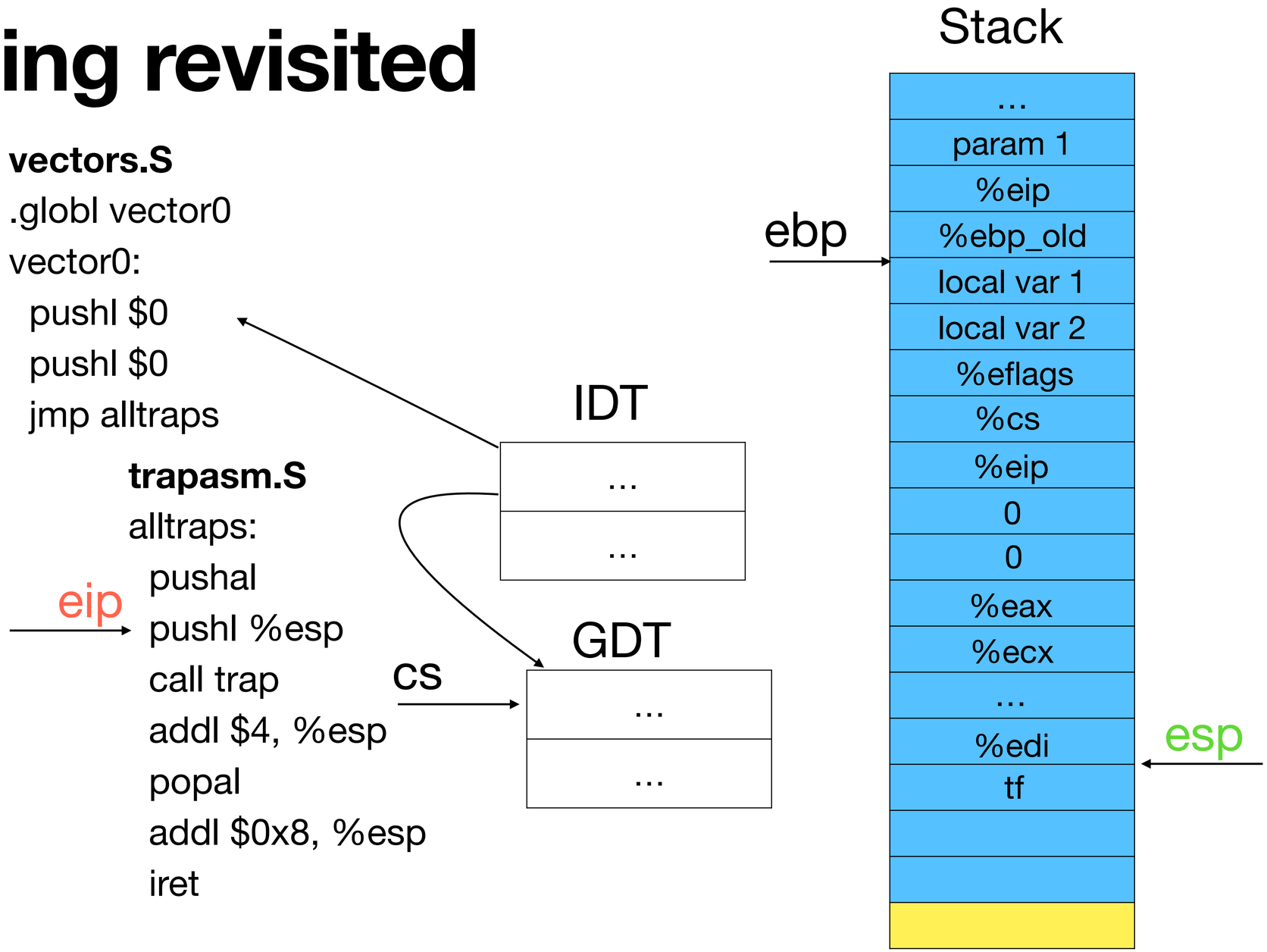

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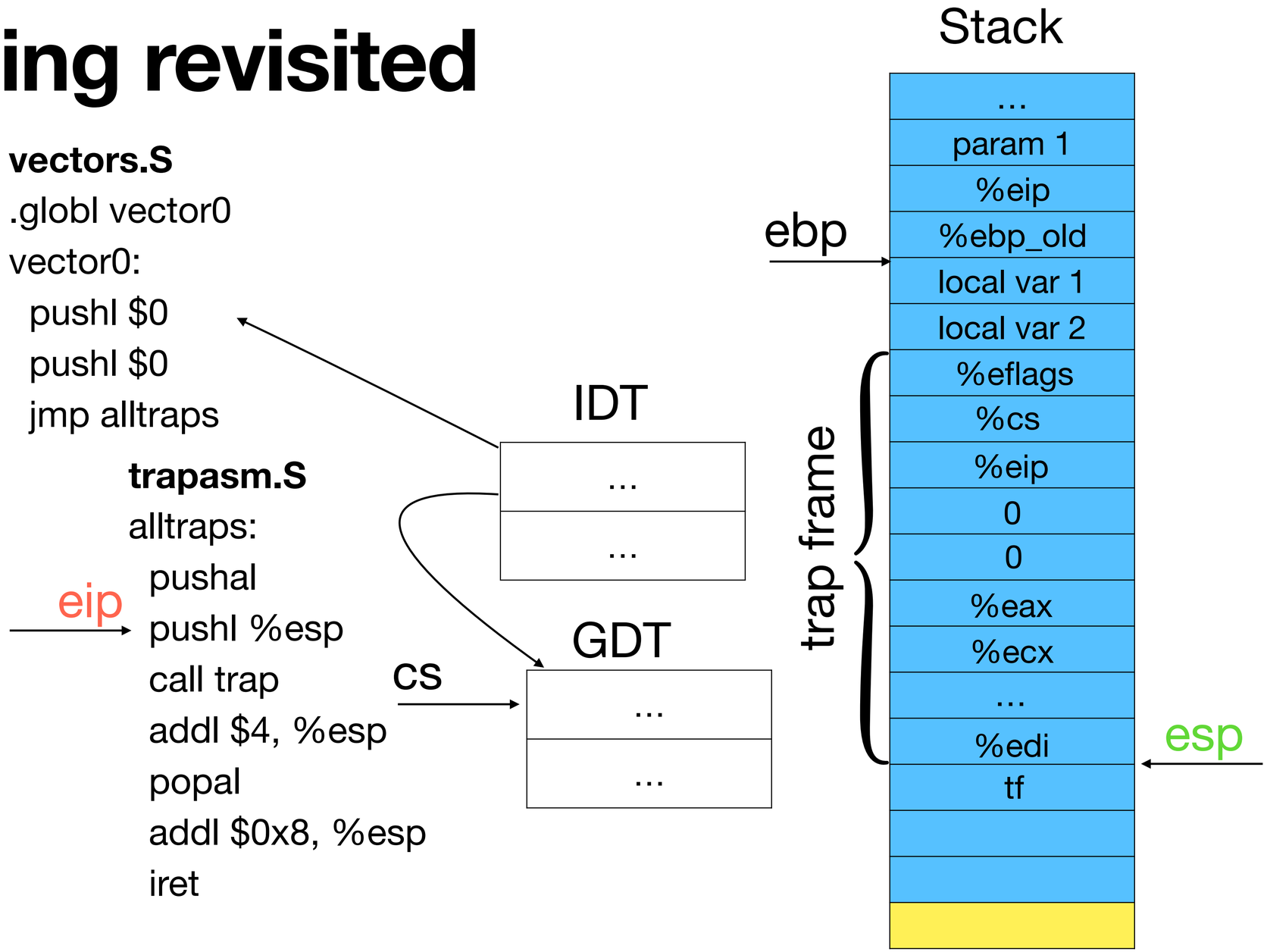

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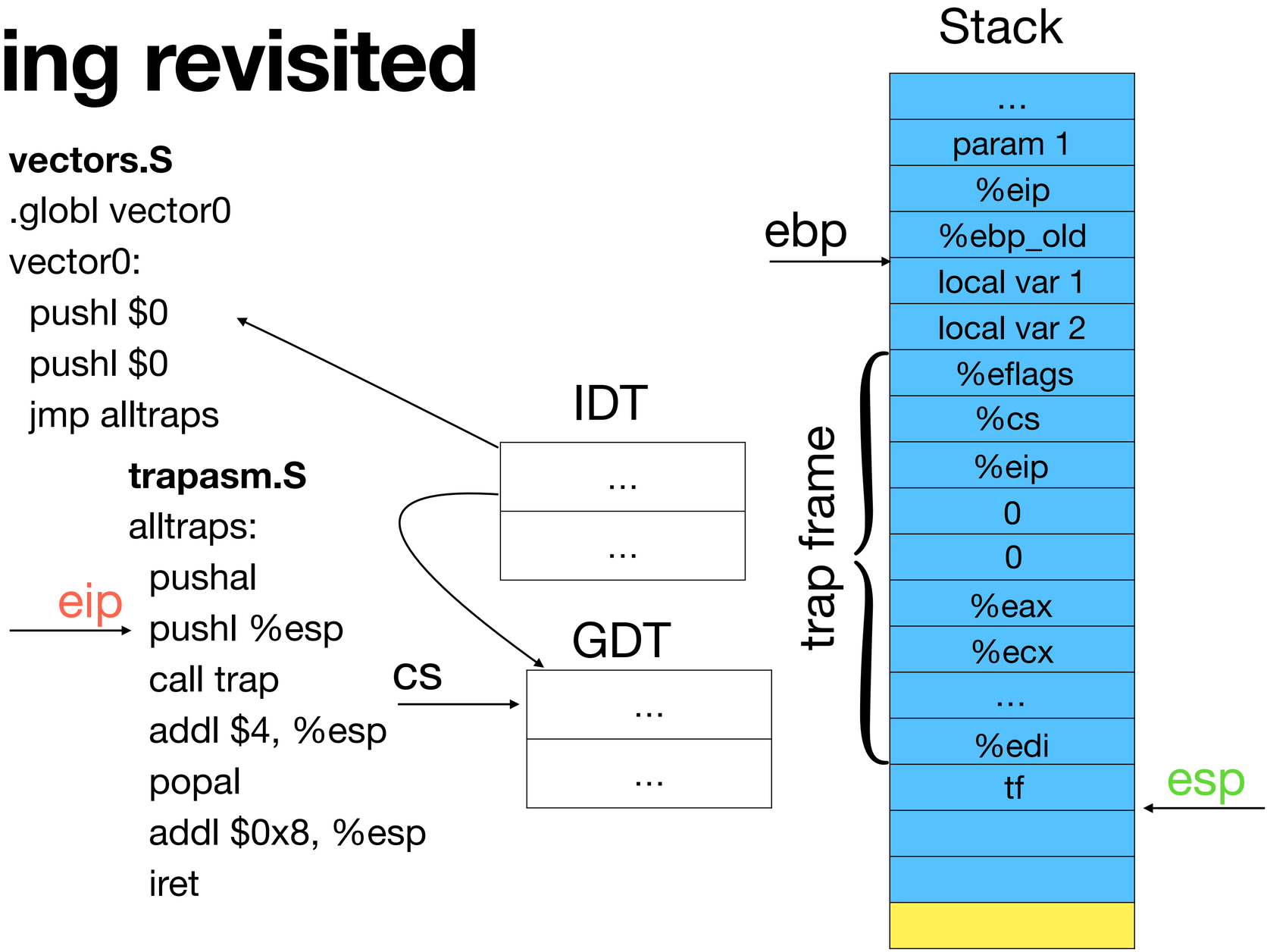

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eip

IDT

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CS

GDT

...
...

Stack

ebp

trap frame

esp

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

Interrupt handling revisited

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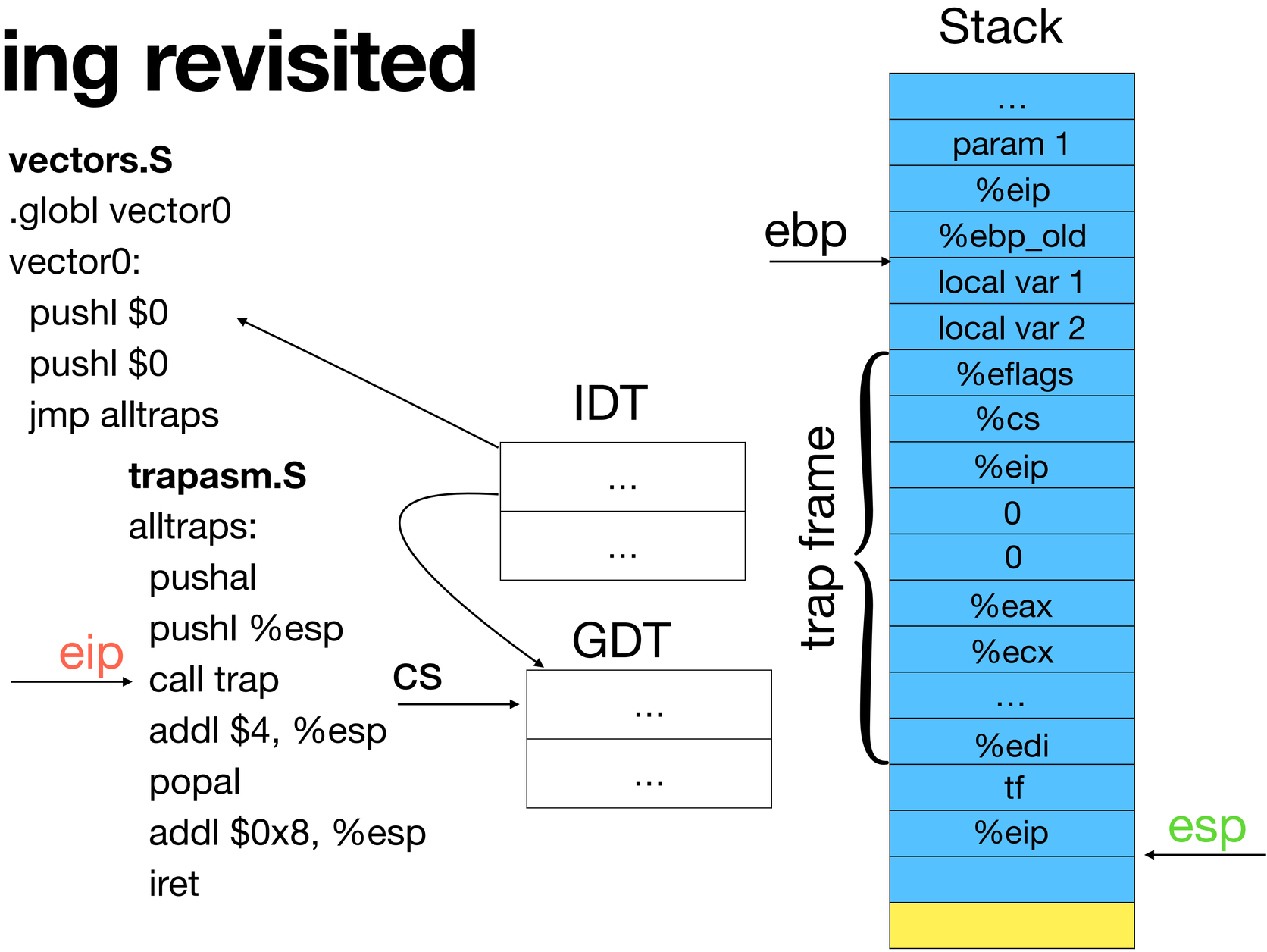

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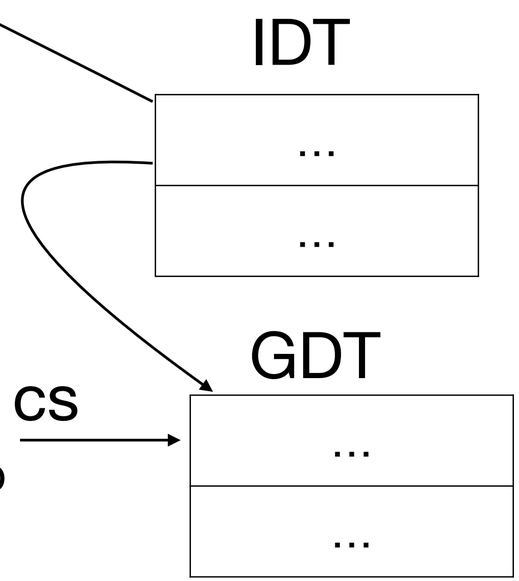

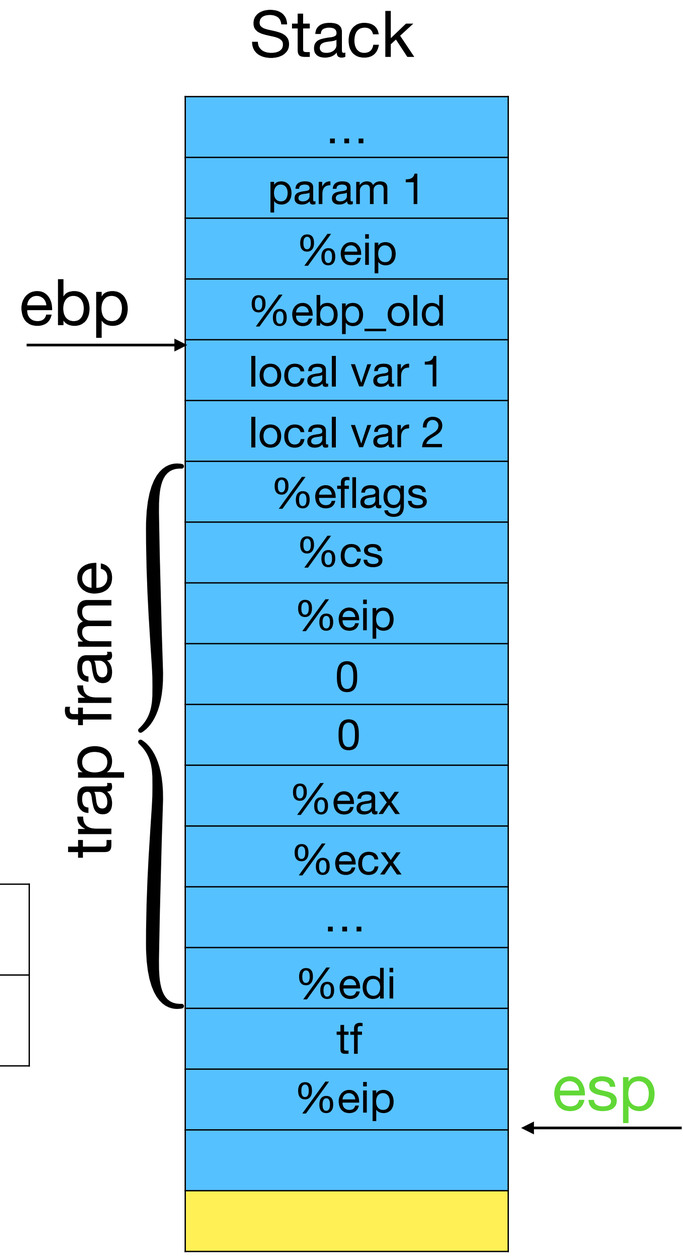

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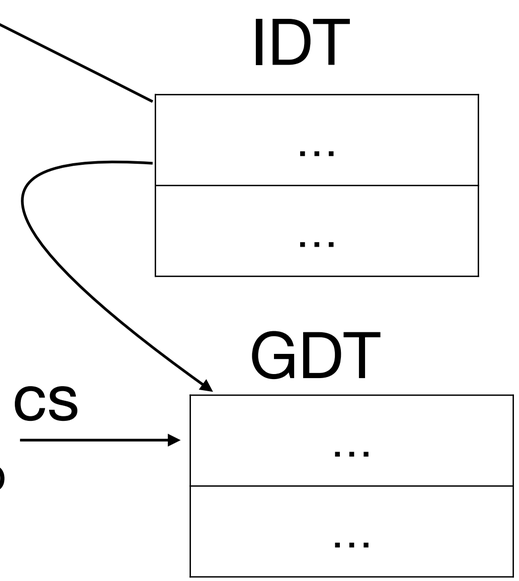

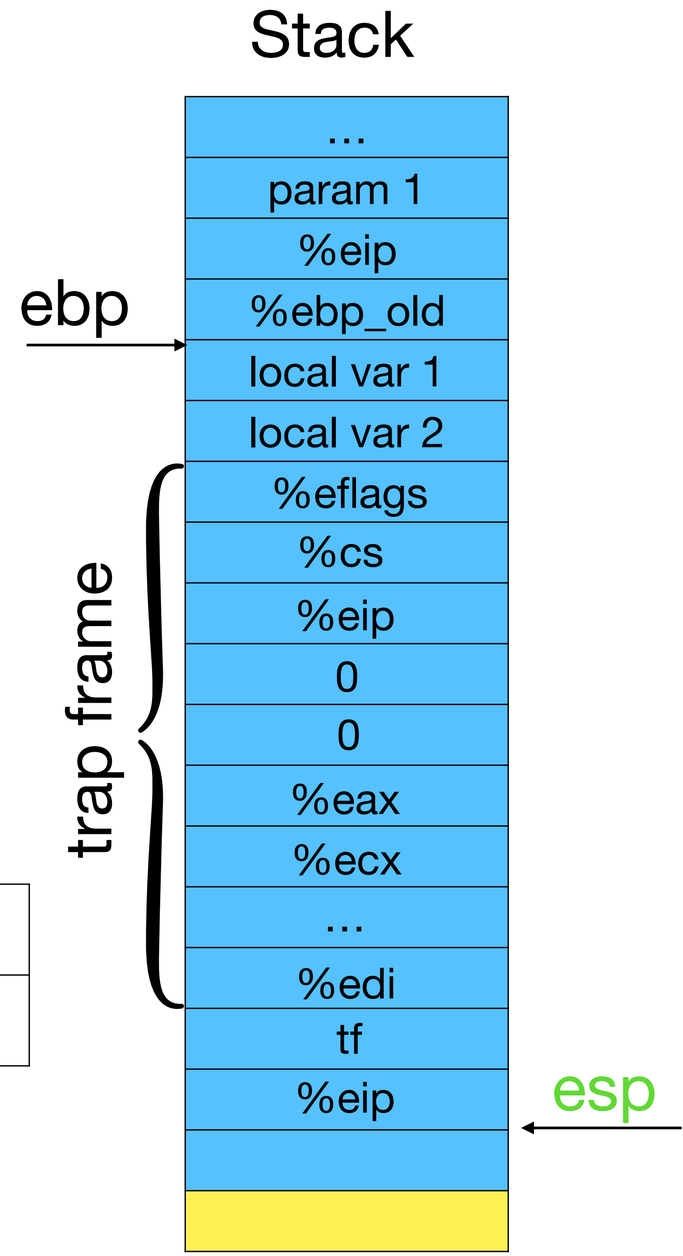

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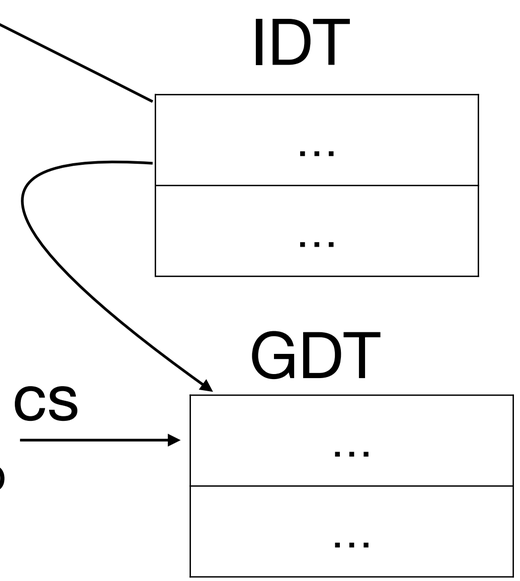

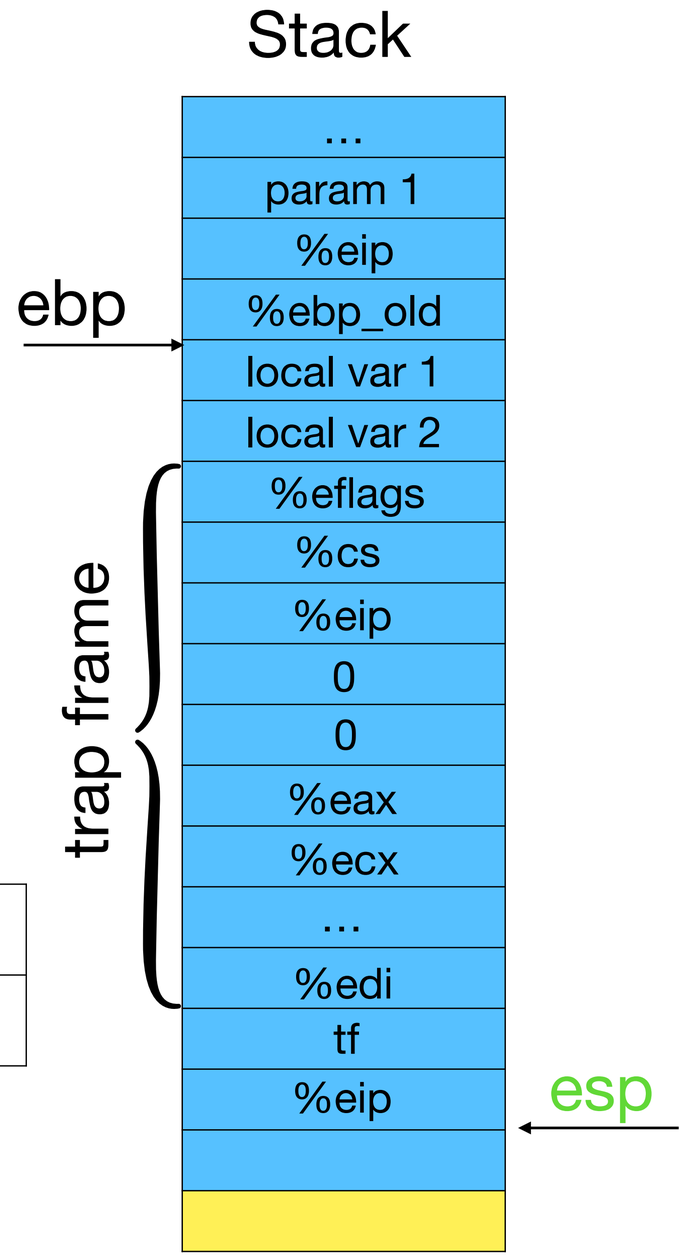

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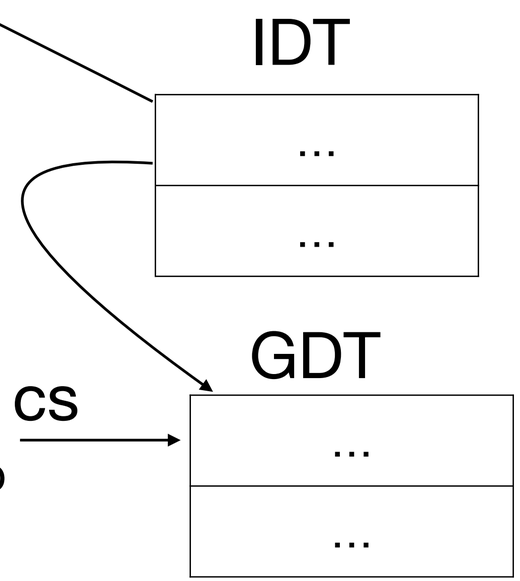

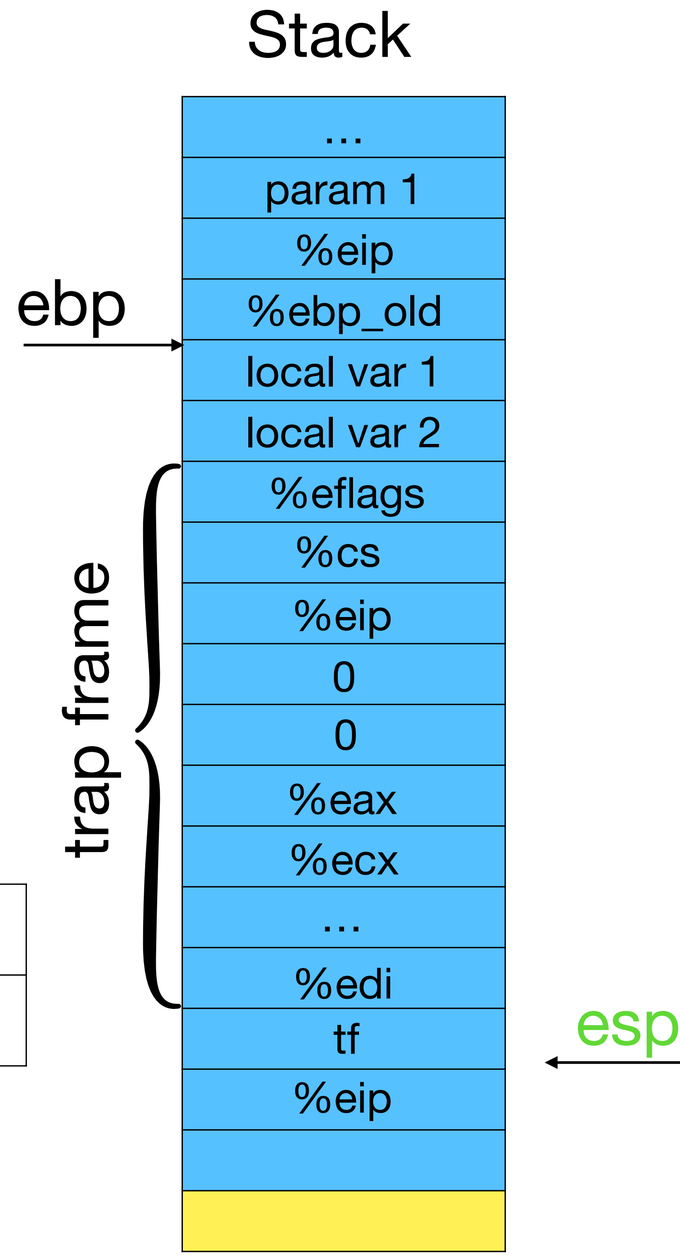

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esp

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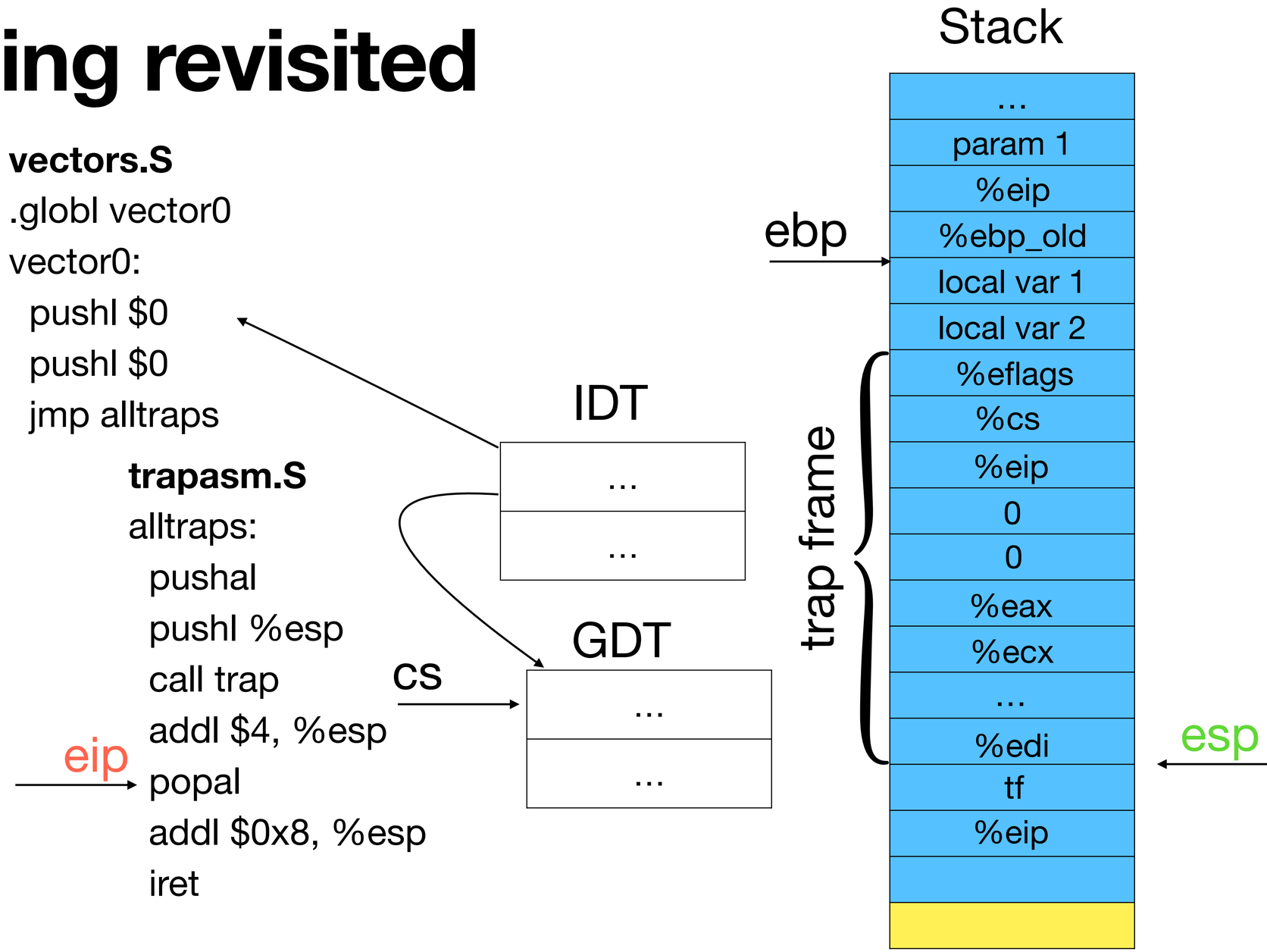

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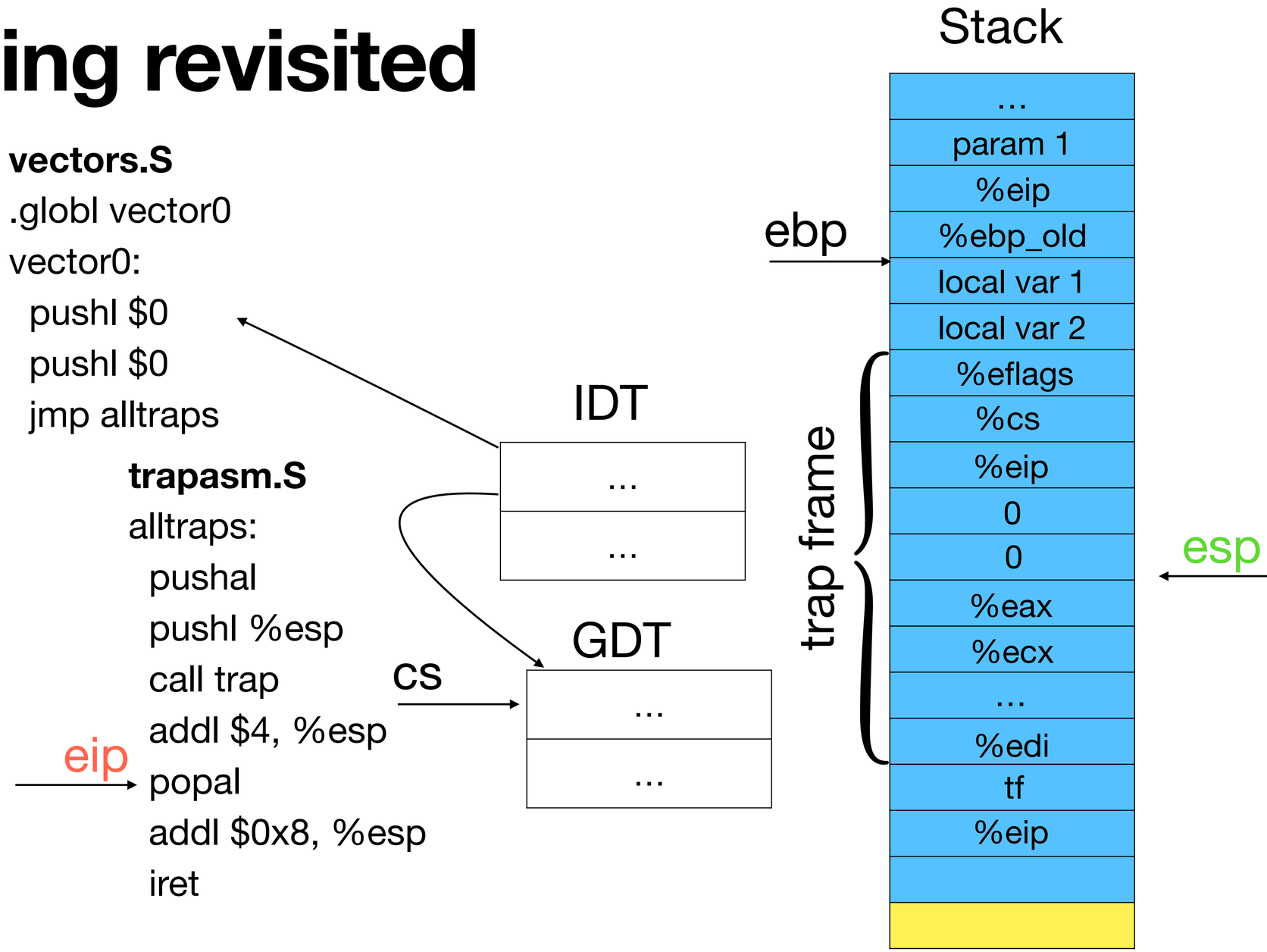

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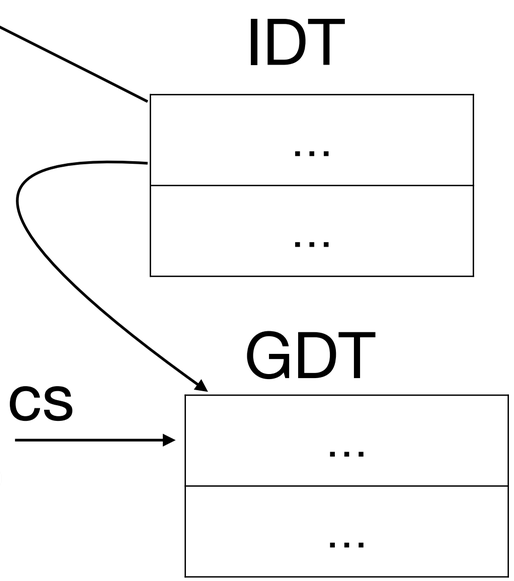

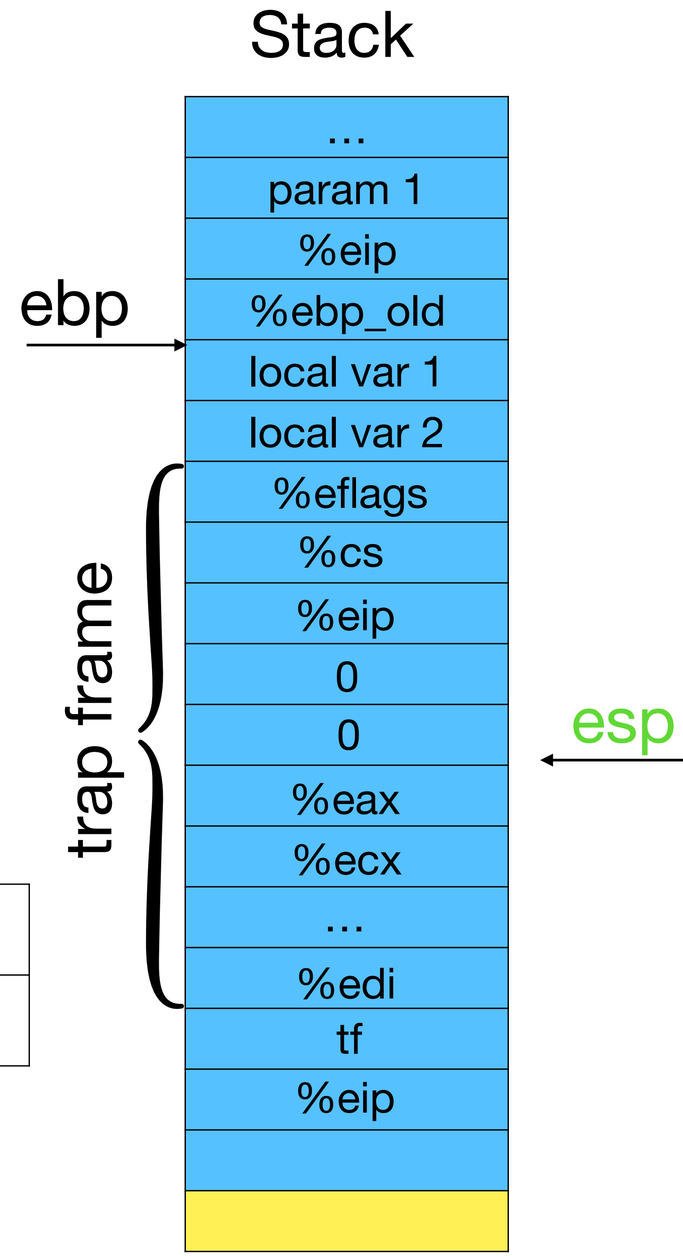

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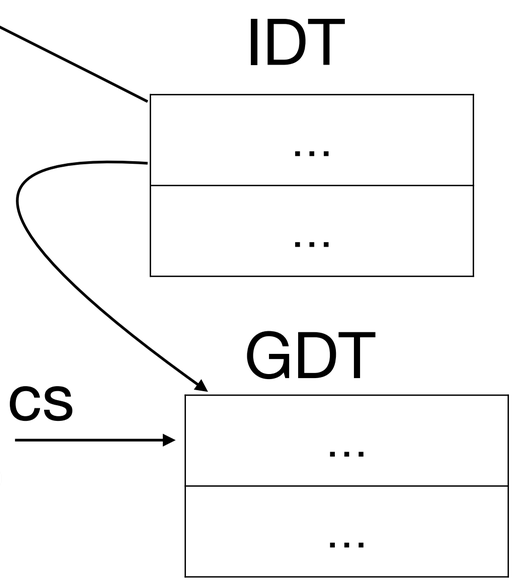

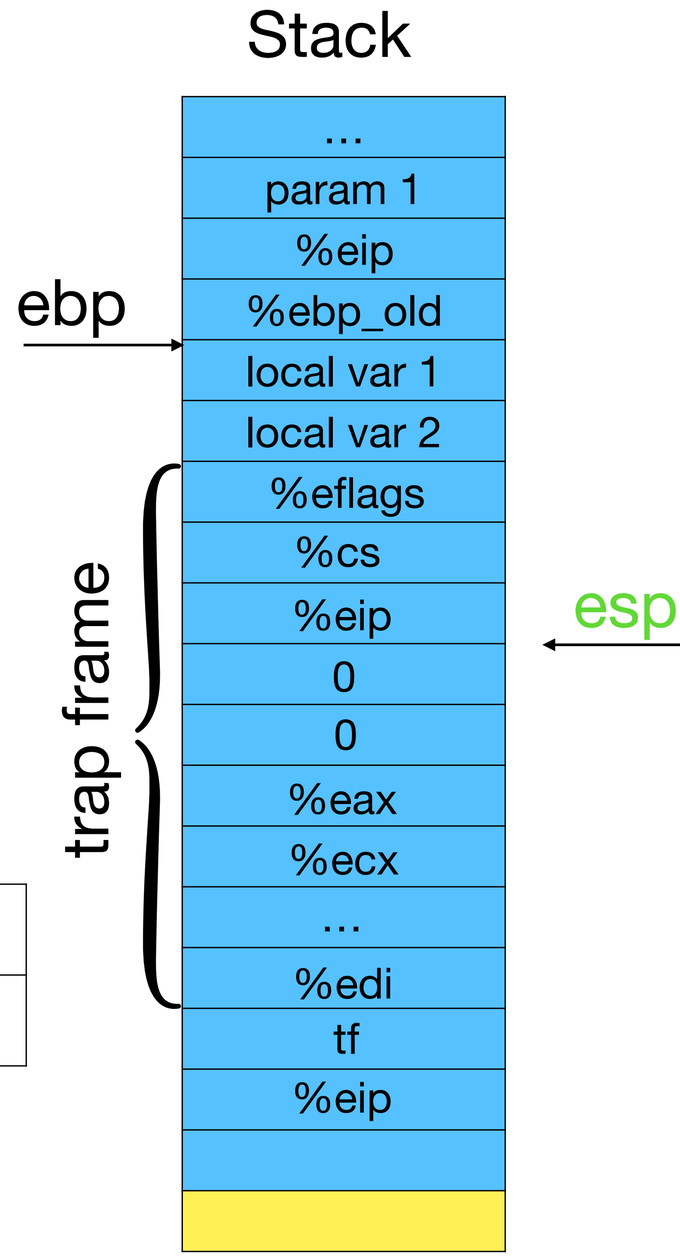

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trap frame

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  jmp alltraps
```

trapasm.S

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

eip

IDT

...
...

GDT

...
...

CS

Stack

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

ebp

esp

trap frame

Interrupt handling revisited

```
for(;;)
;
```

trap.c

```
void
trap(struct trapframe *tf)
{
  switch(tf->trapno){
  case T_IRQ0 + IRQ_TIMER:
    ticks++;
    cprintf("Tick! %d\n\0", ticks);
    lapiceoi();
..
return
```

vectors.S

```
.globl vector0
vector0:
  pushl $0
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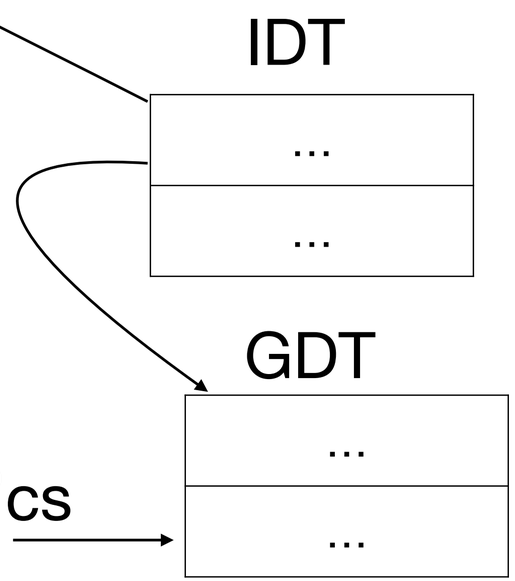

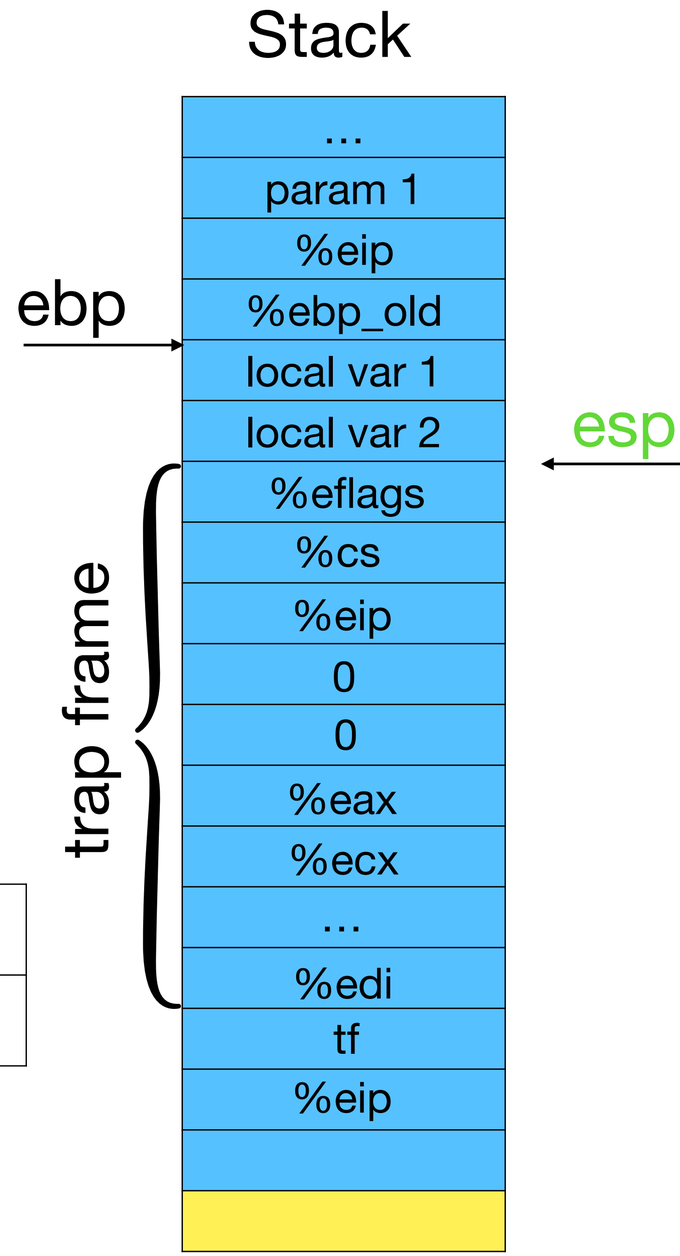

Interrupt handling revisited

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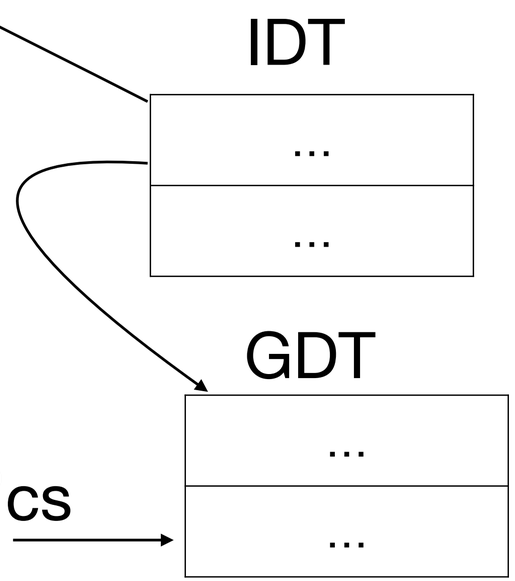
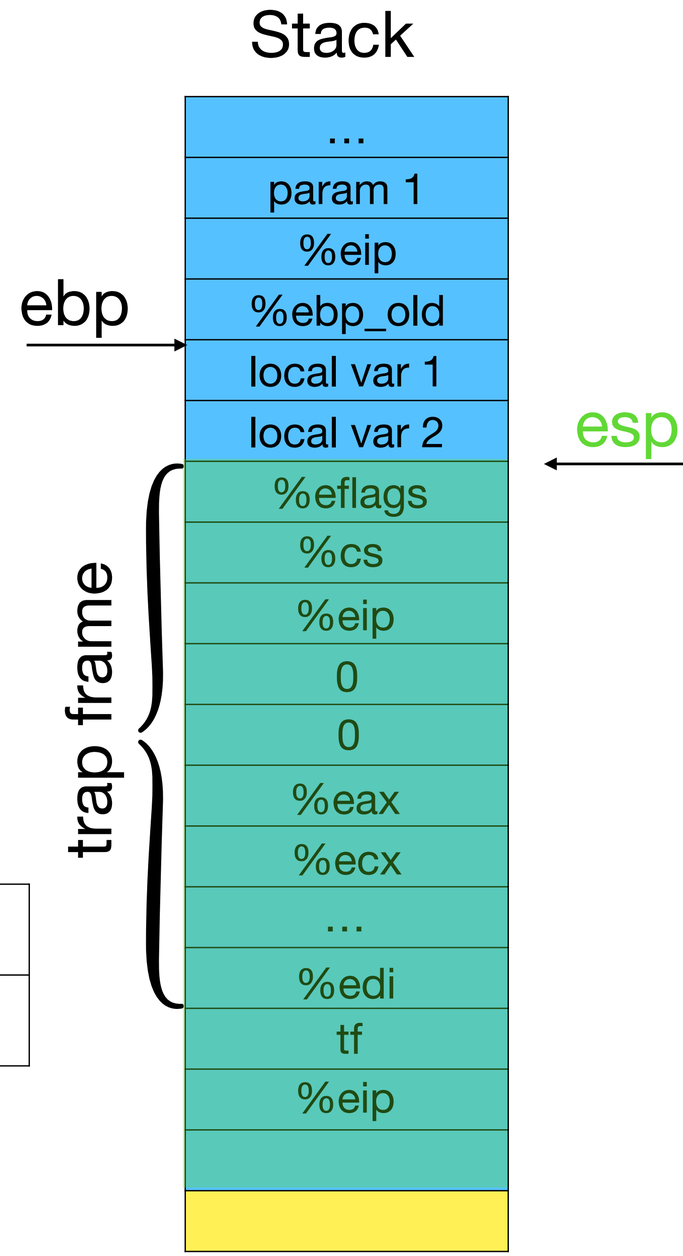
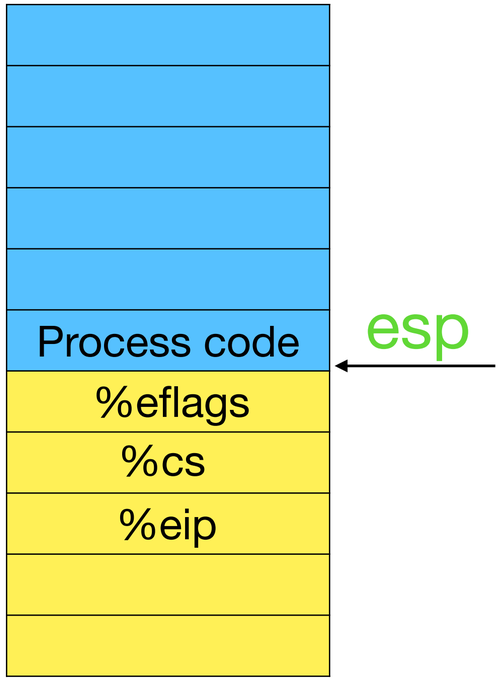




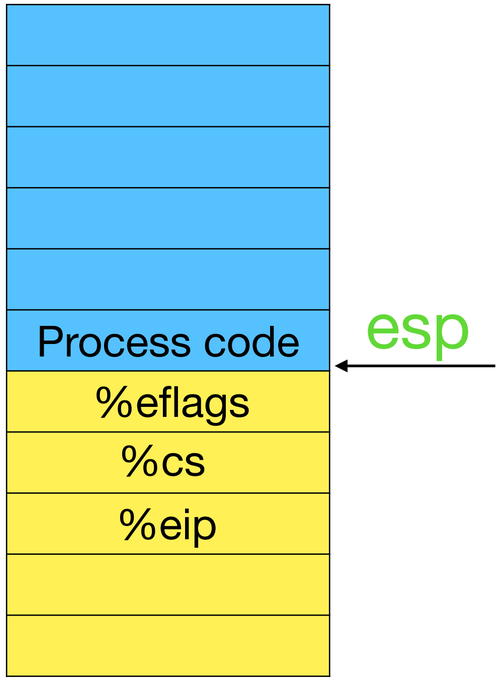
Interrupt handling problem

- We cannot trust %esp of the process. Hardware might write (%eflags, %cs, %eip) into another process' address space or into OS memory.



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!



Interrupt handling problem

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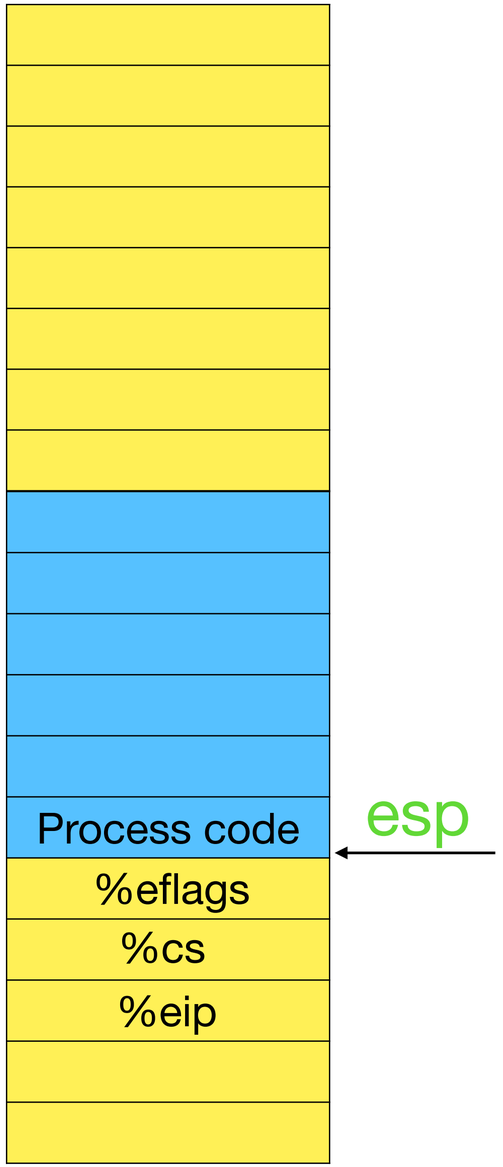

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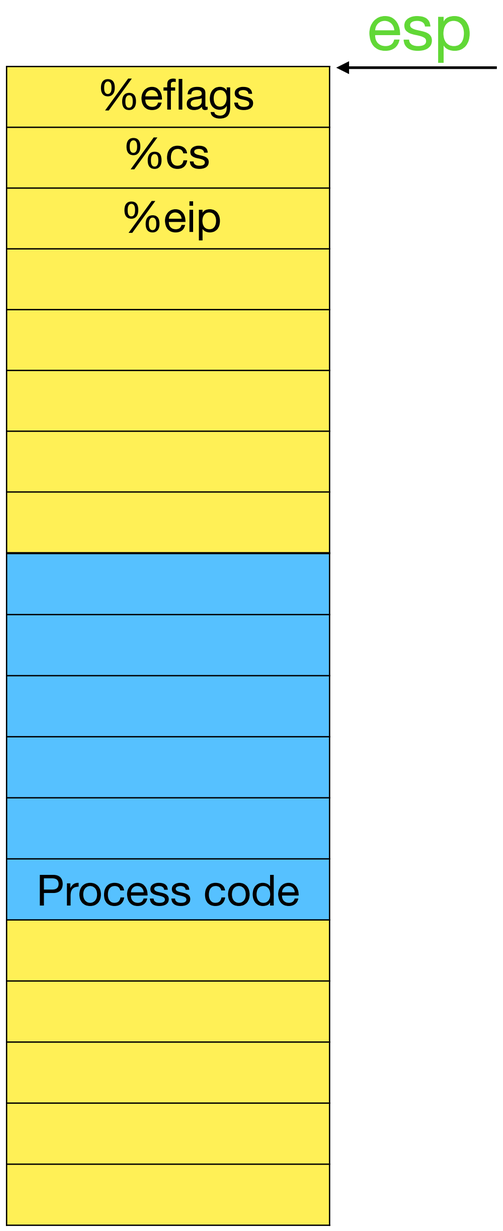


OS tells hardware where the kernel stack is

- 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

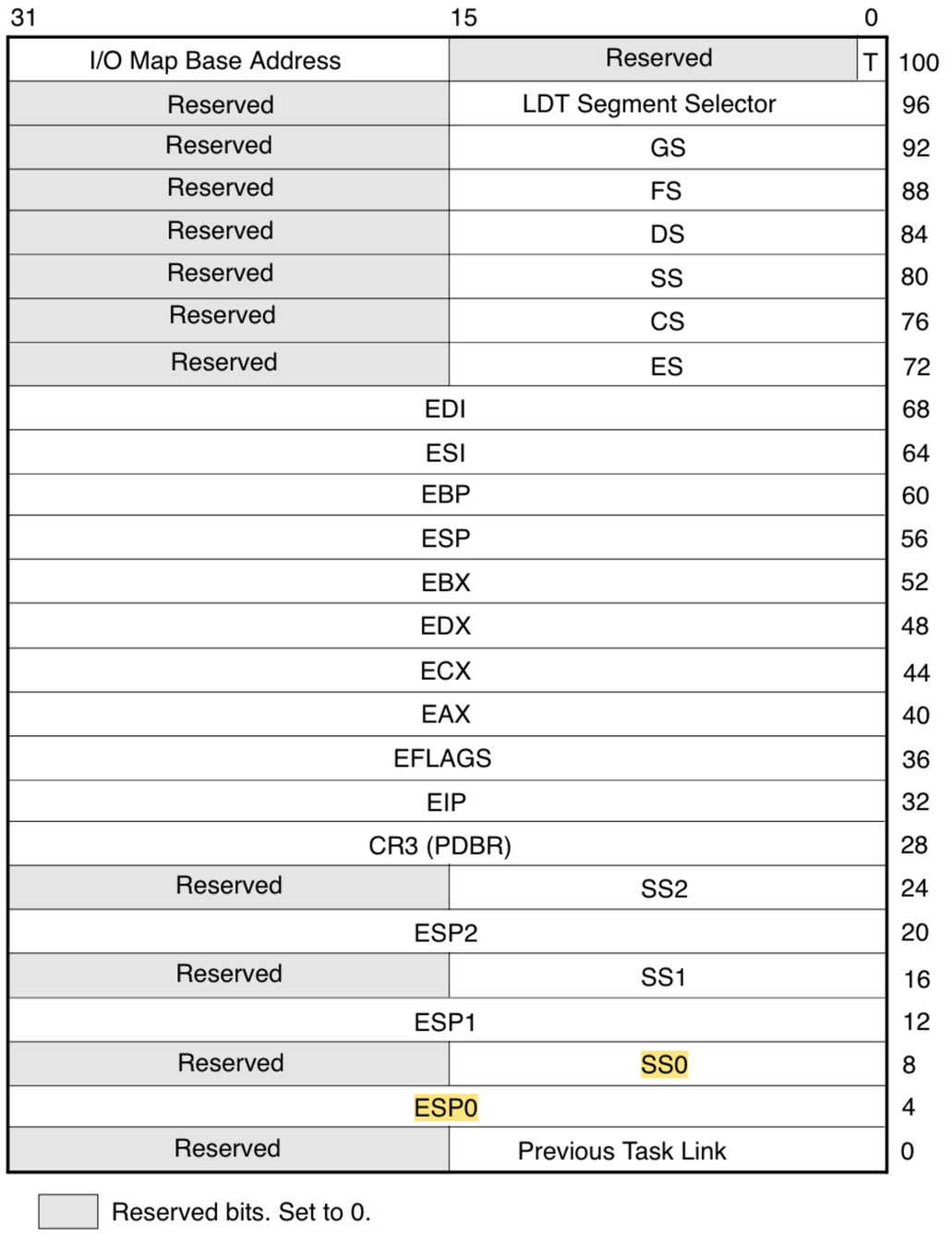
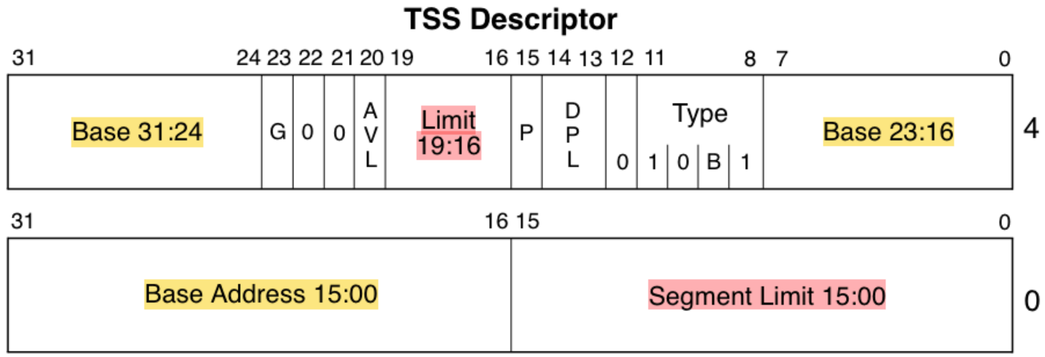


Figure 7-2. 32-Bit Task-State Segment (TSS)

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

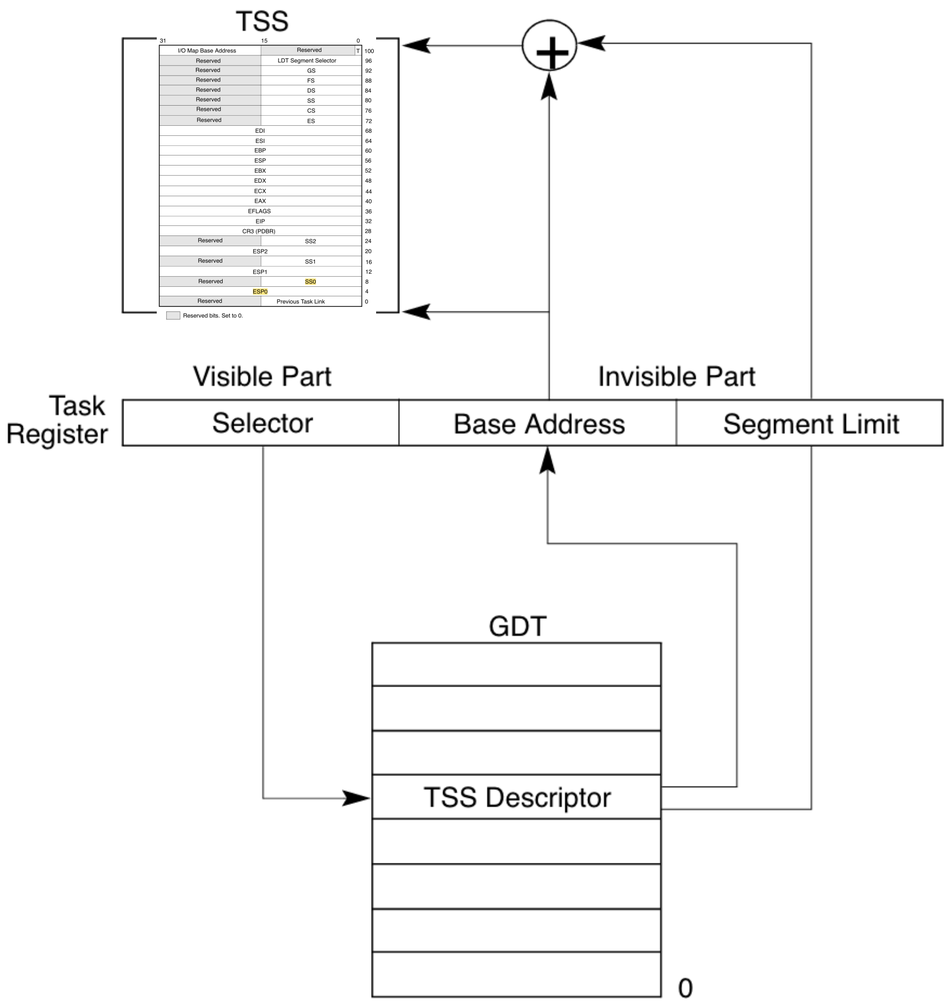
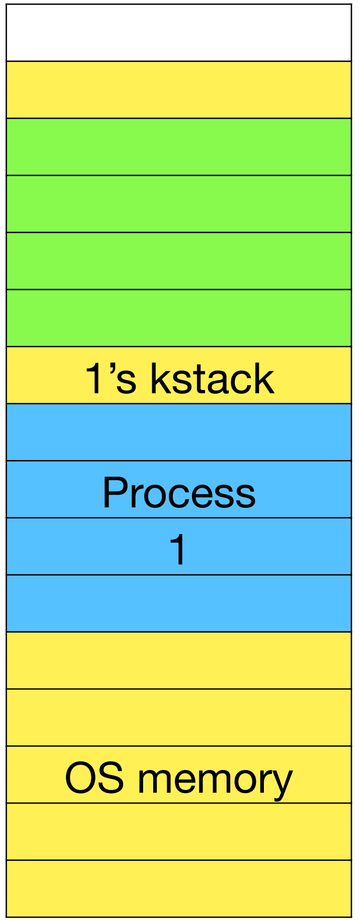


Figure 7-5. Task Register

Code walkthrough: setting up kernel stack

p16-tss

```
void seginit(void) {
  c->gdt[SEG_UCODE] = SEG(.., STARTPROC, (PROCSIZE-1) << 12, DPL_USER);
  c->gdt[SEG_UDATA] = SEG(.., STARTPROC, (PROCSIZE-1) << 12, DPL_USER);
}
```



Code walkthrough: setting up kernel stack

p16-tss

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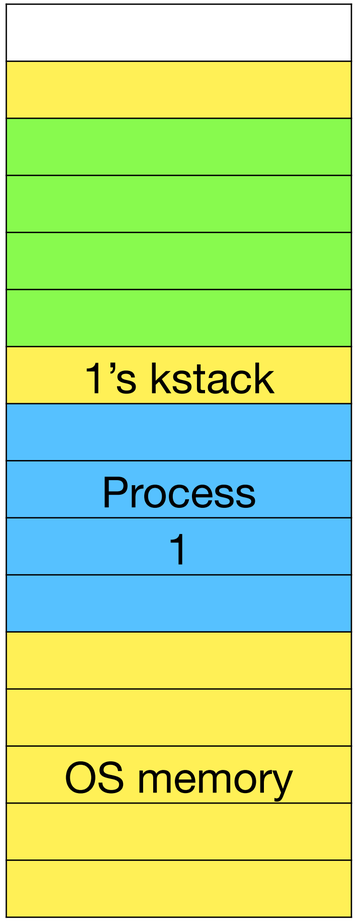
  c->gdt[SEG_UDATA] = SEG(.., STARTPROC, (PROCSIZE-1) << 12, DPL_USER);
}

static struct proc* allocproc(void) {
  sp = (char*)(STARTPROC + (PROCSIZE>>12));
  p->kstack = sp - KSTACKSIZE;
}
```



Code walkthrough: setting up kernel stack

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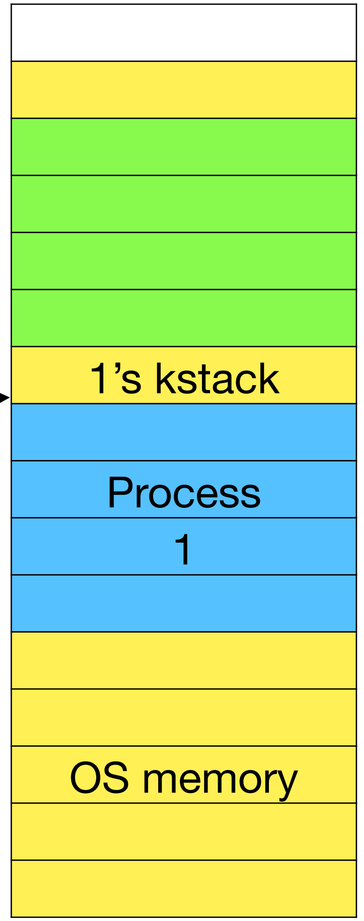

Code walkthrough: setting up kernel stack

p16-tss

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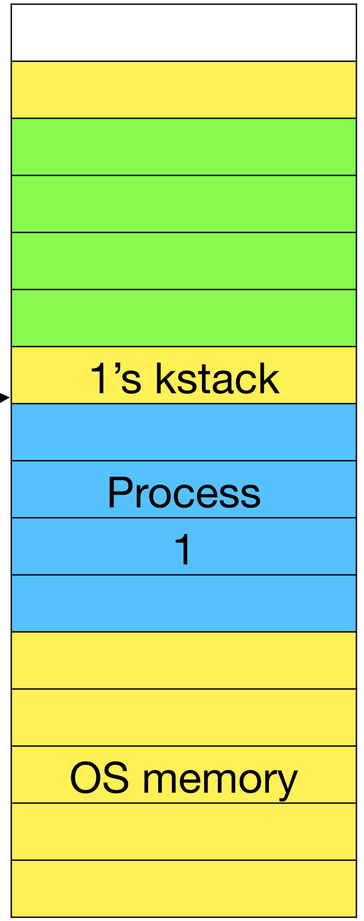
static struct proc* allocproc(void) {
  sp = (char*)(STARTPROC + (PROCSIZE>>12));
  p->kstack = sp - KSTACKSIZE;
}
```

```
void scheduler(void) {
 // pick RUNNABLE process p
 switchuvm(p);
 swtch(p->context);
}
```



Code walkthrough: setting up kernel stack

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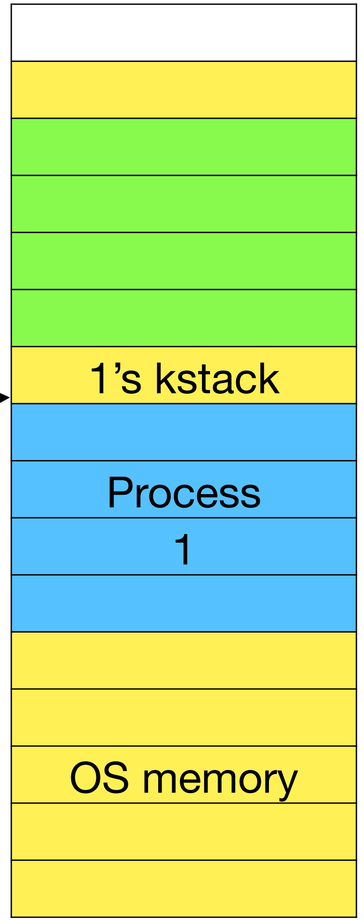
}

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);
}
```

```
void scheduler(void) {
  // pick RUNNABLE process p
  switchuvm(p);
  swtch(p->context);
}
```



Code walkthrough: setting up kernel stack

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  mycpu()->ts.ss0 = SEG_KDATA << 3;
  mycpu()->ts.esp0 = (uint)p->kstack + KSTACKSIZE;
  ltr(SEG_TSS << 3);
}
```

```
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  // pick RUNNABLE process p
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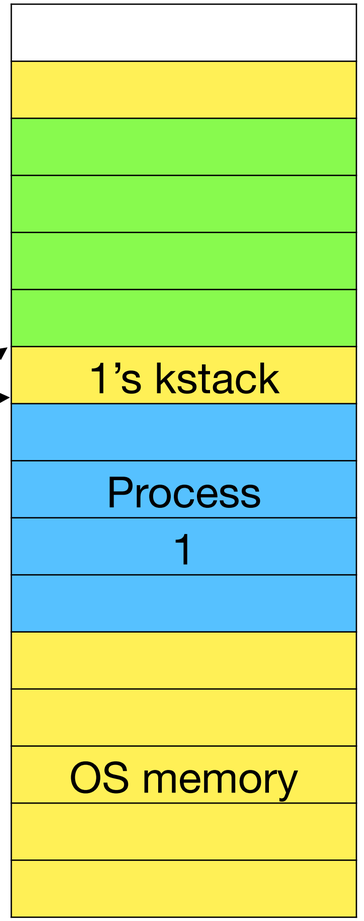
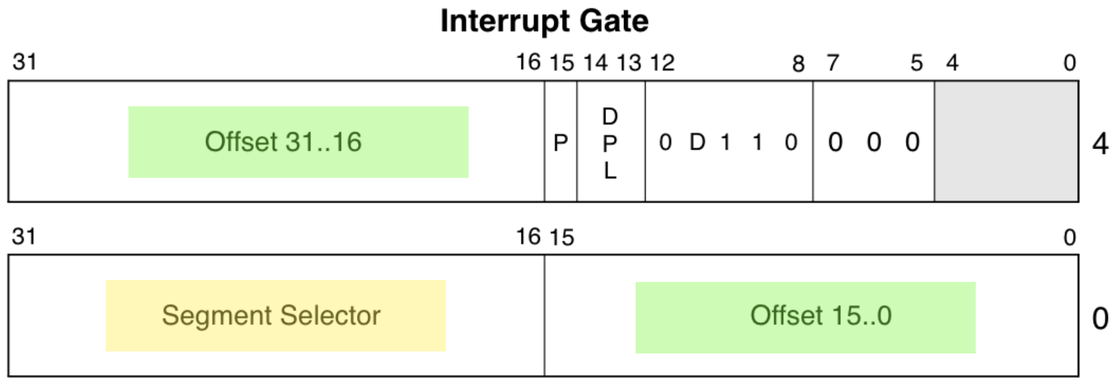
  swtch(p->context);
}
```



Interrupt handling



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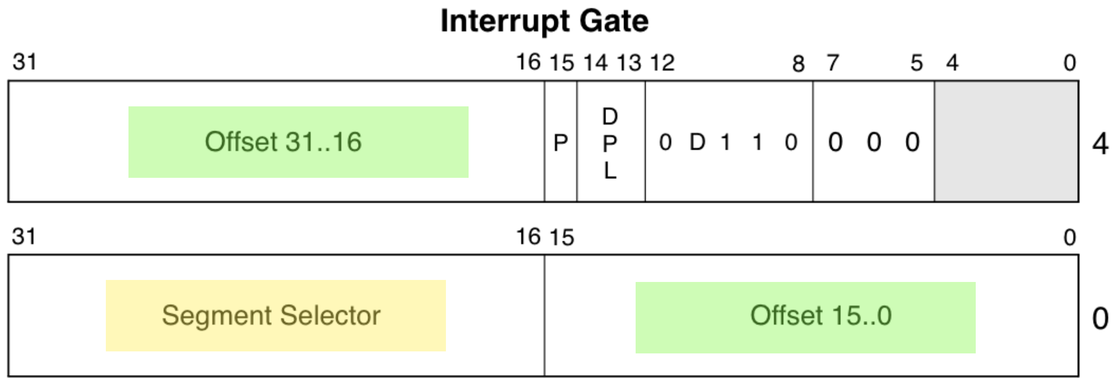
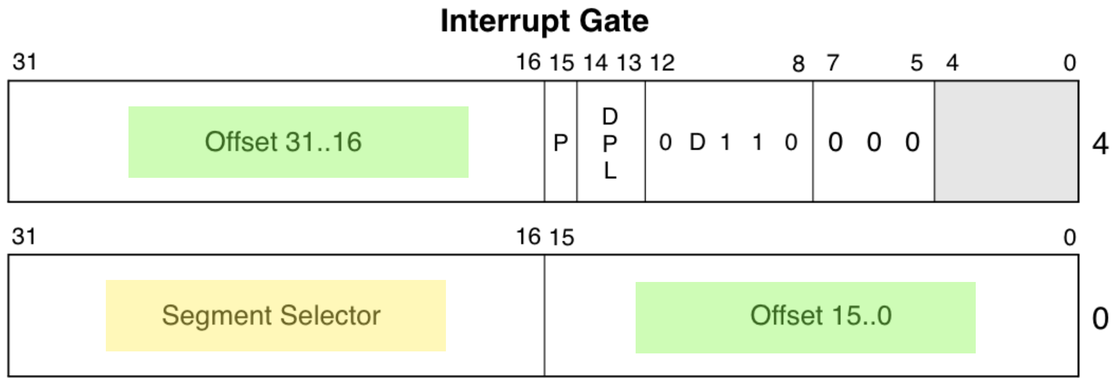


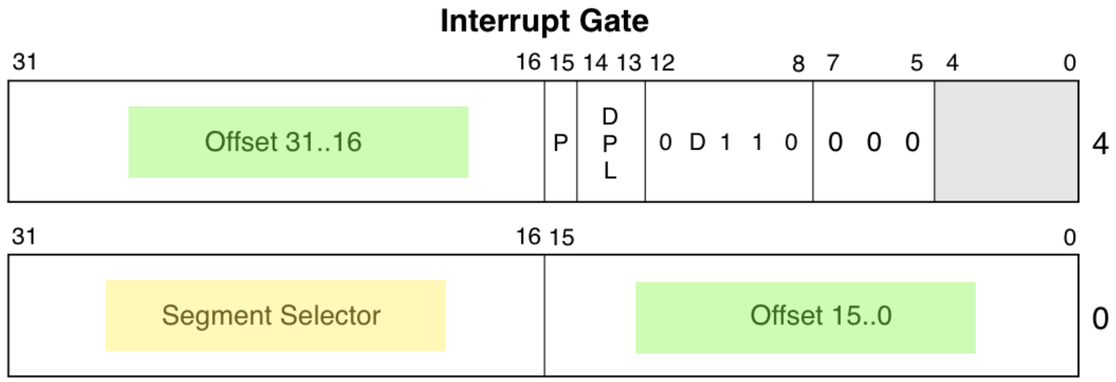
- Each IDT entry is 64-bits. Contains code segment and eip

Interrupt handling



- Each IDT entry is 64-bits. Contains code segment and eip
- When interrupt appears,

Interrupt handling



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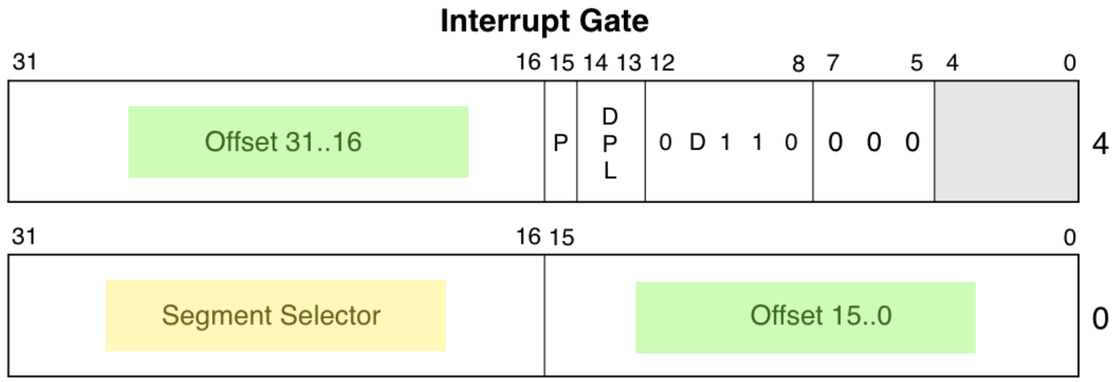
- When interrupt appears,
  - Hardware changes SS and ESP according to the TSS

Interrupt handling



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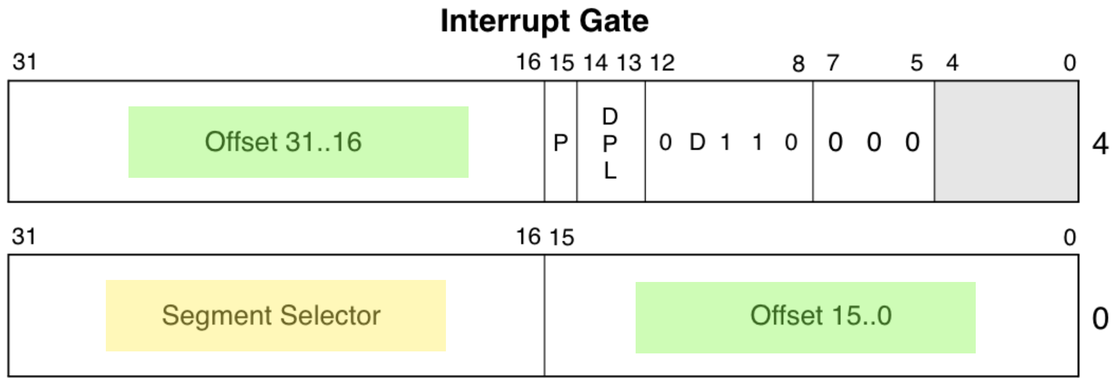

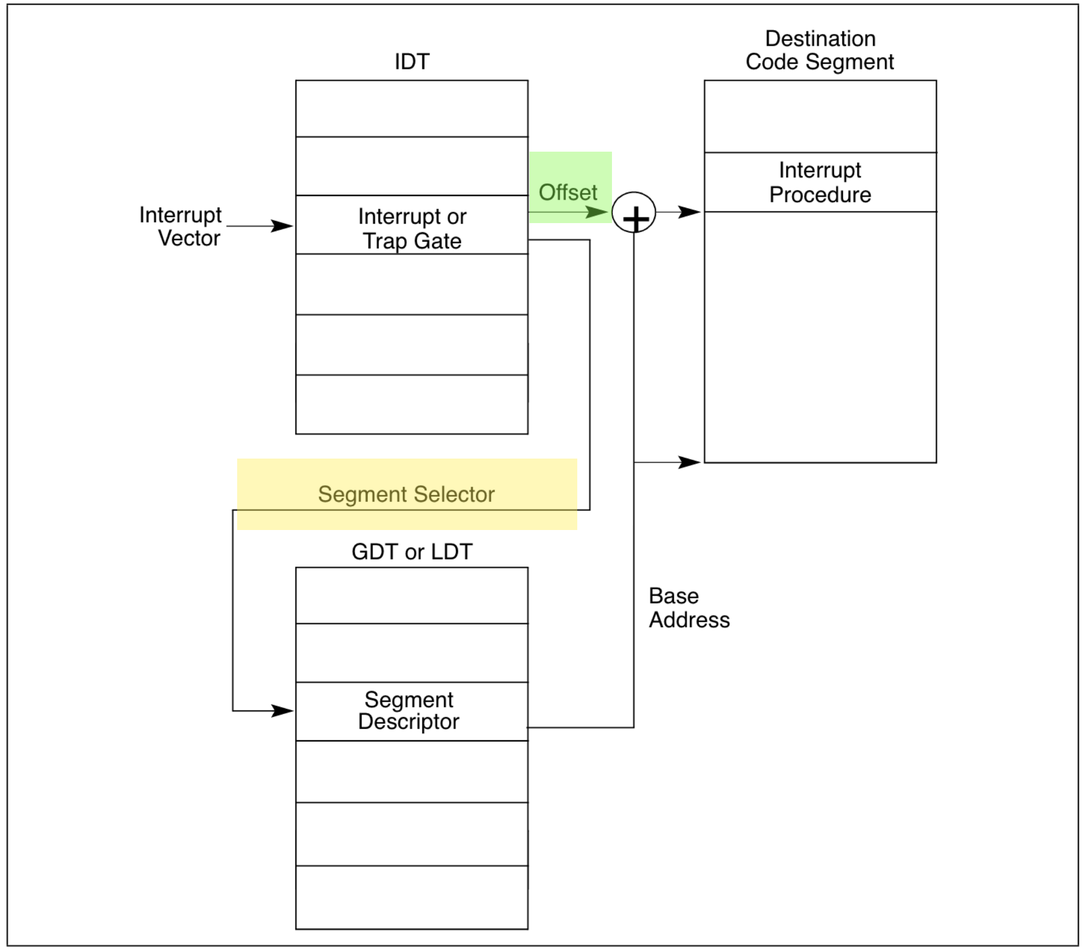

Figure 6-3. Interrupt Procedure Call

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
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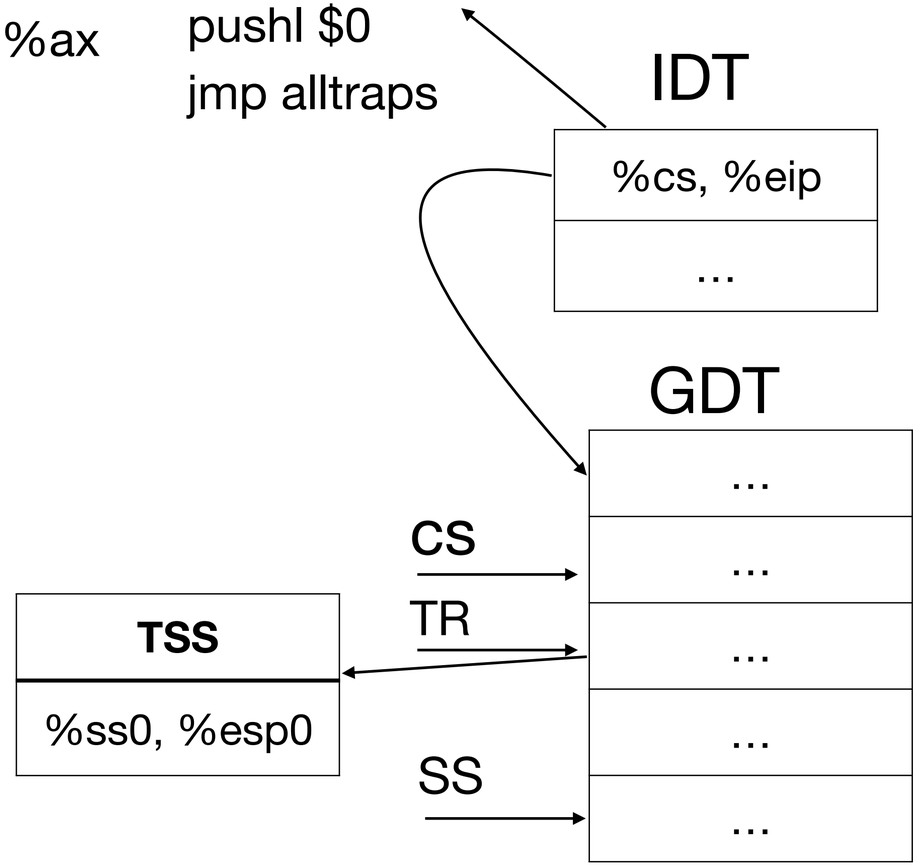
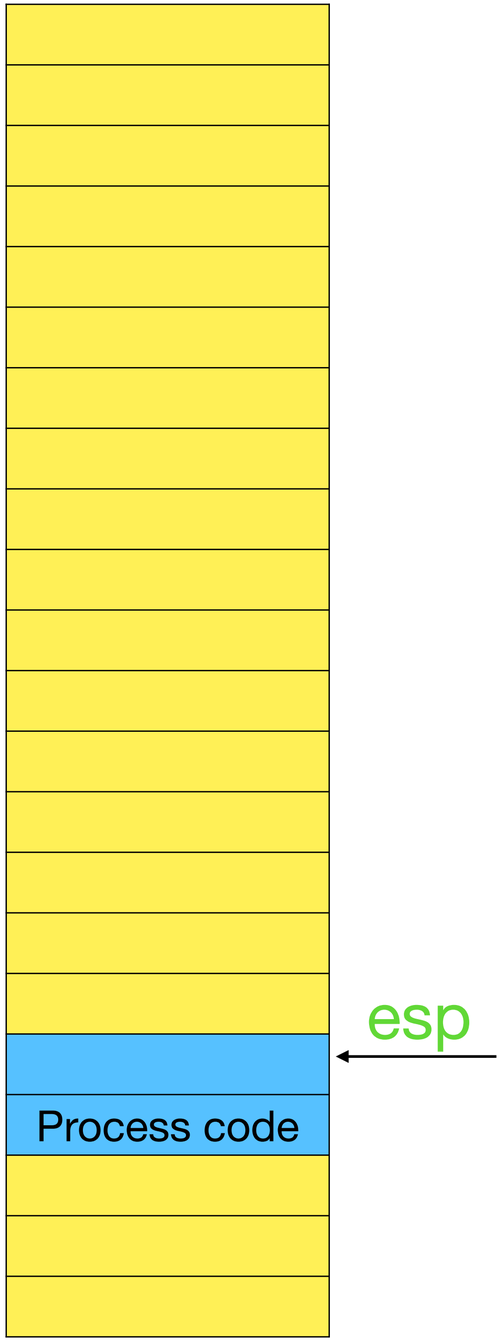
  jmp alltraps
```





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  pushl %esp
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  popl %ds..
  addl $0x8, %esp
  iret
```

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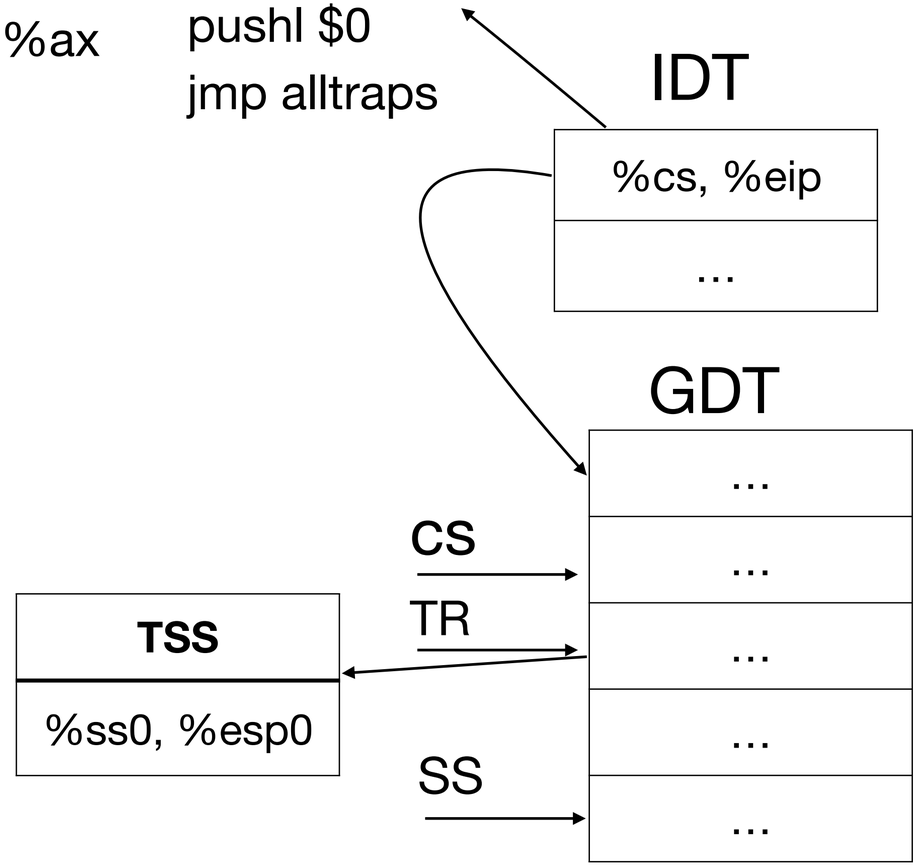

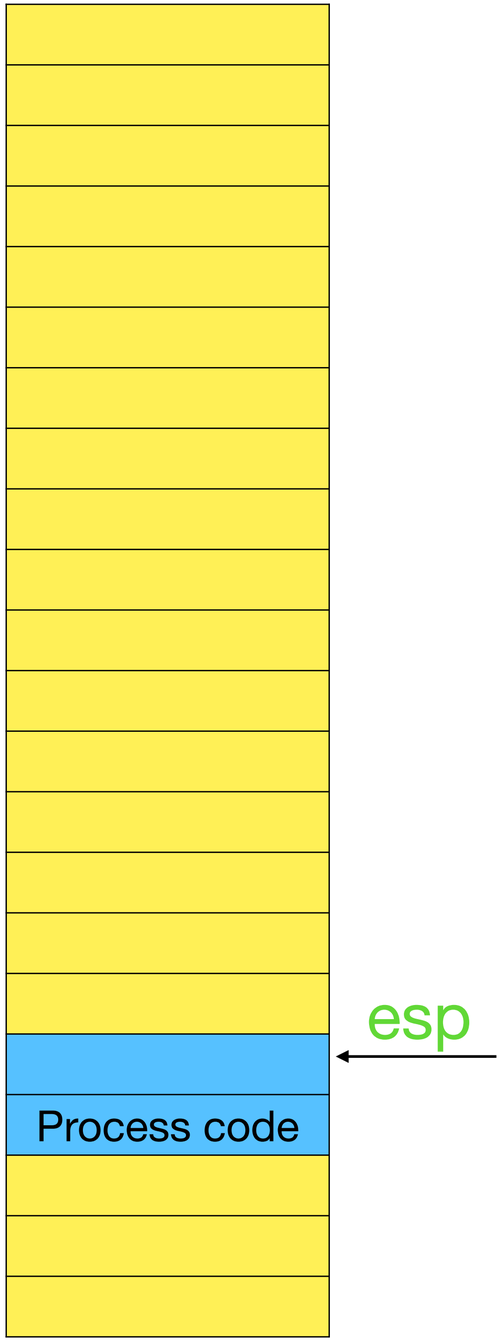

Interrupt handling with user process running

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trapasm.S

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  movw %ax, %ds..
  pushl %esp
  call trap
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  popal
  popl %ds..
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vectors.S

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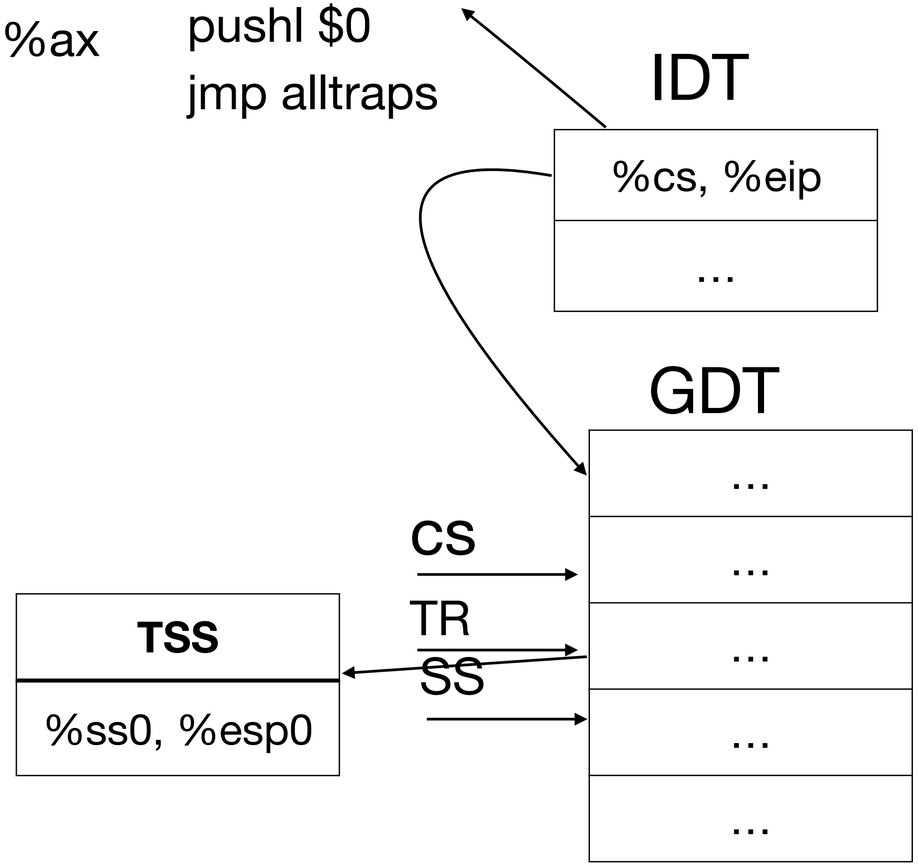

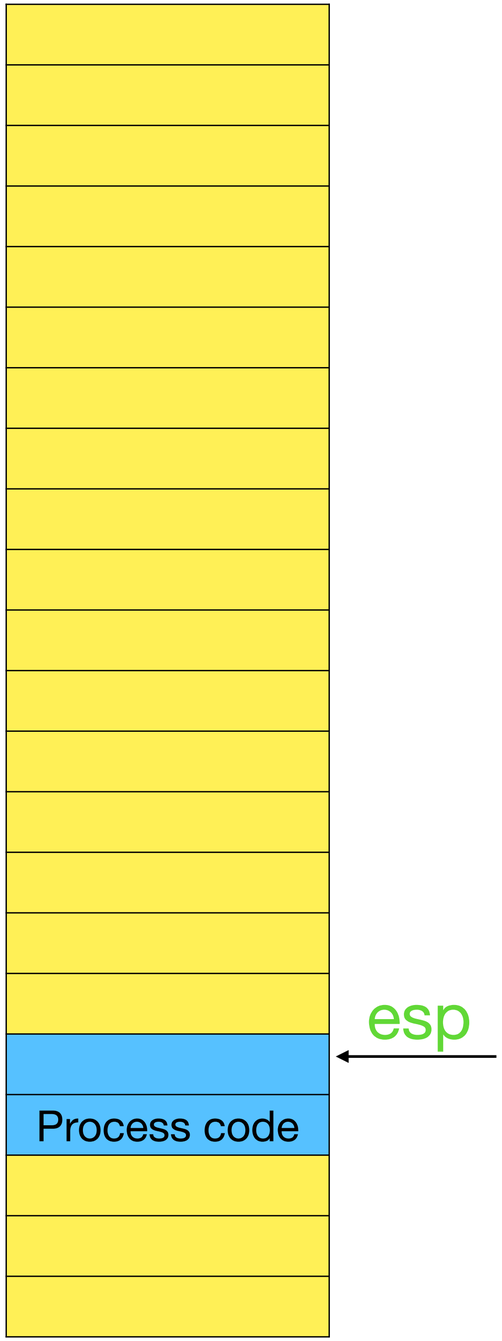

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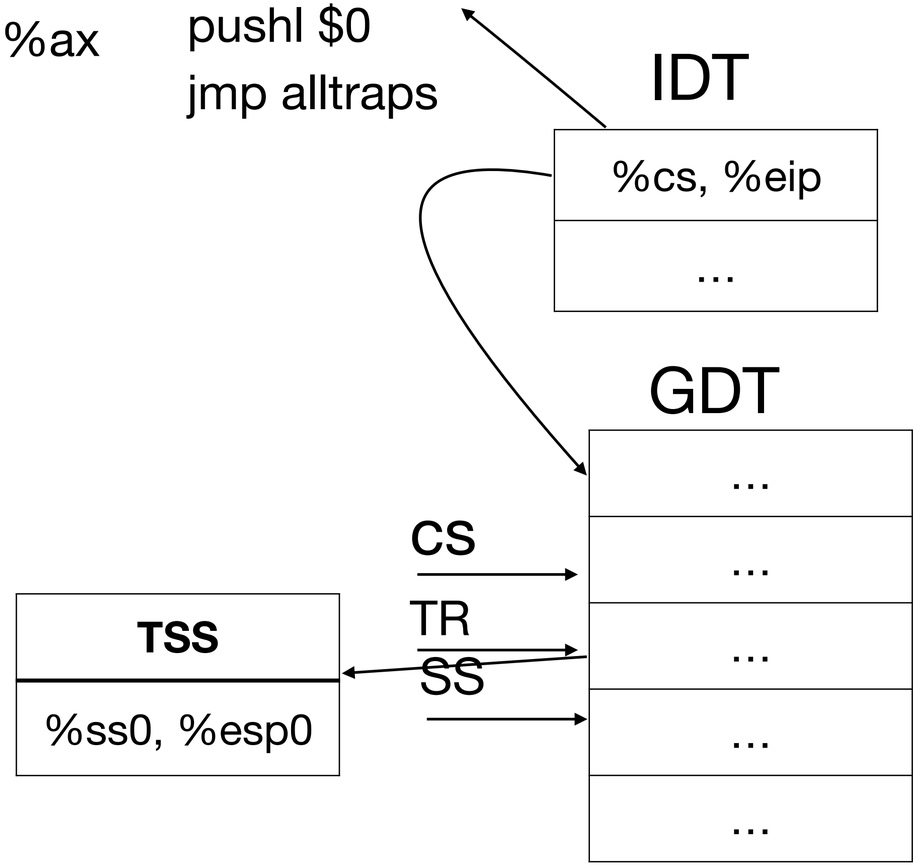

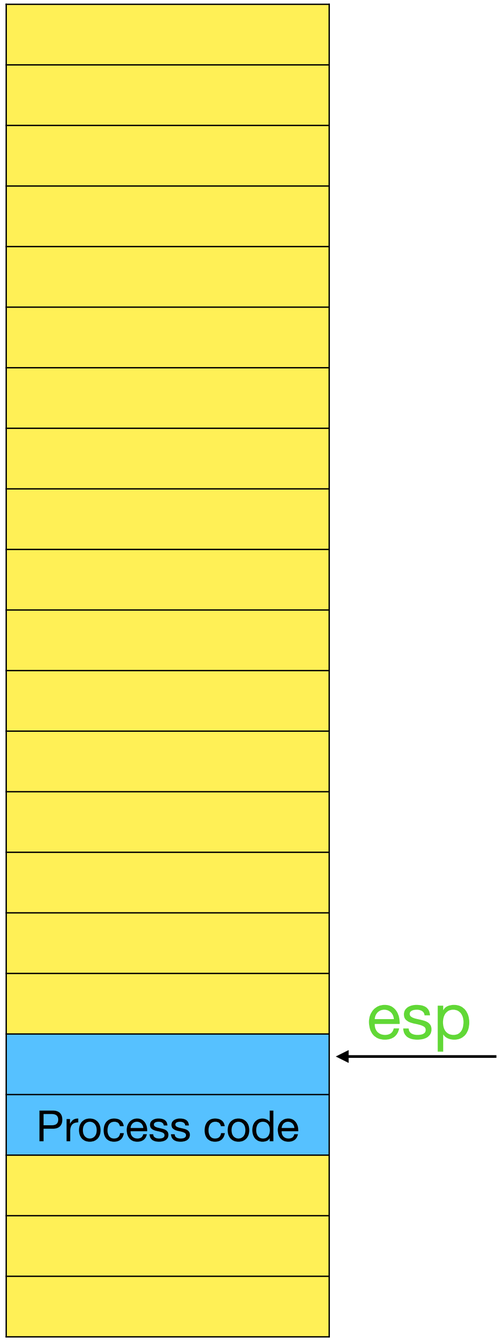

Interrupt handling with user process running

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;

trapasm.S

```
alltraps:
  pushl %ds..
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  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
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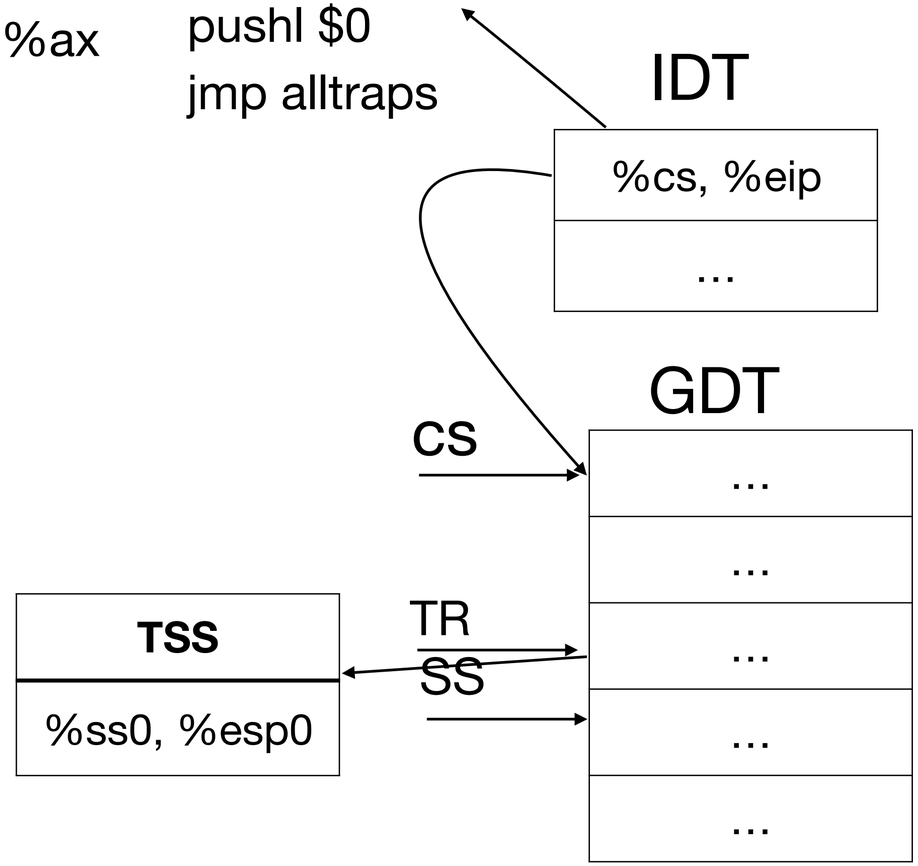
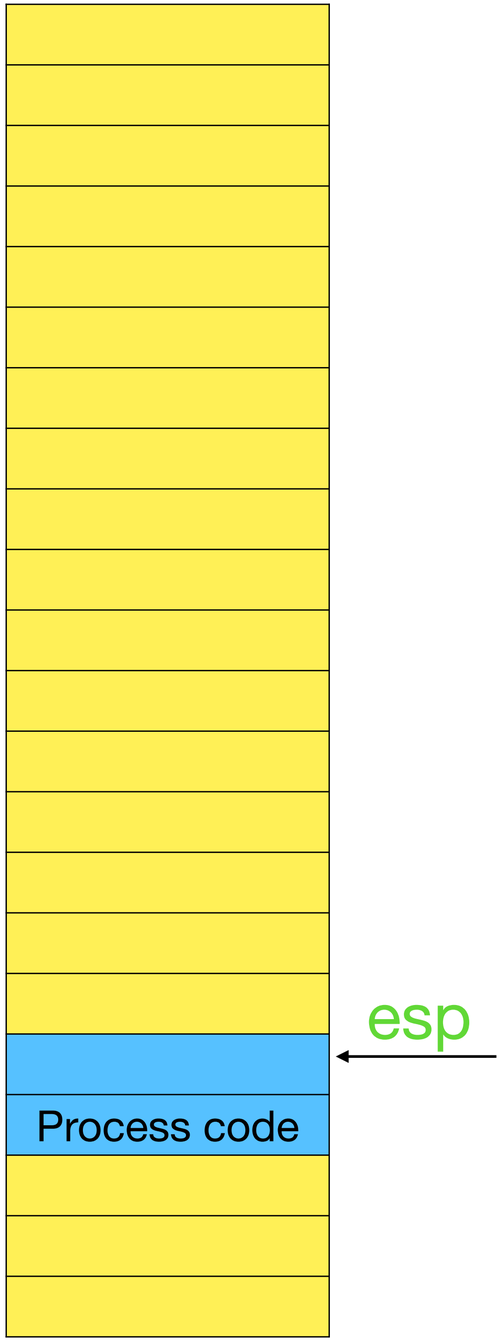
  jmp alltraps
```





Interrupt handling with user process running

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vectors.S

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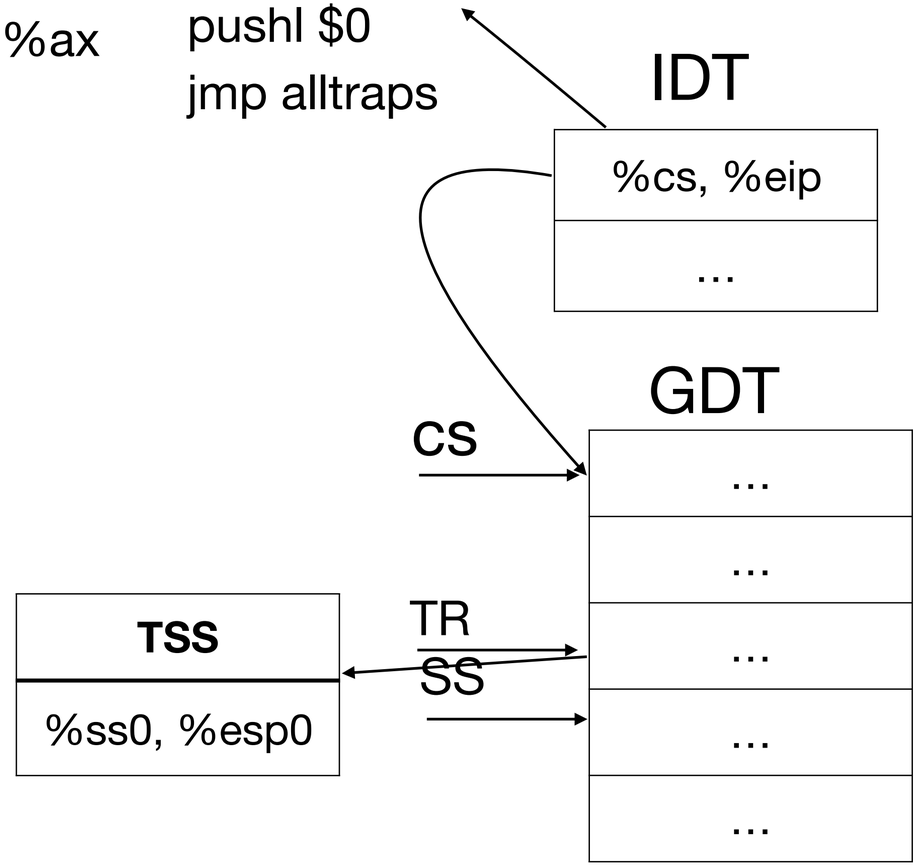

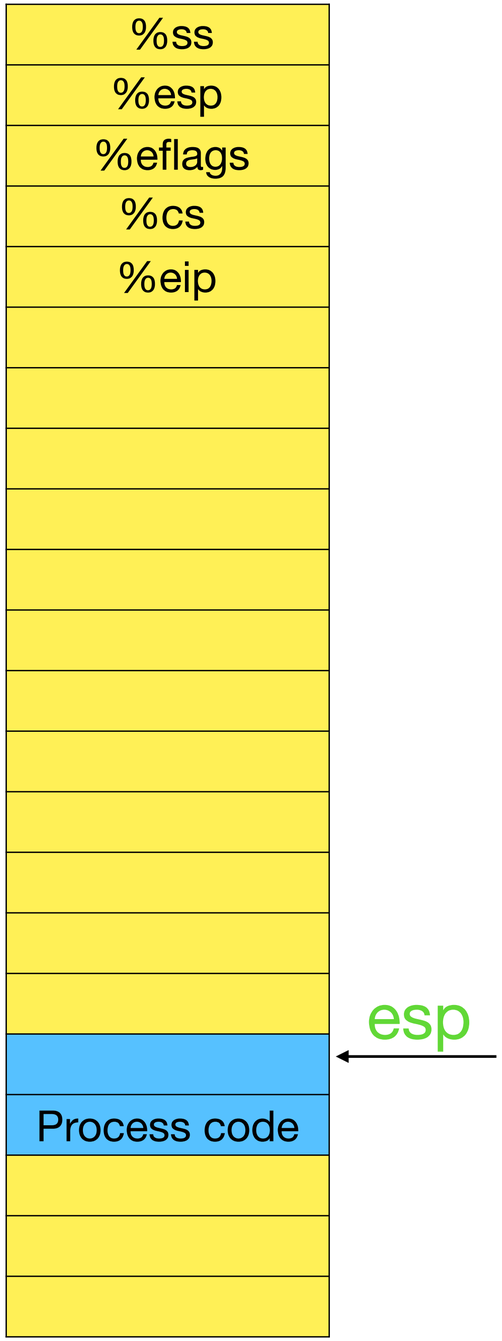

Interrupt handling with user process running

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vectors.S

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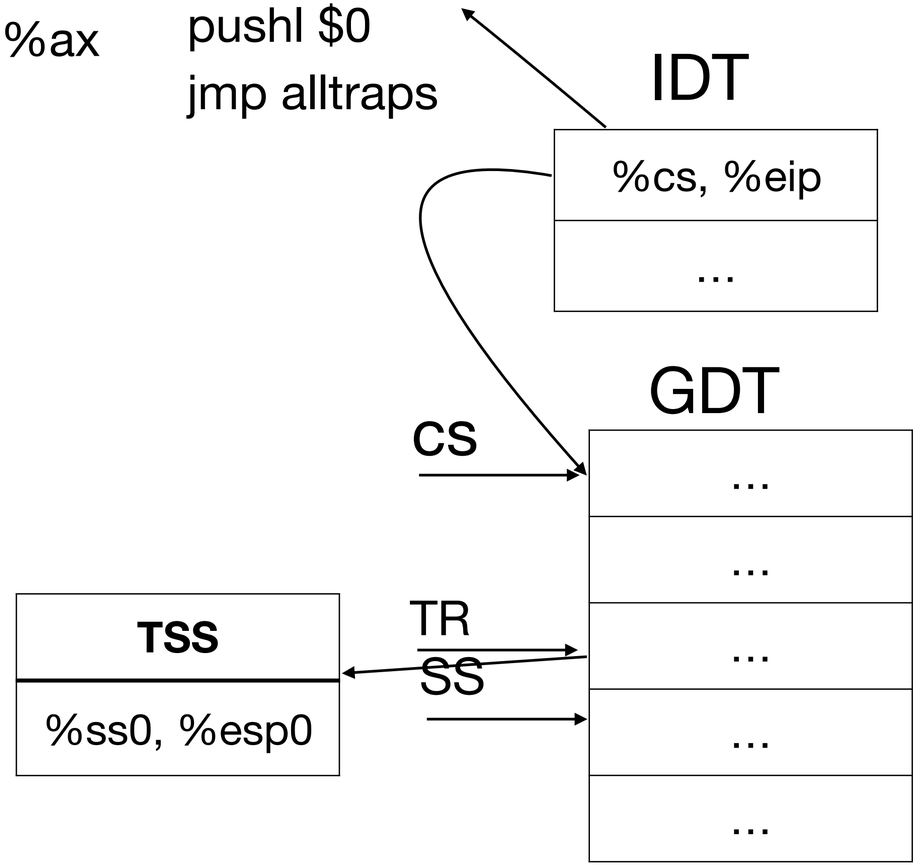

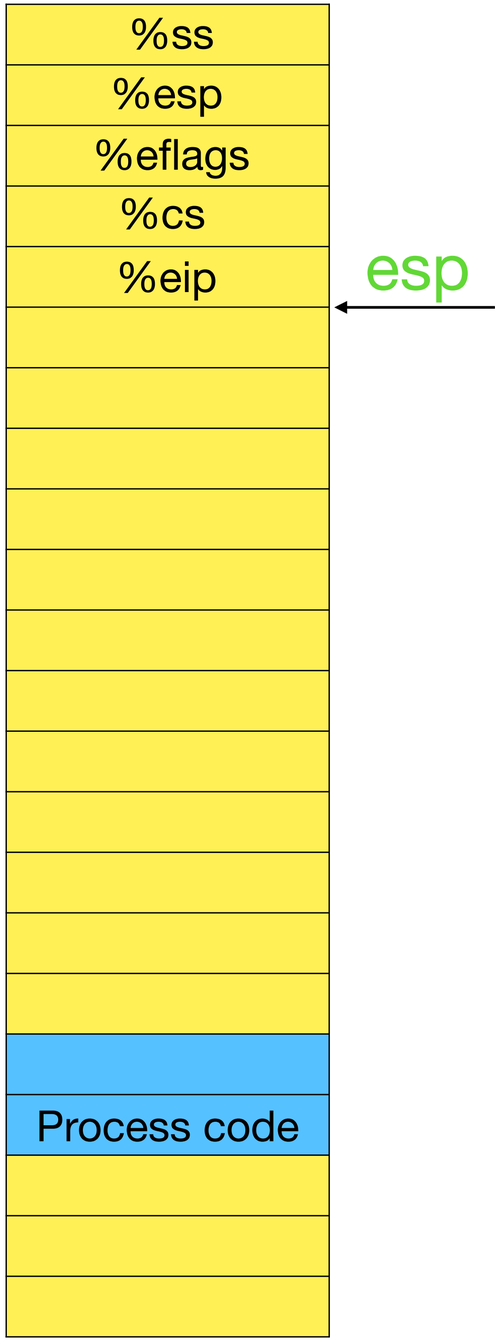

Interrupt handling with user process running

```
for(;;)
;
```

trapasm.S

```
alltraps:
  pushl %ds..
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  popl %ds..
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vectors.S

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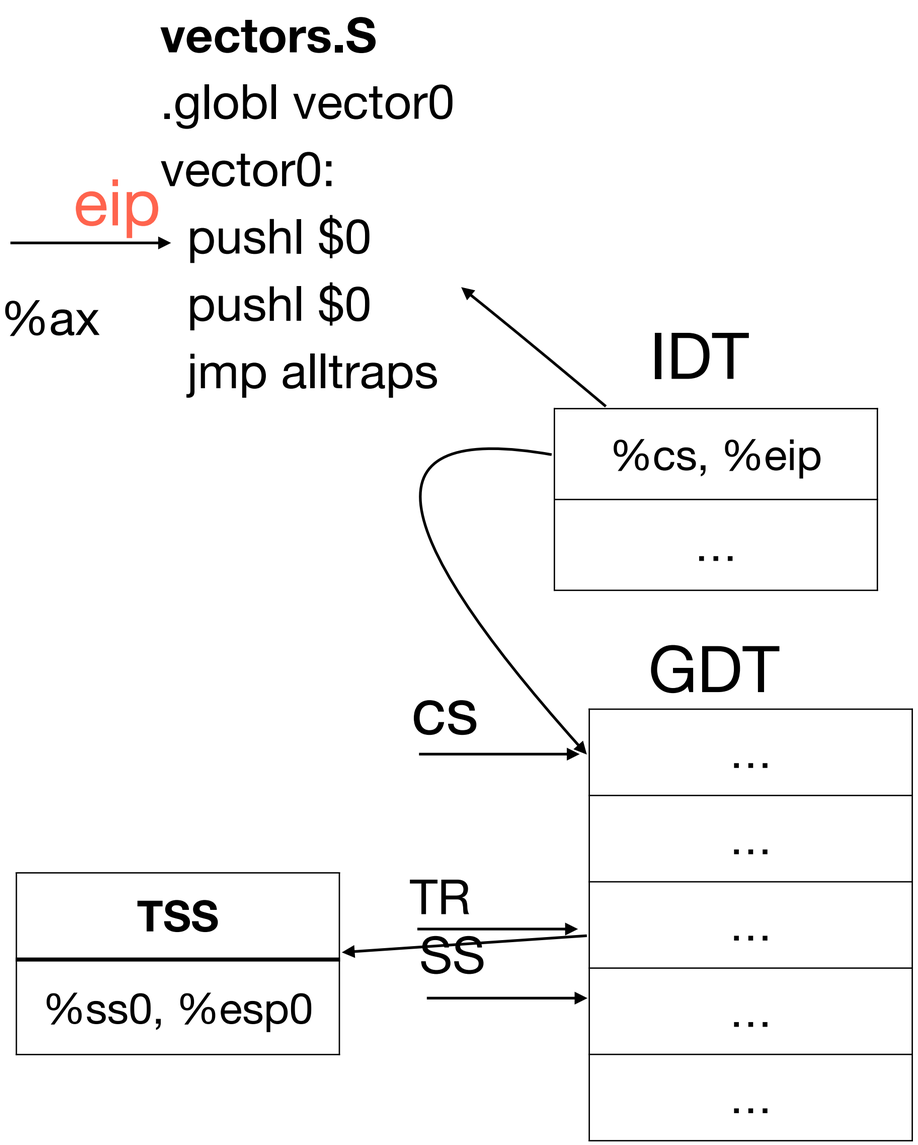

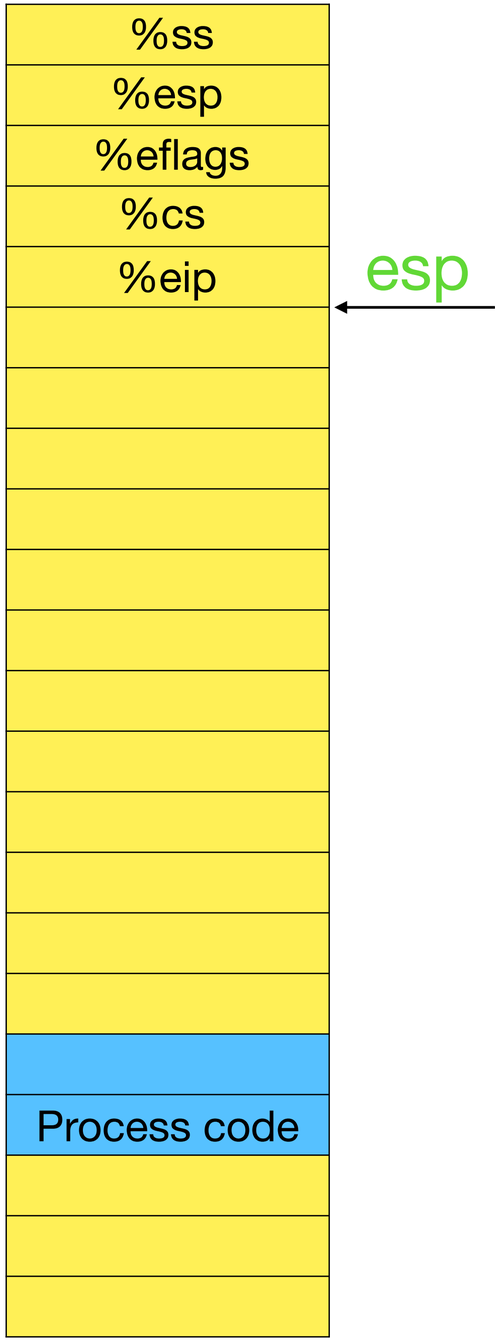

Interrupt handling with user process running

```
for(;;)
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```

trapasm.S

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  popl %ds..
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vectors.S

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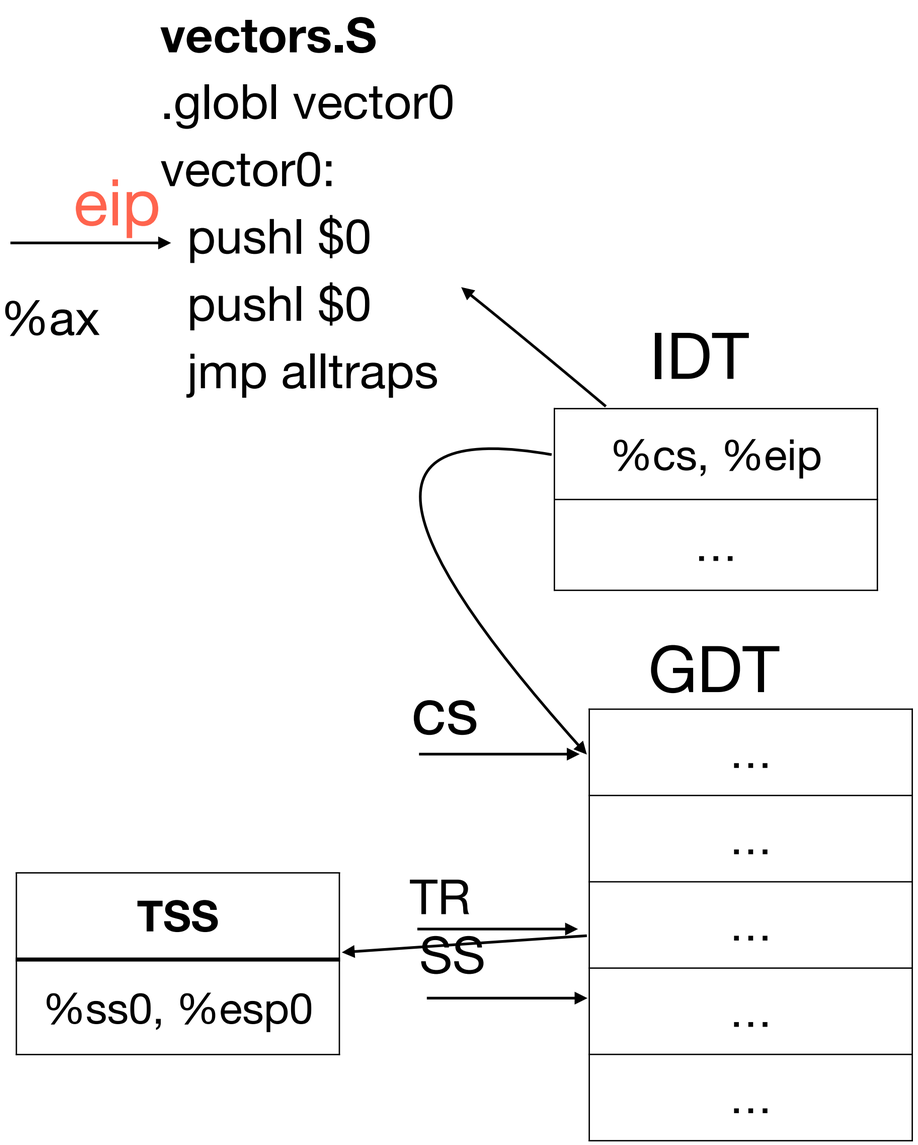

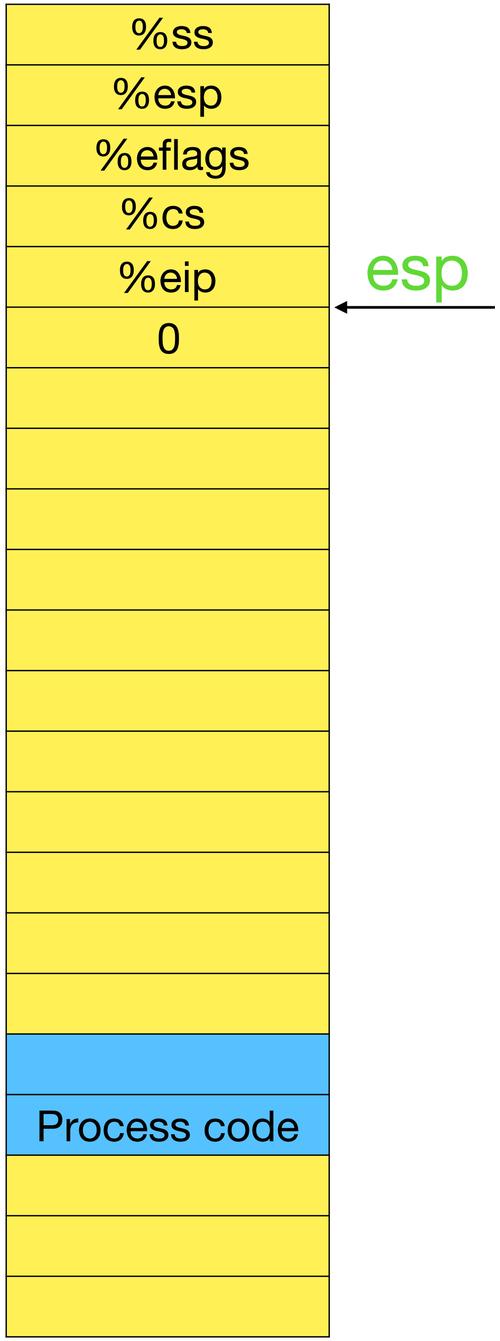

Interrupt handling with user process running

```
for(;;)
;
```

trapasm.S

```
alltraps:
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  movw $(SEG_KDATA<<3), %ax
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  popal
  popl %ds..
  addl $0x8, %esp
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vectors.S

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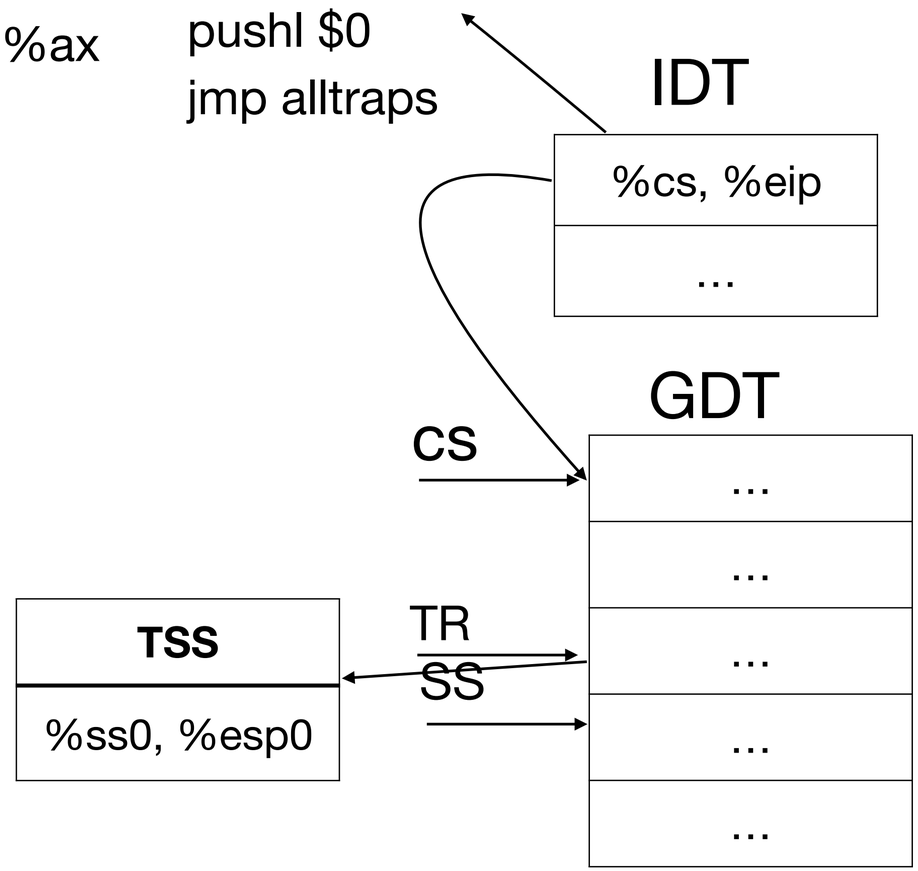

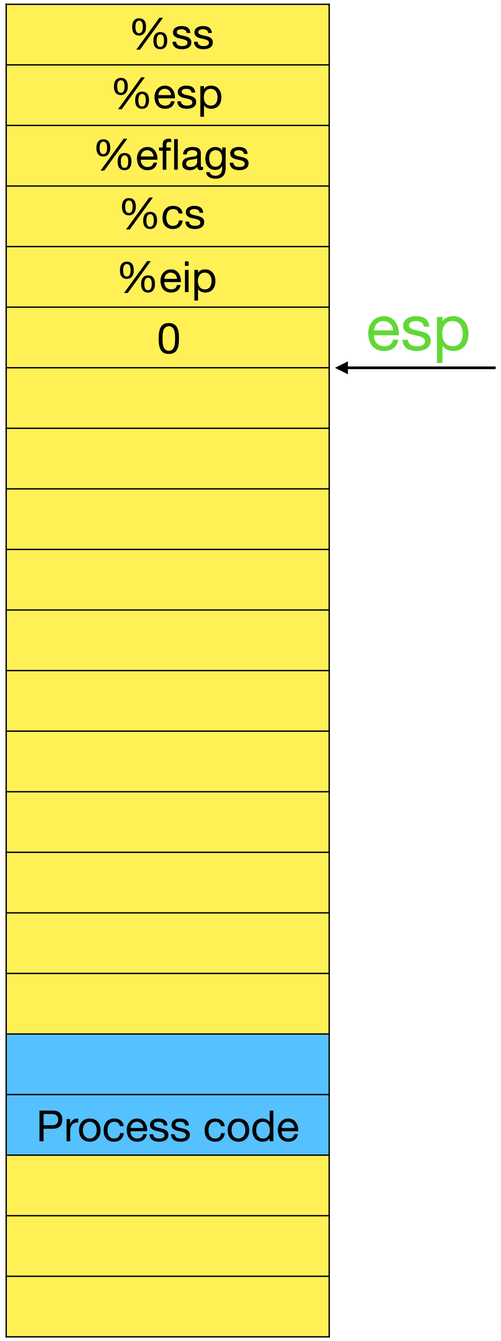

Interrupt handling with user process running

```
for(;;)
;
```

trapasm.S

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  movw $(SEG_KDATA<<3), %ax
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vectors.S

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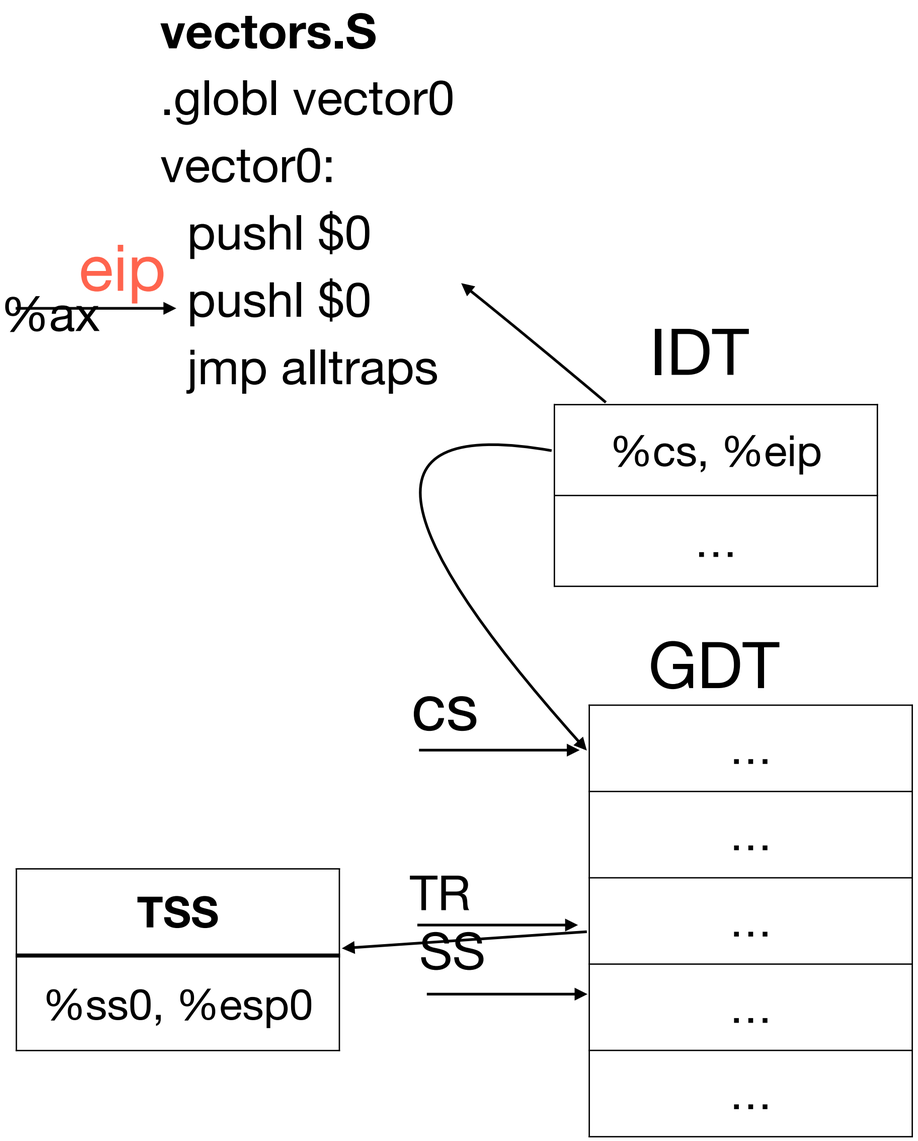

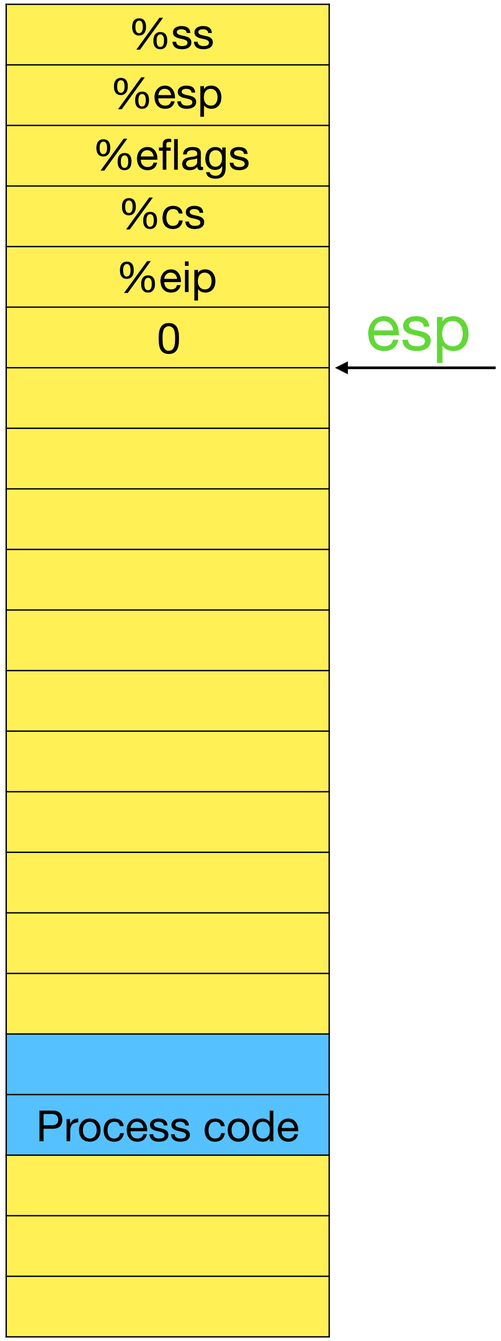

Interrupt handling with user process running

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for(;;)
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```

trapasm.S

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vectors.S

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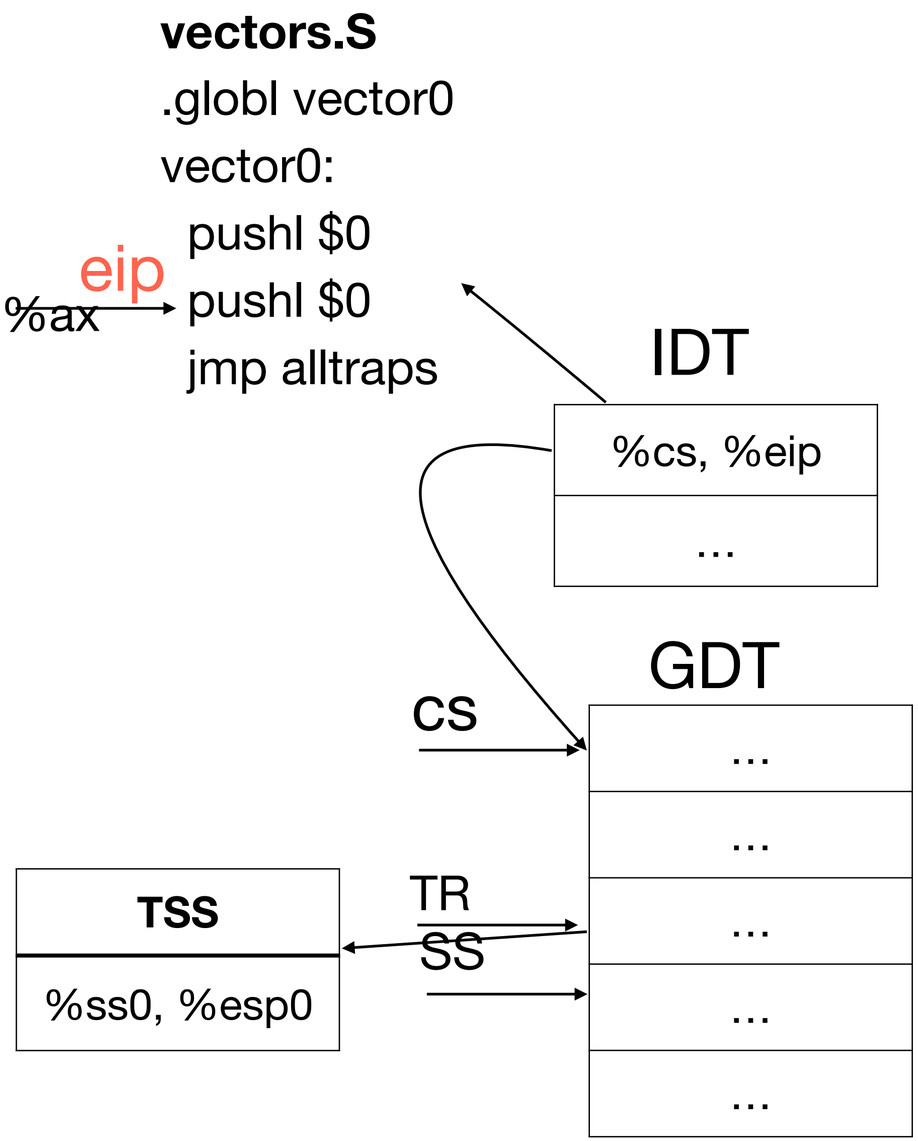

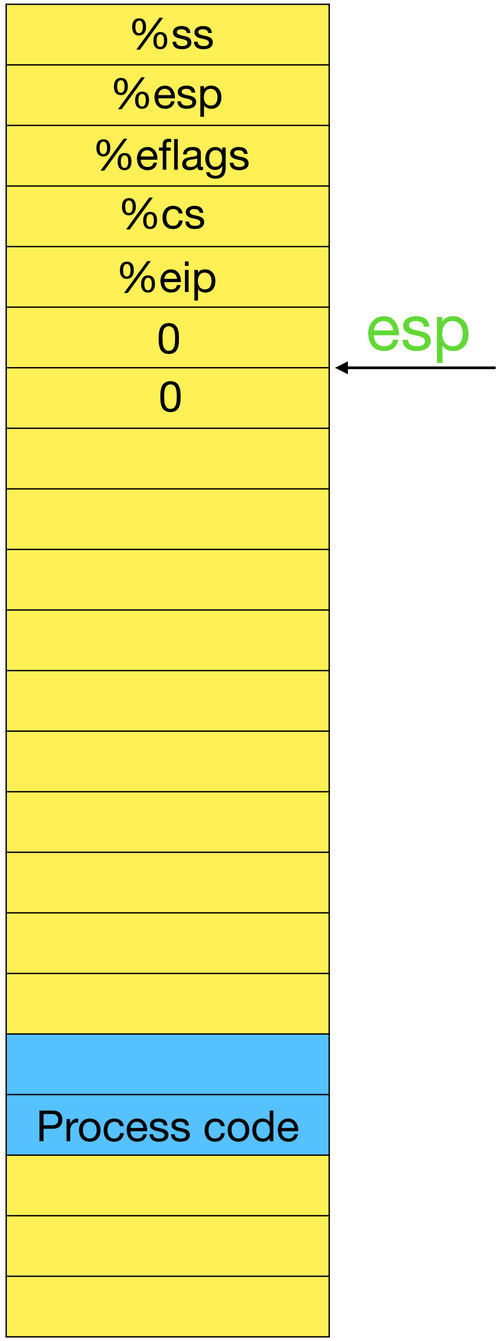

Interrupt handling with user process running

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trapasm.S

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vectors.S

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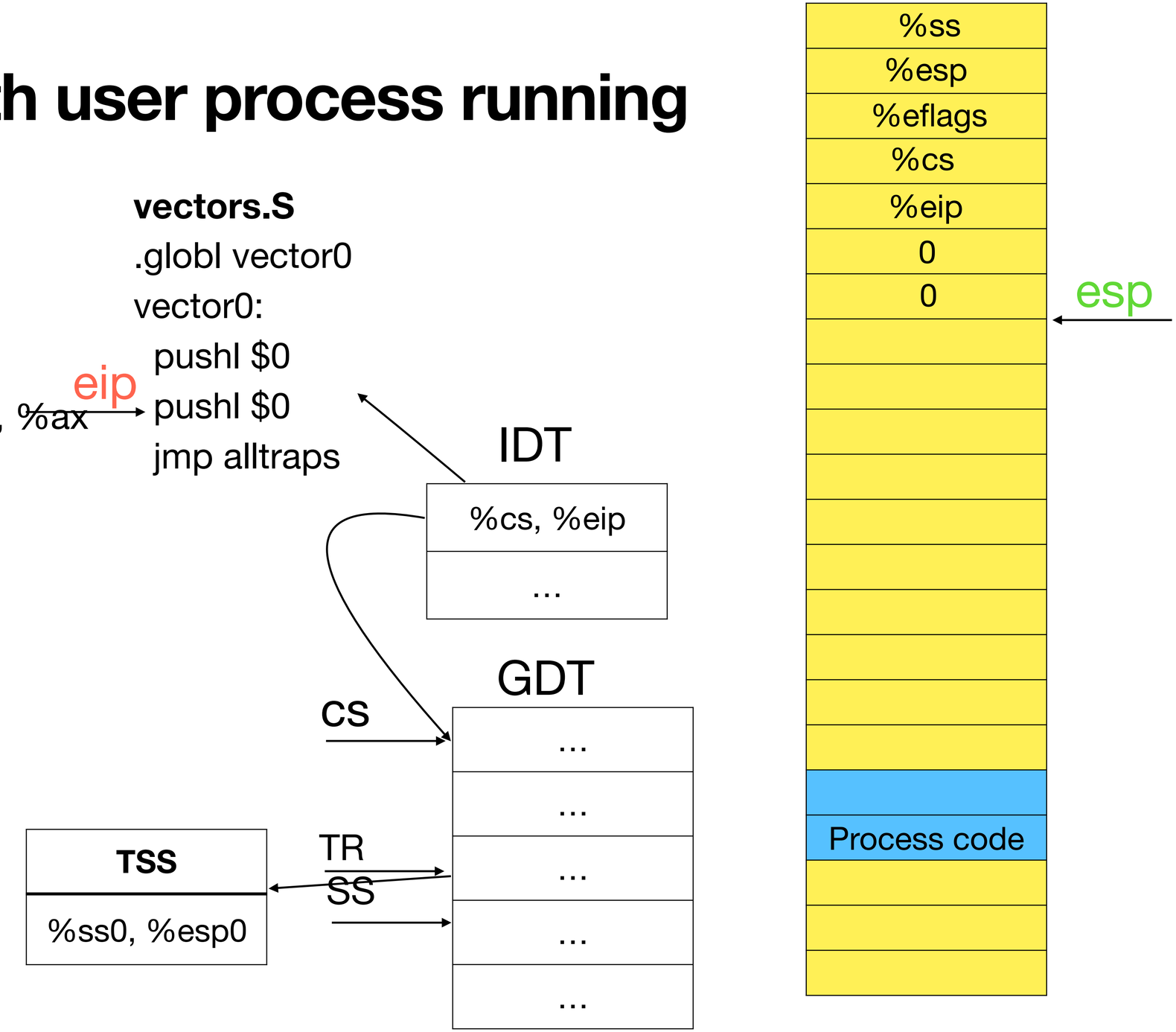

Interrupt handling with user process running

```
for(;;)
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```

trapasm.S

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```

eip

vectors.S

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.globl vector0
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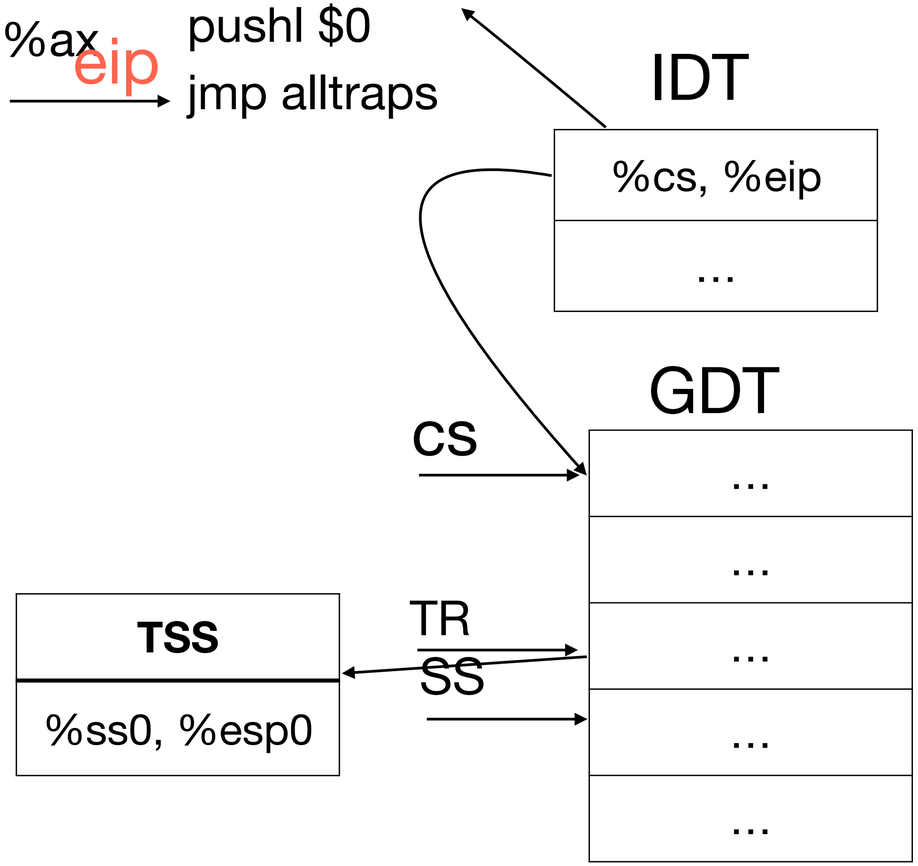

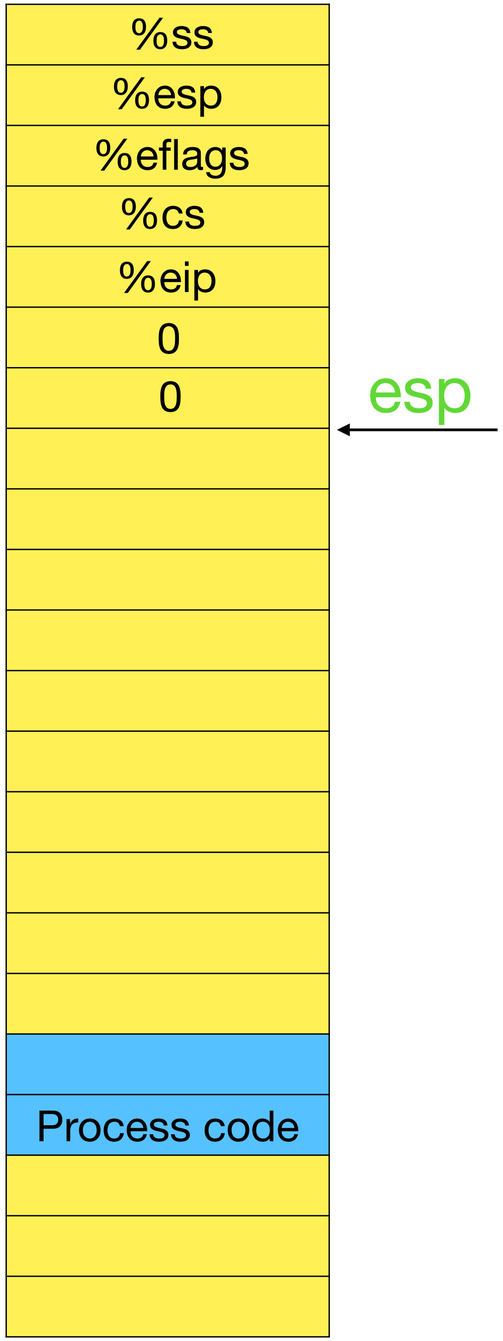

Interrupt handling with user process running

for(;;)
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eip

trapasm.S

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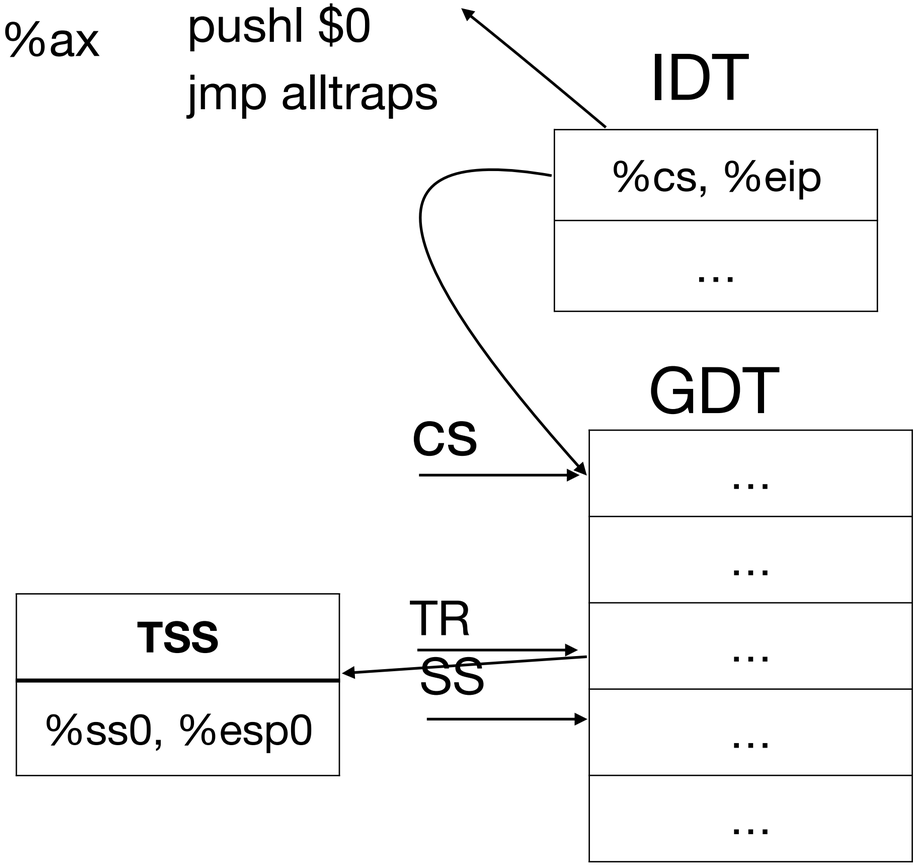

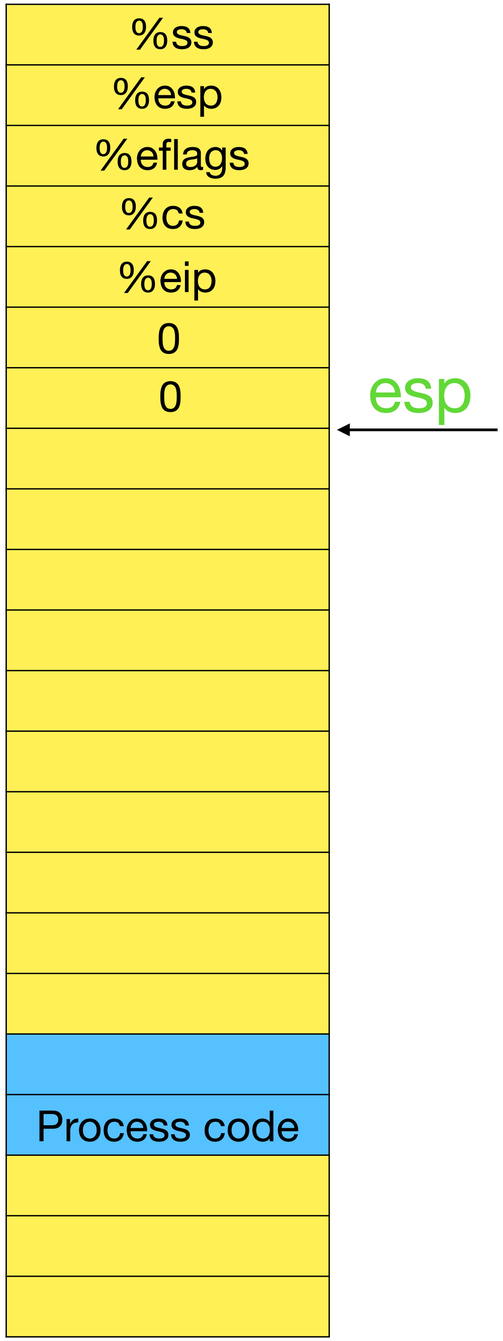

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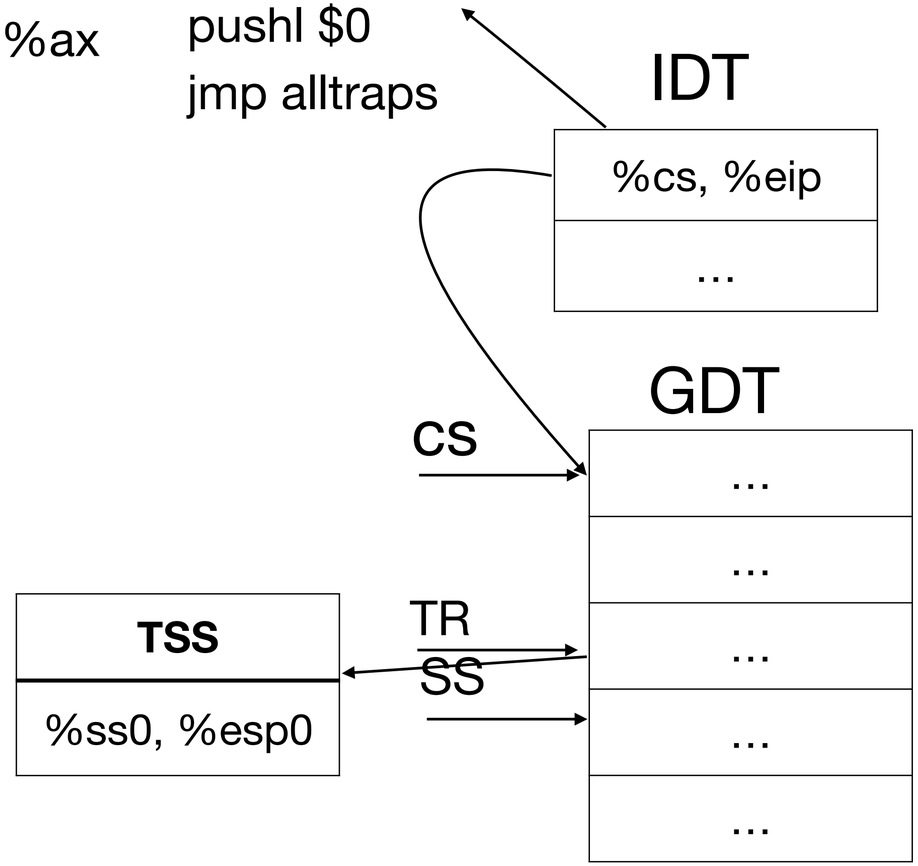

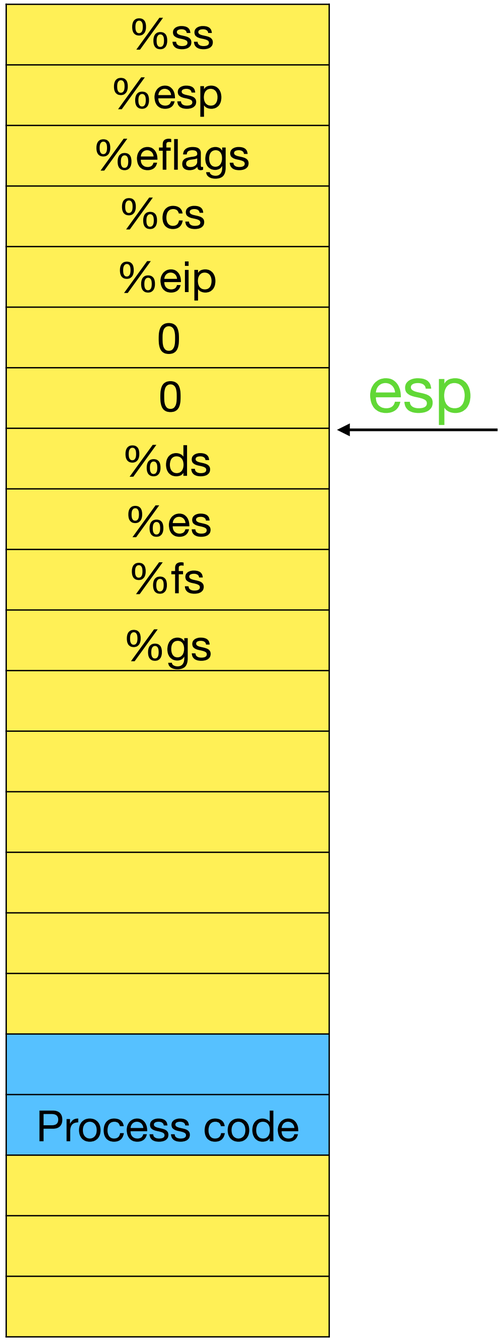

Interrupt handling with user process running

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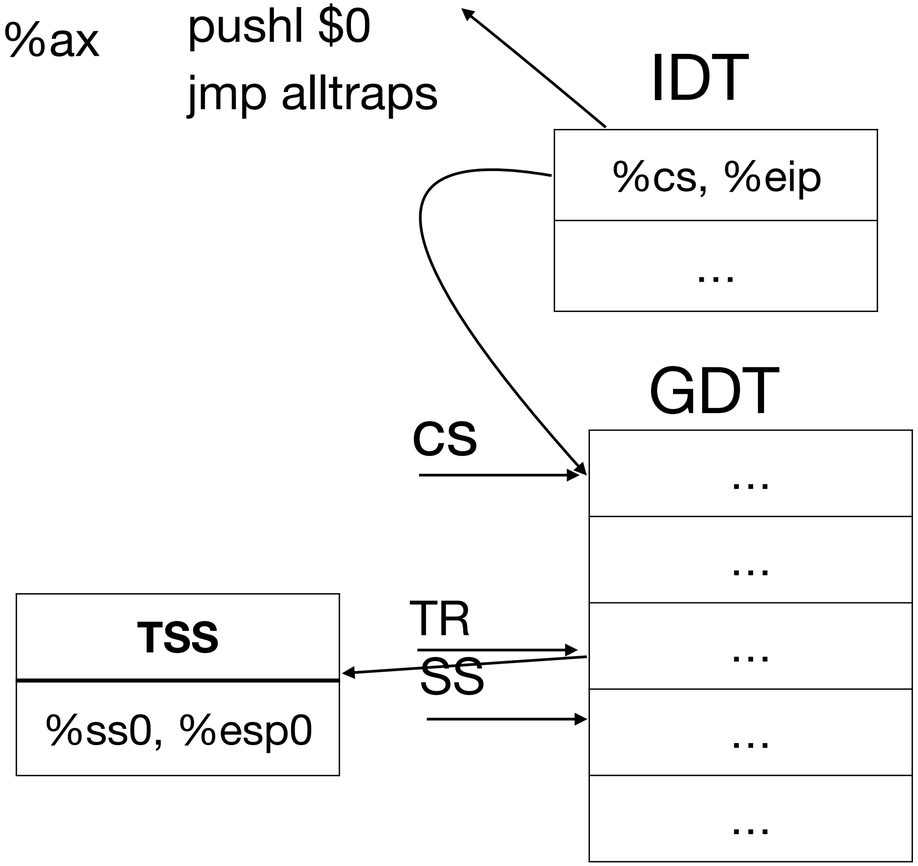

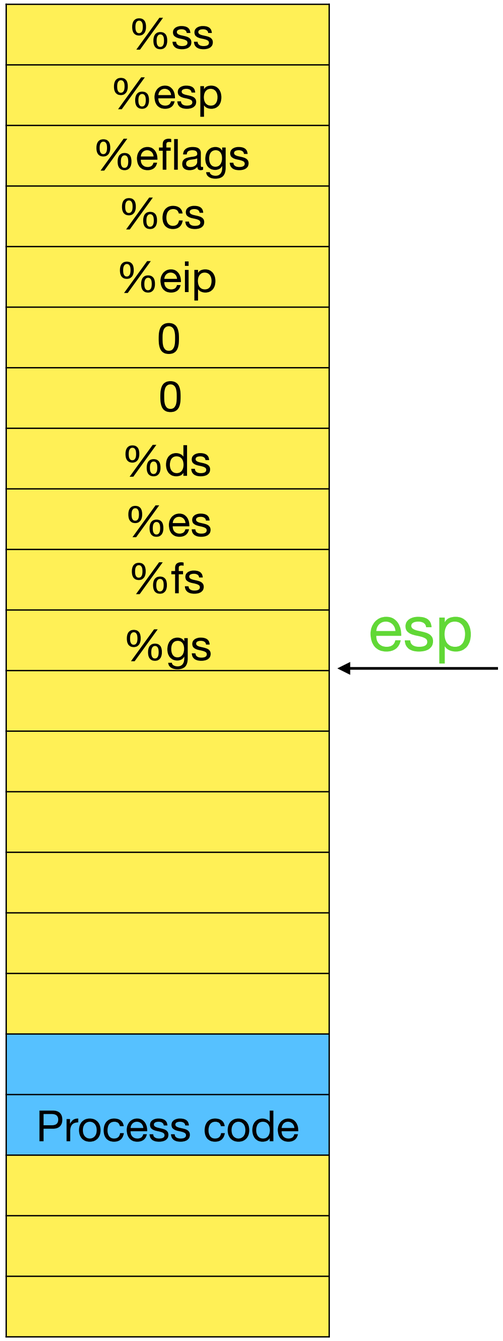

Interrupt handling with user process running

```
for(;;)
;
```

eip →

trapasm.S

```
alltraps:
  pushl %ds..
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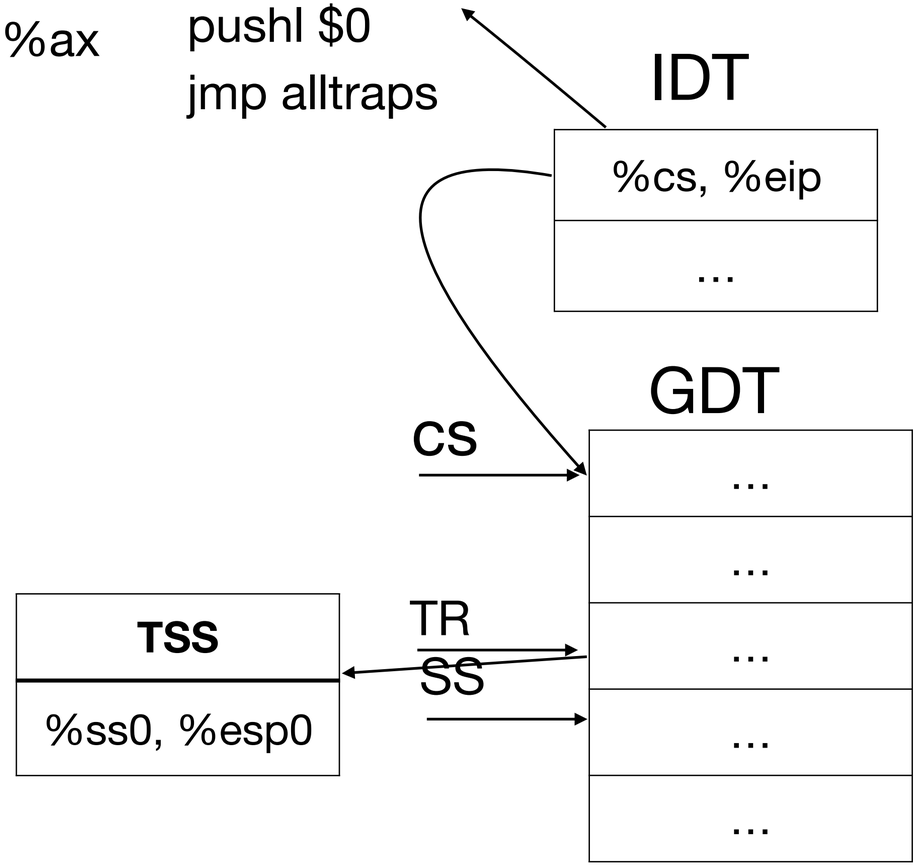

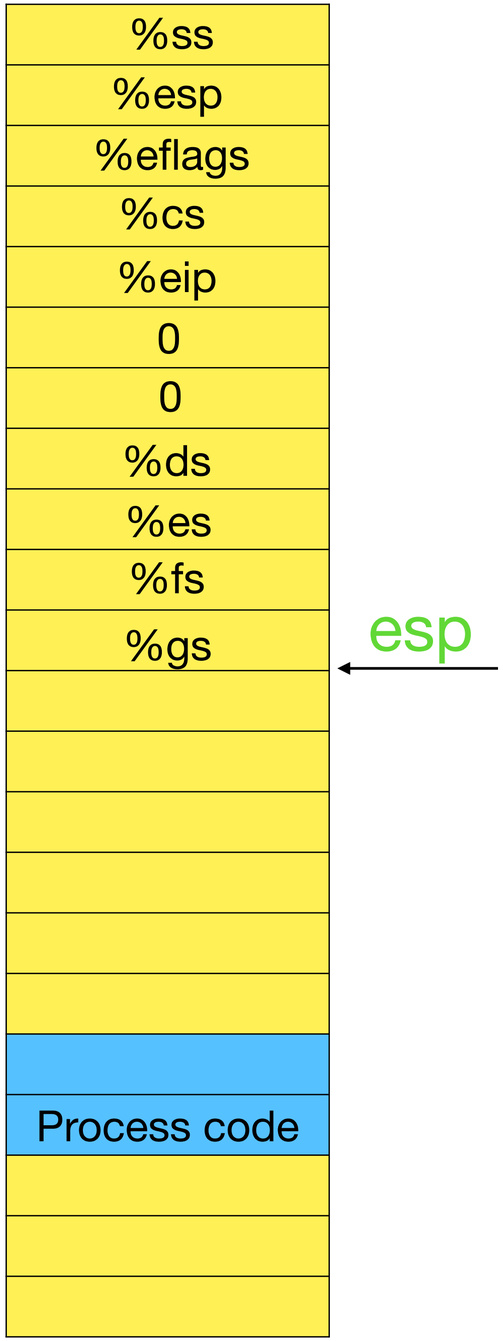

Interrupt handling with user process running

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eip →

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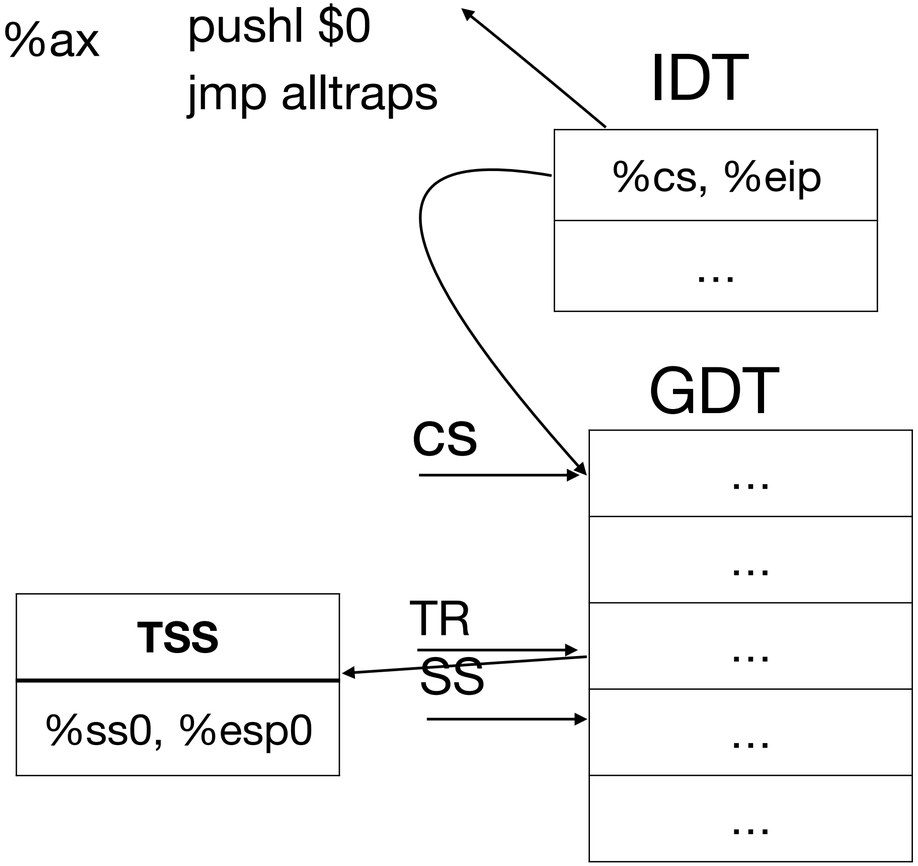

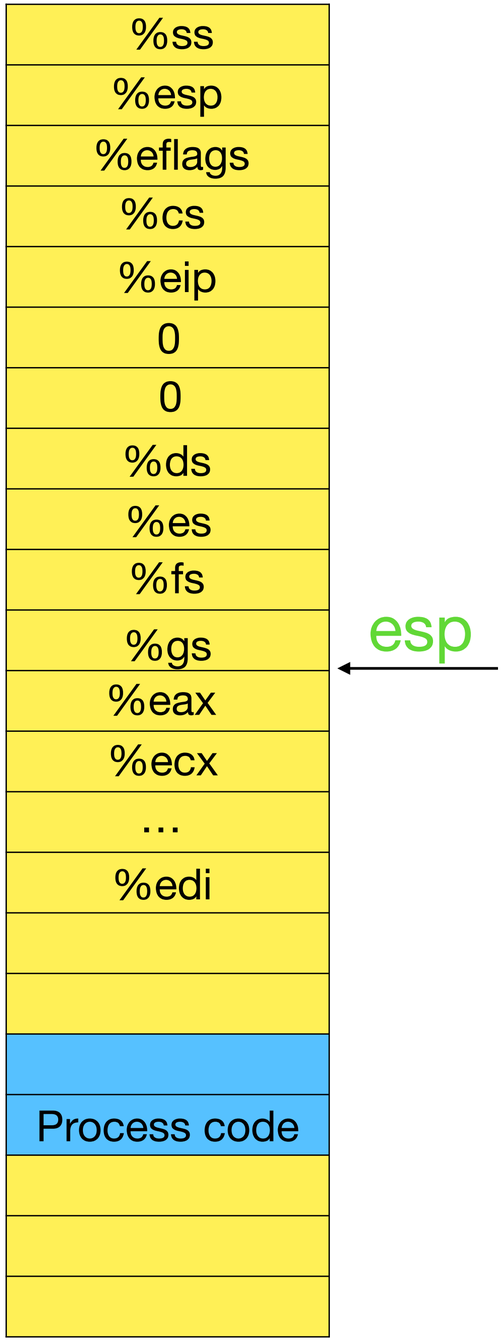

Interrupt handling with user process running

```
for(;;)
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eip →

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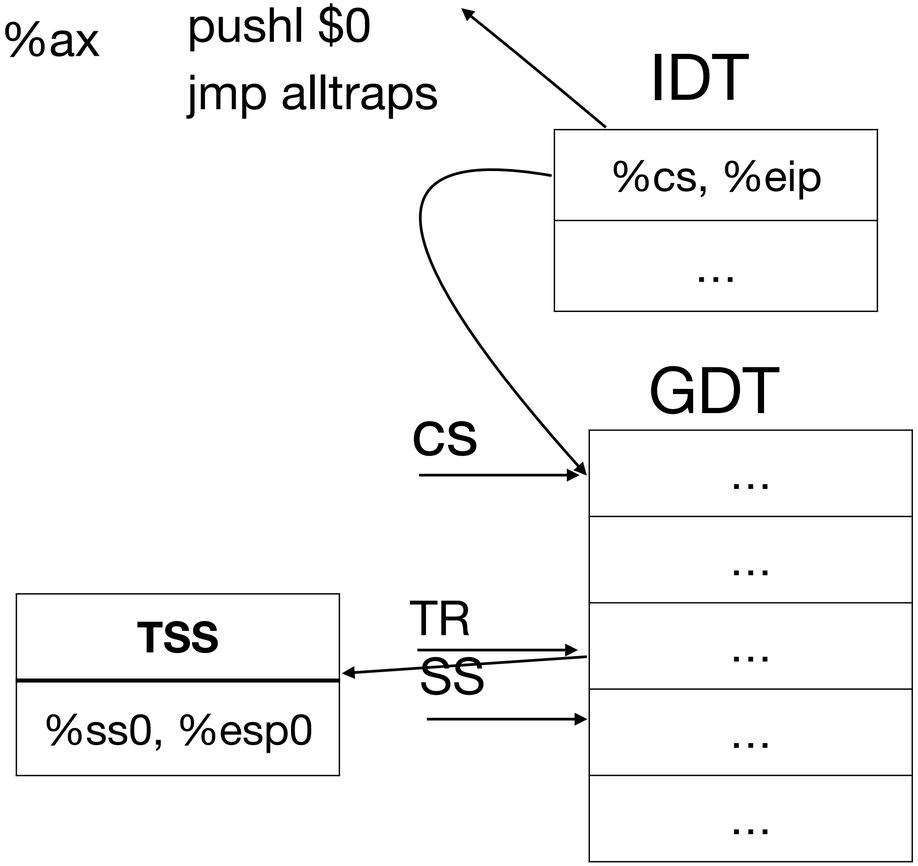

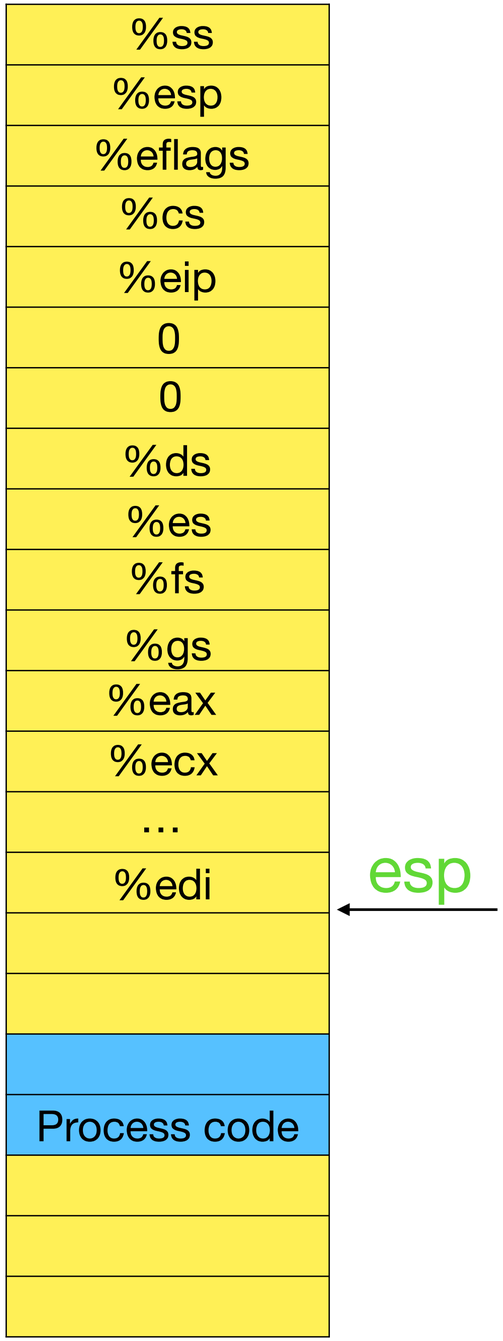

Interrupt handling with user process running

```
for(;;)
;
```

trapasm.S

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alltraps:
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  addl $4, %esp
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```

eip → pushl %esp

vectors.S

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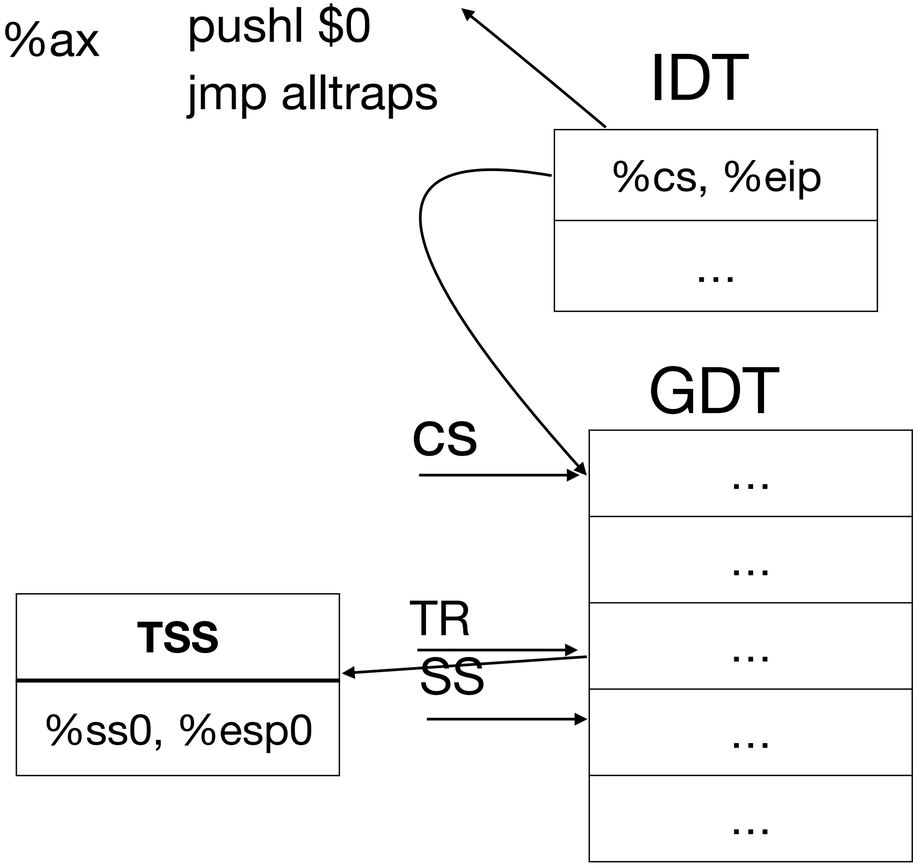

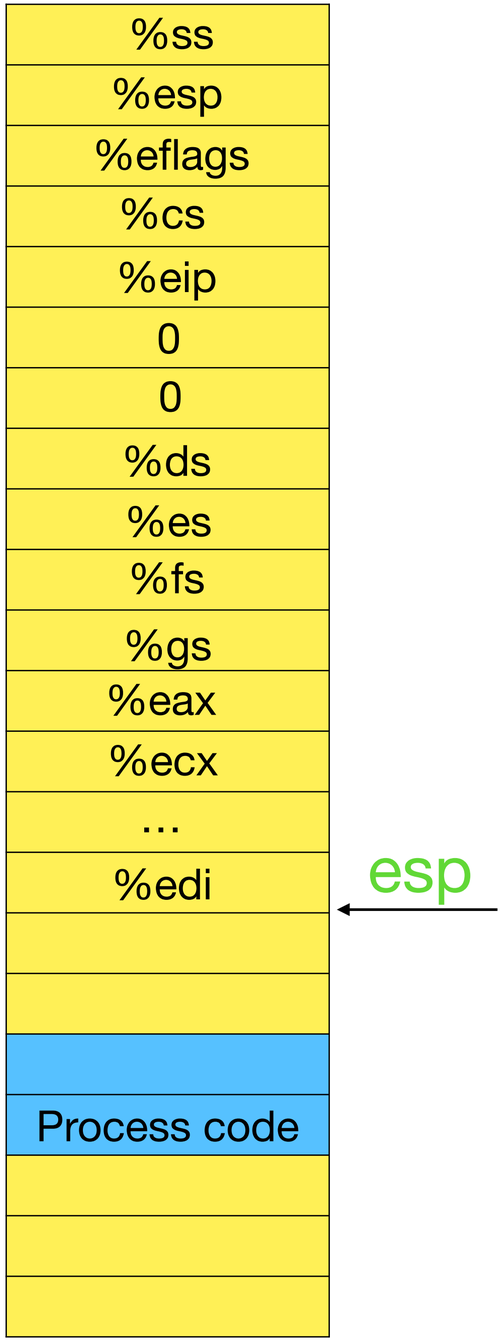

Interrupt handling with user process running

```
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
```

eip → pushl %esp

vectors.S

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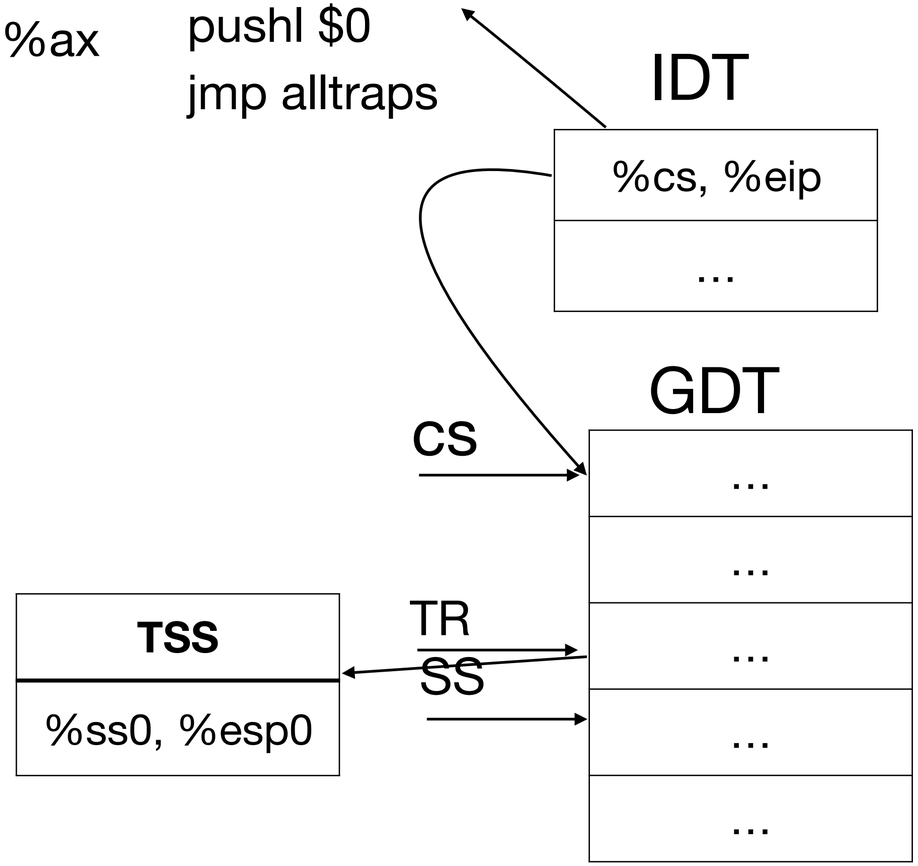
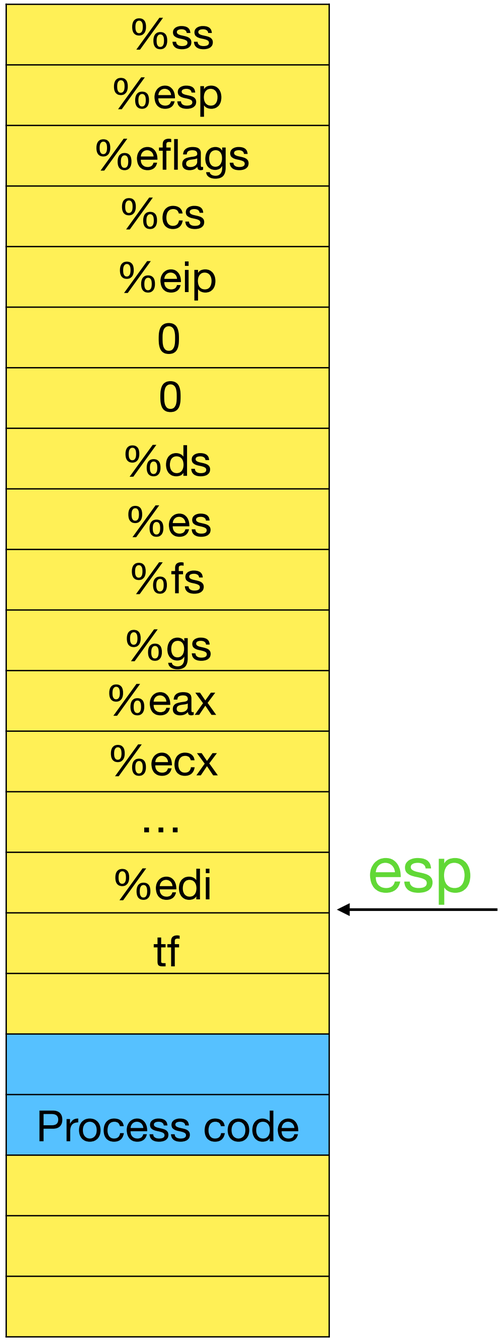




Interrupt handling with user process running

```
for(;;)
;
```

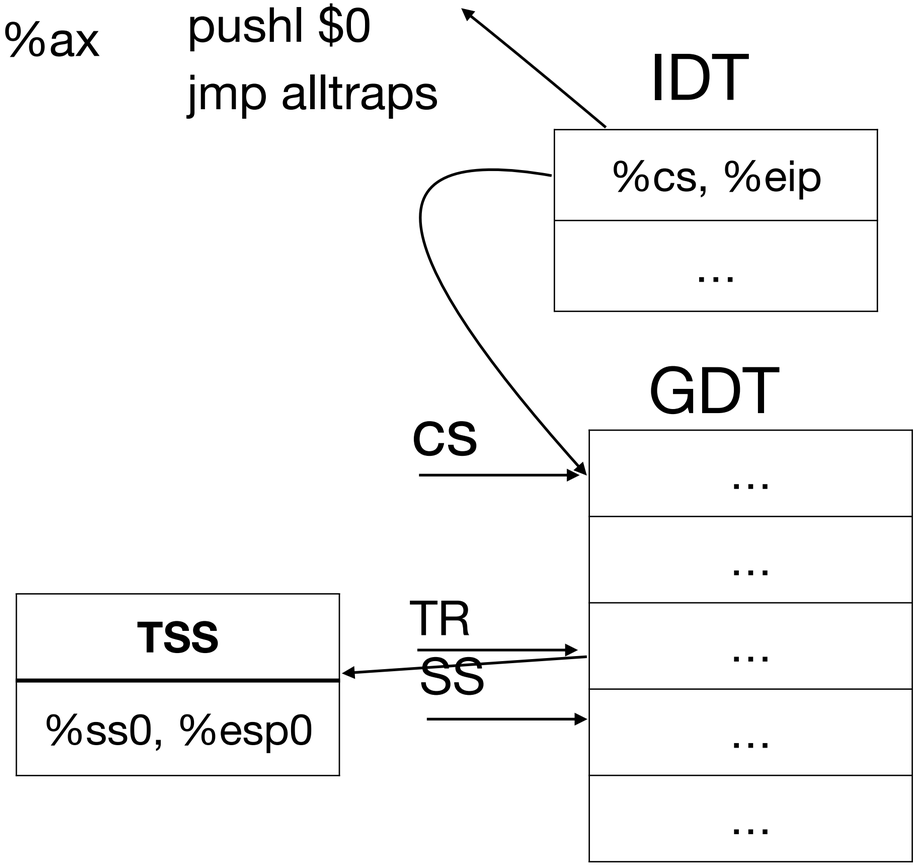
trapasm.S

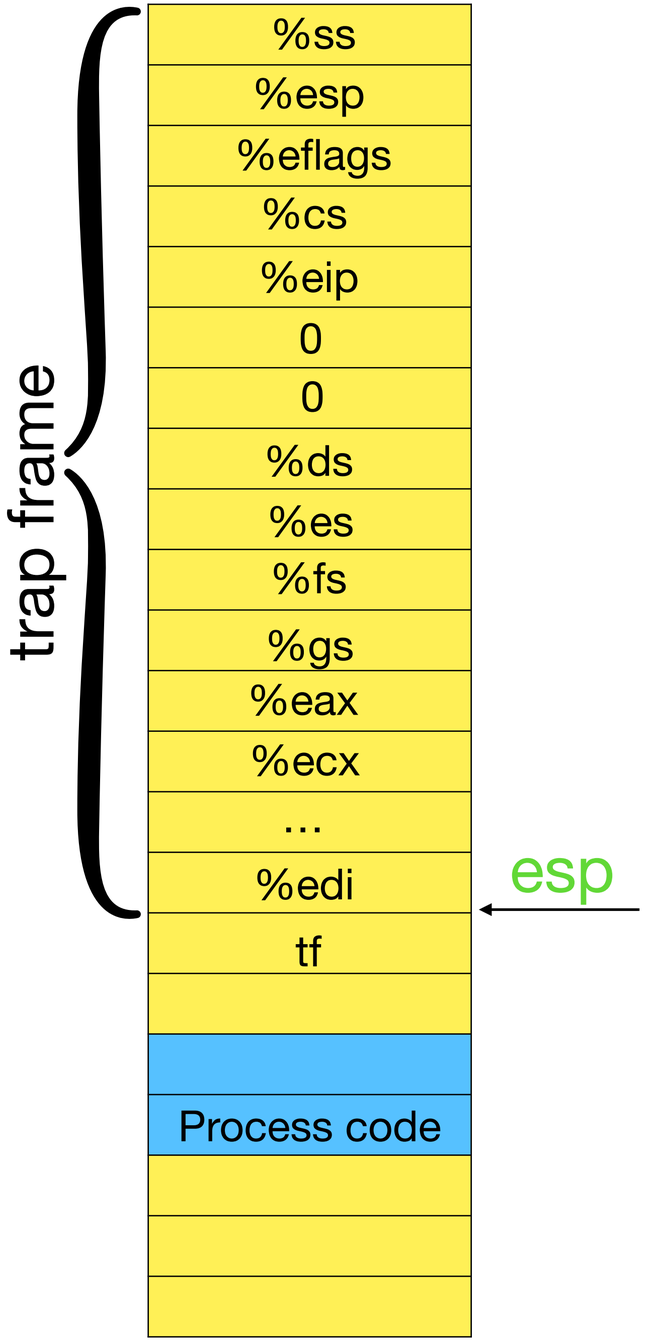
```
alltraps:
  pushl %ds..
  pushal
  movw $(SEG_KDATA<<3), %ax
  movw %ax, %ds..
  pushl %esp
  call trap
  addl $4, %esp
  popal
  popl %ds..
  addl $0x8, %esp
  iret
```

eip → pushl %esp

vectors.S

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





Interrupt handling with user process running

```
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
```

eip → pushl %esp

vectors.S

```
.globl vector0
vector0:
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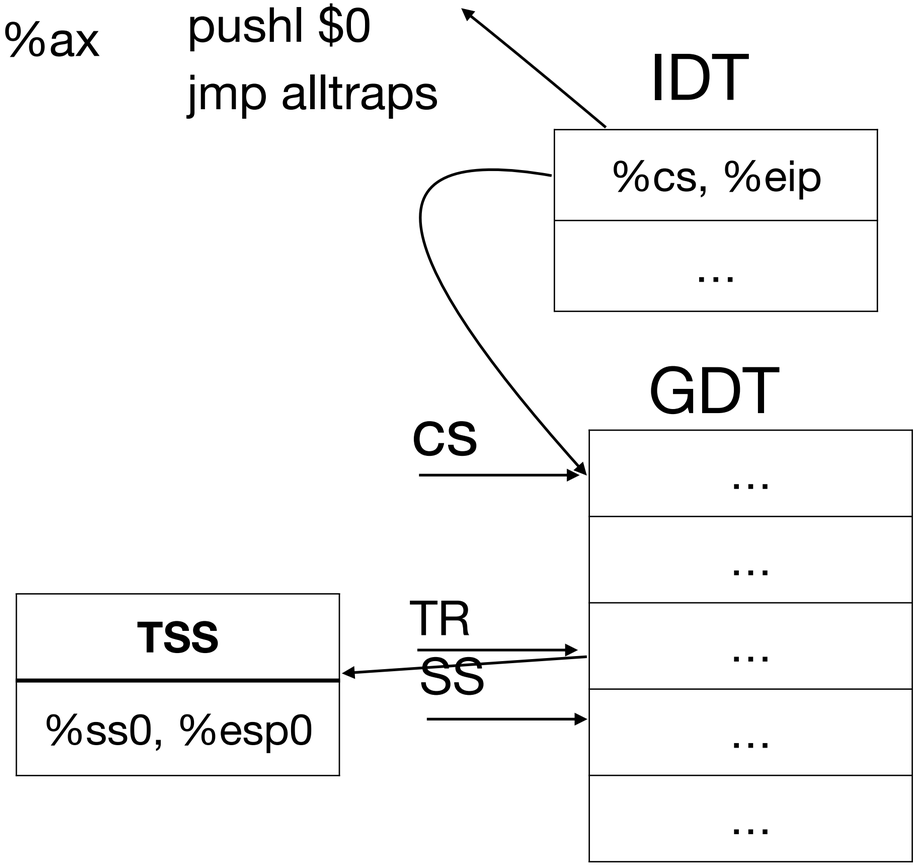

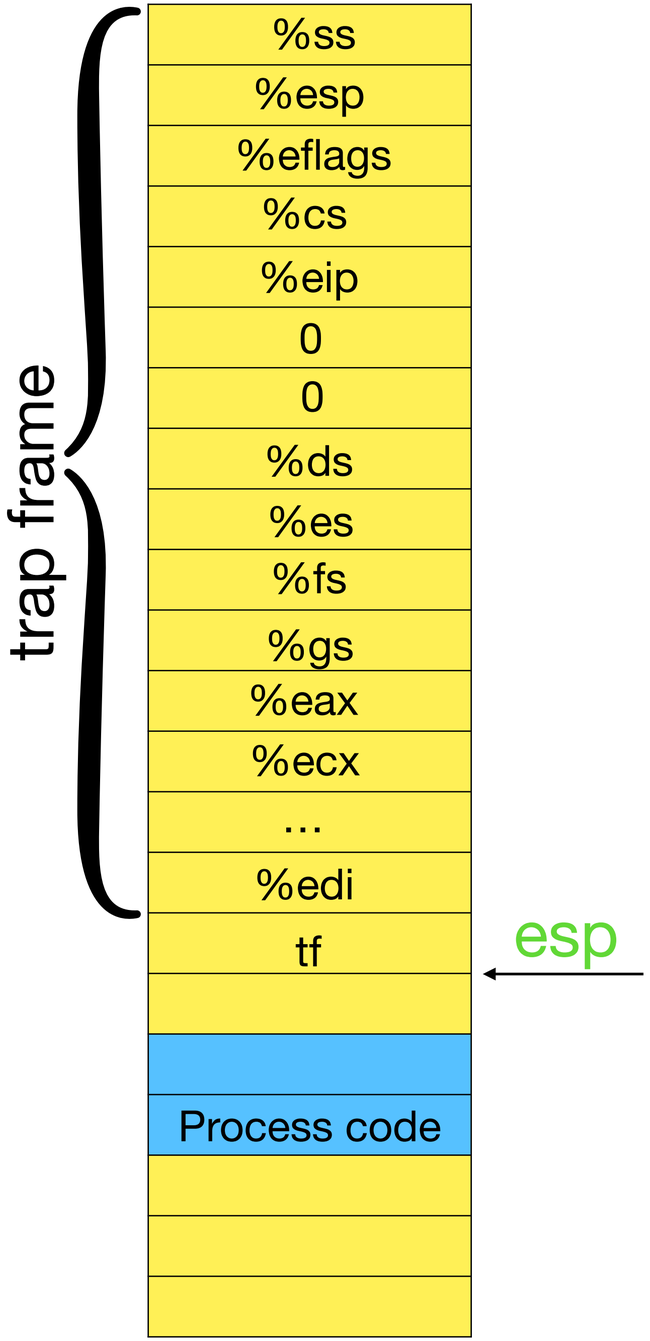

Interrupt handling with user process running

```
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
```

eip

vectors.S

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.globl vector0
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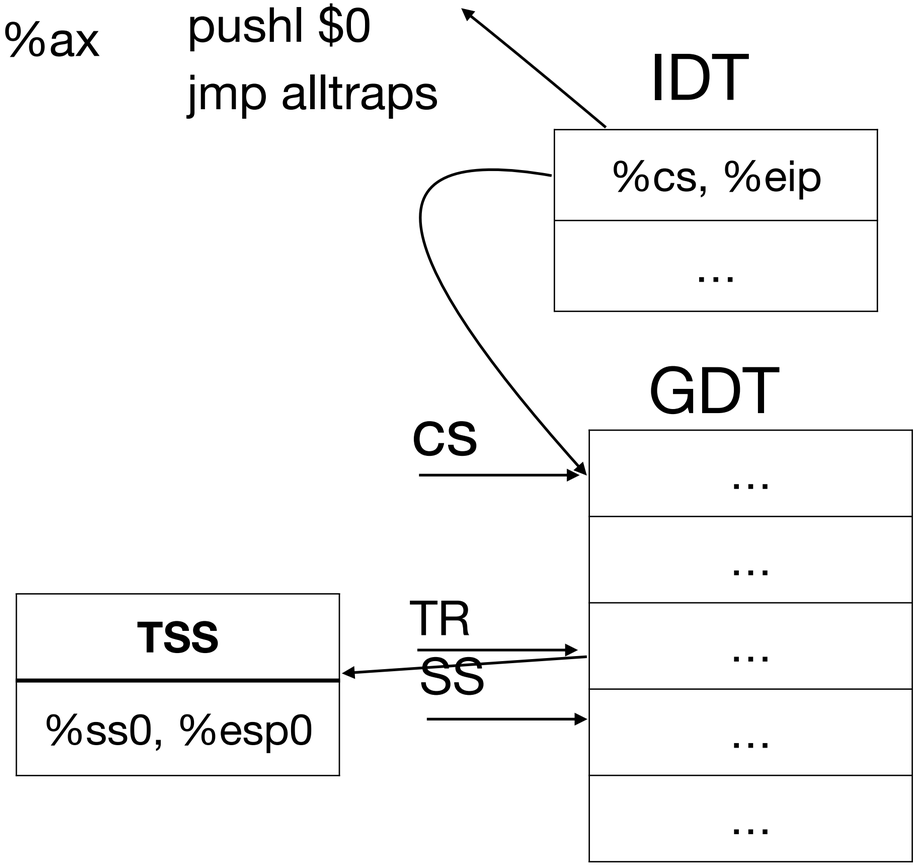

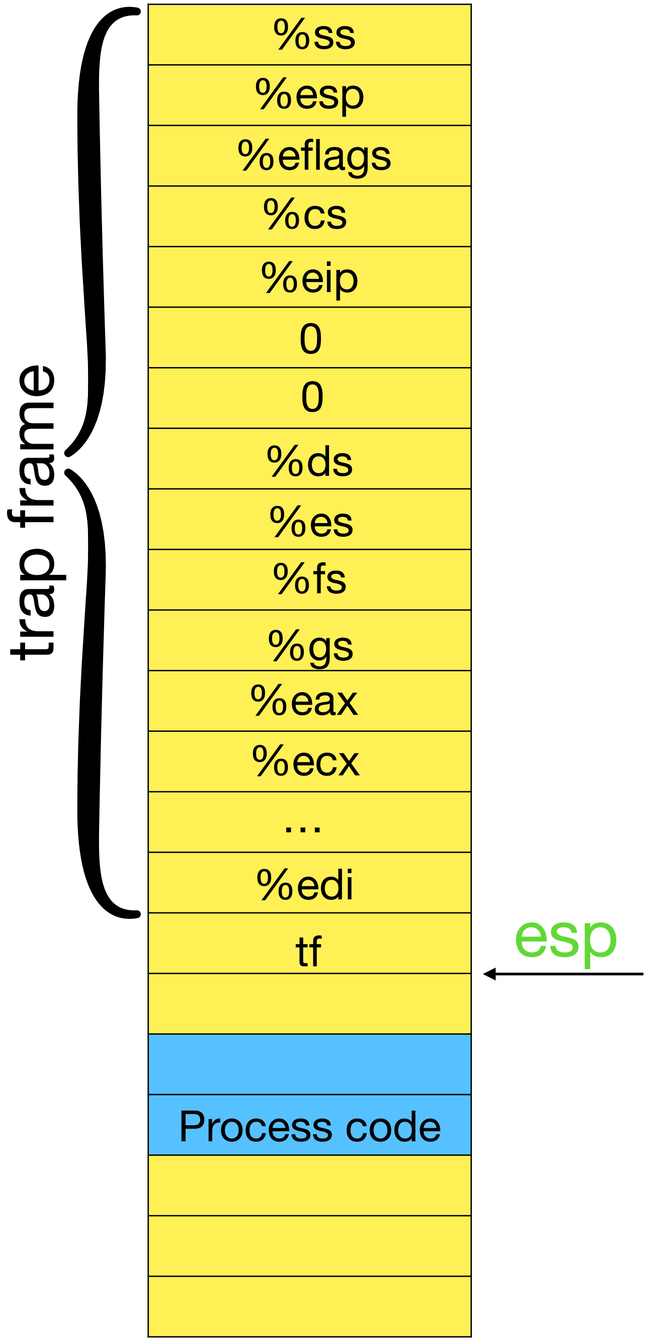

Interrupt handling with user process running

```
for(;;)
;
```

trapasm.S

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alltraps:
  pushl %ds..
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  pushl %esp
  call trap
  addl $4, %esp
  popal
  popl %ds..
  addl $0x8, %esp
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eip

vectors.S

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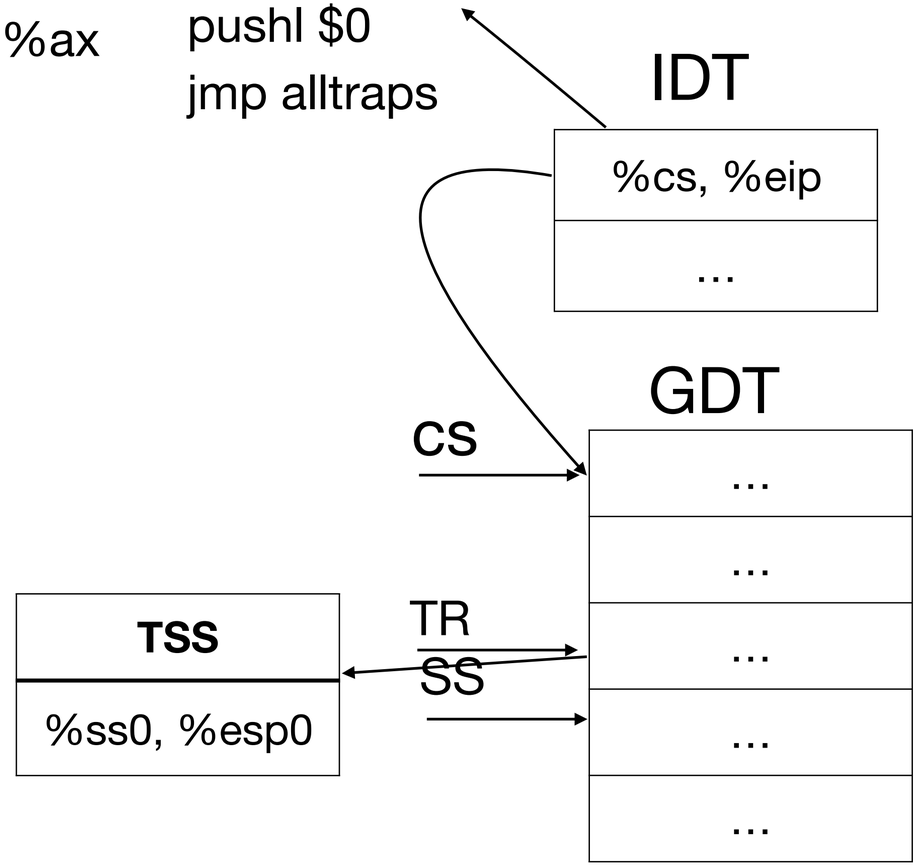

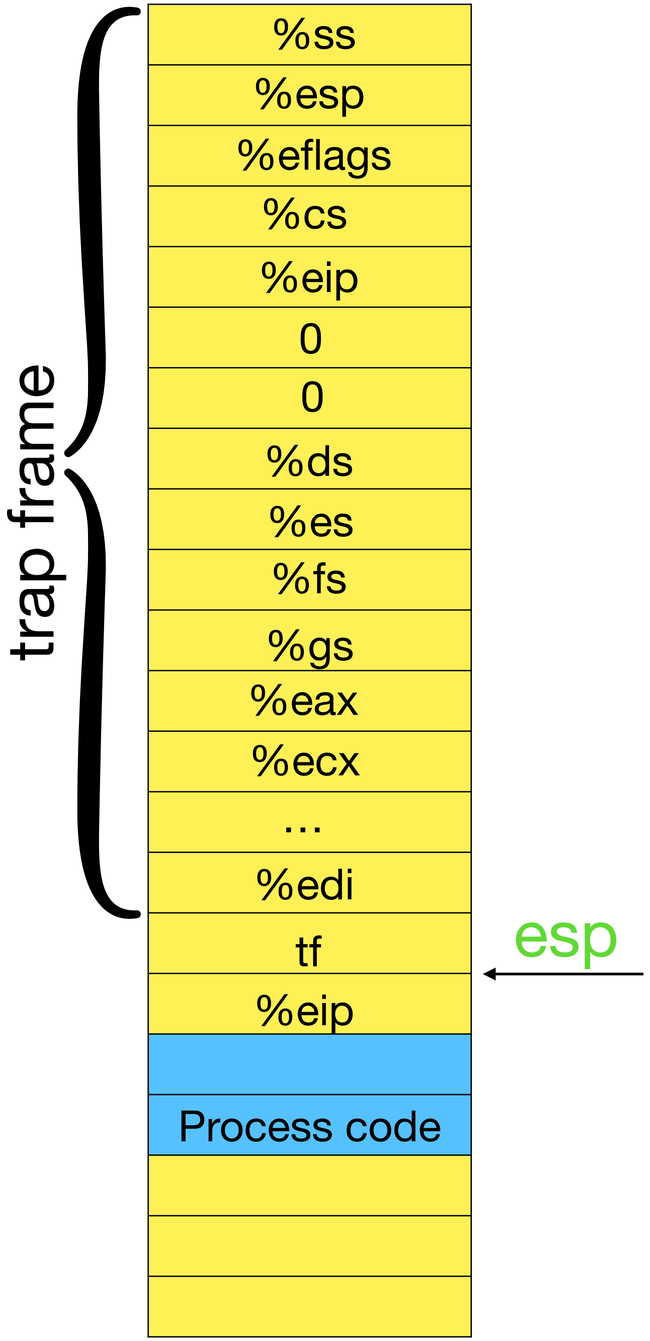

Interrupt handling with user process running

```
for(;;)
;
```

trapasm.S

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

eip

vectors.S

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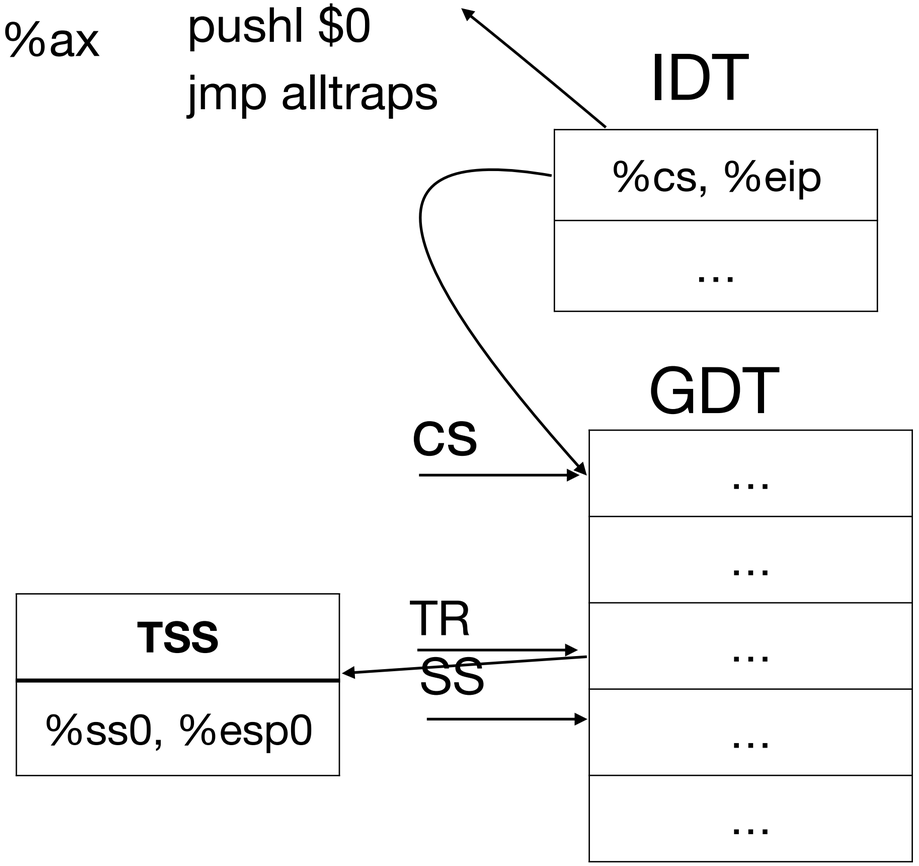

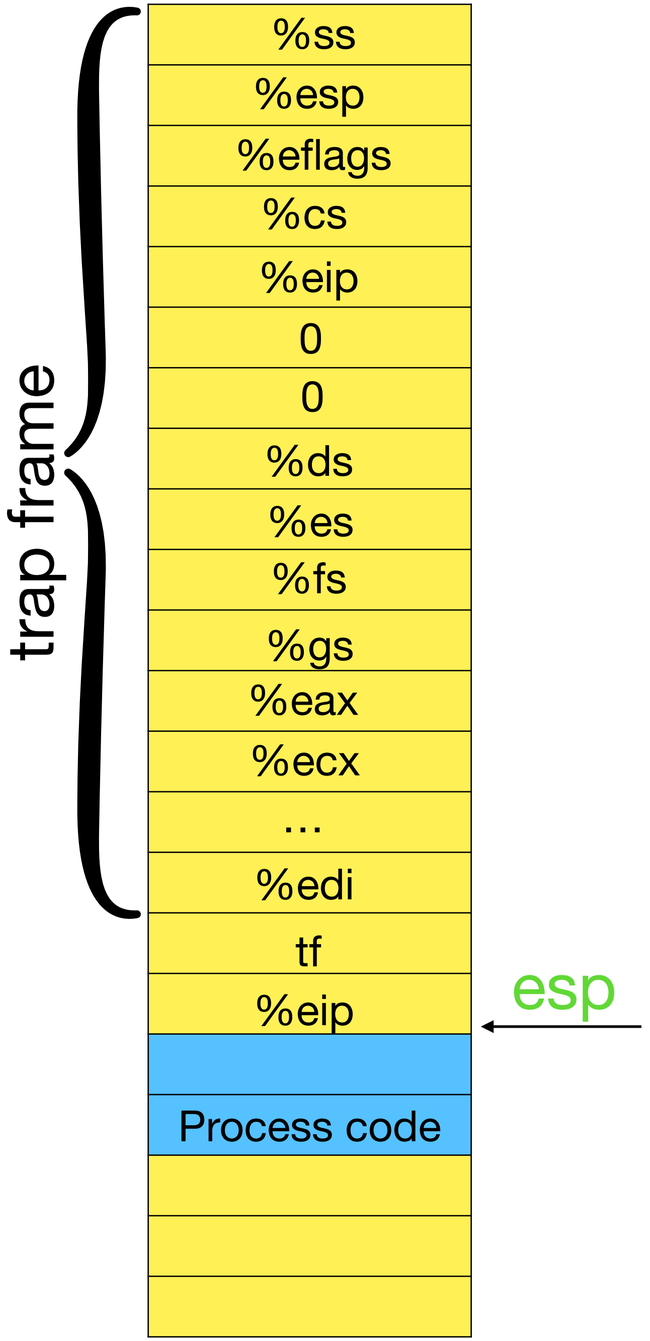

Interrupt handling with user process running

```
for(;;)
;
```

trapasm.S

```
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  movw %ax, %ds..
  pushl %esp
  call trap
  addl $4, %esp
  popal
  popl %ds..
  addl $0x8, %esp
  iret
```

eip

vectors.S

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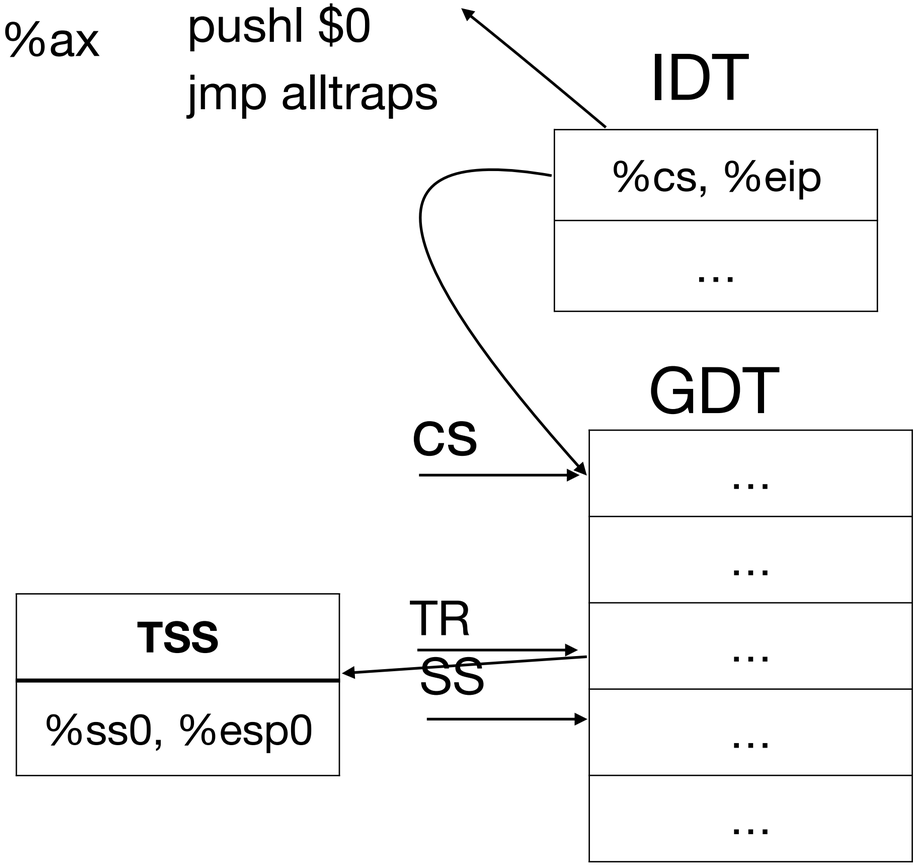

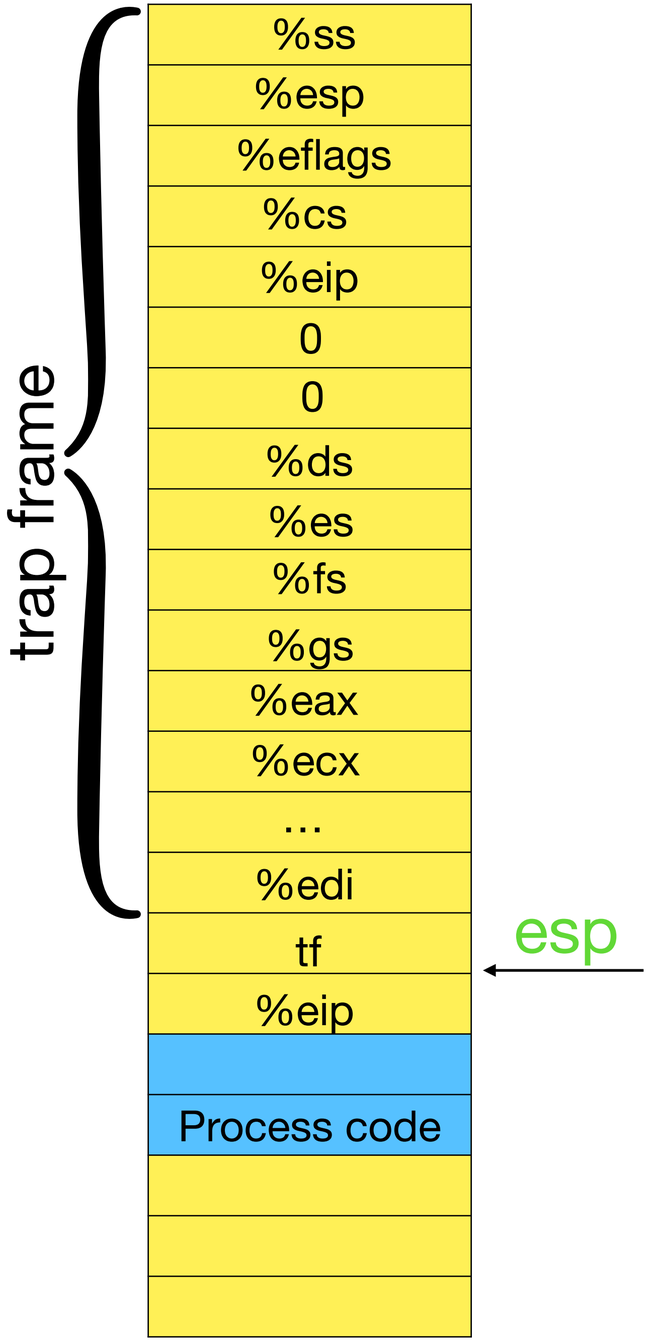

Interrupt handling with user process running

```
for(;;)
;
```

trapasm.S

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

eip

vectors.S

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.globl vector0
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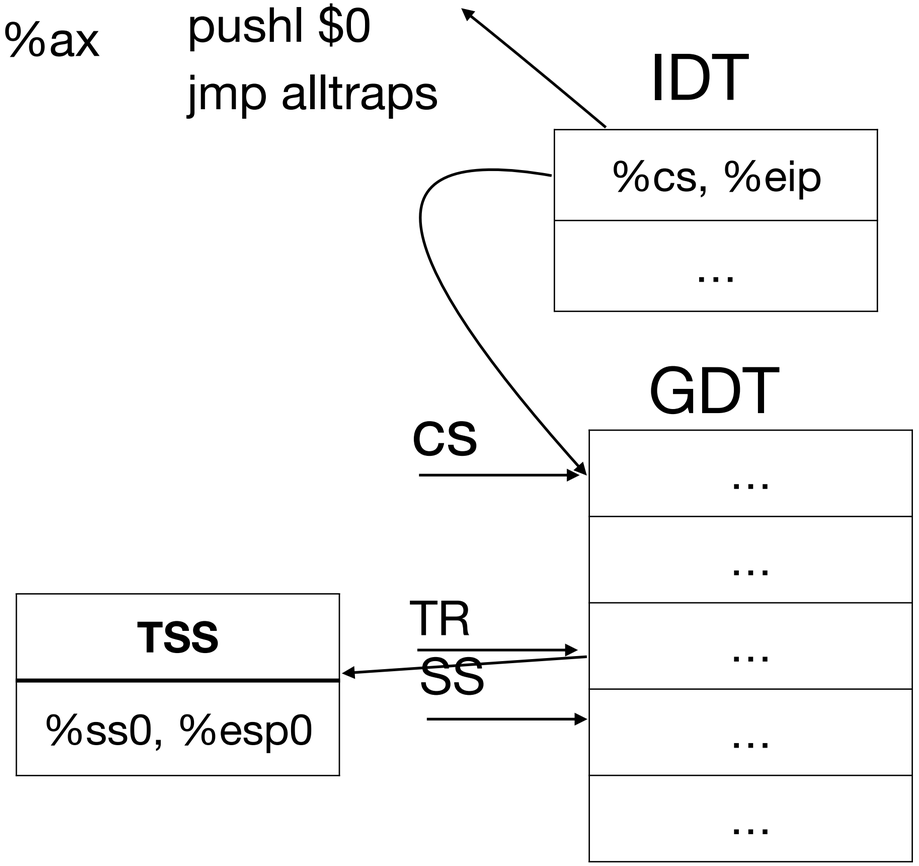

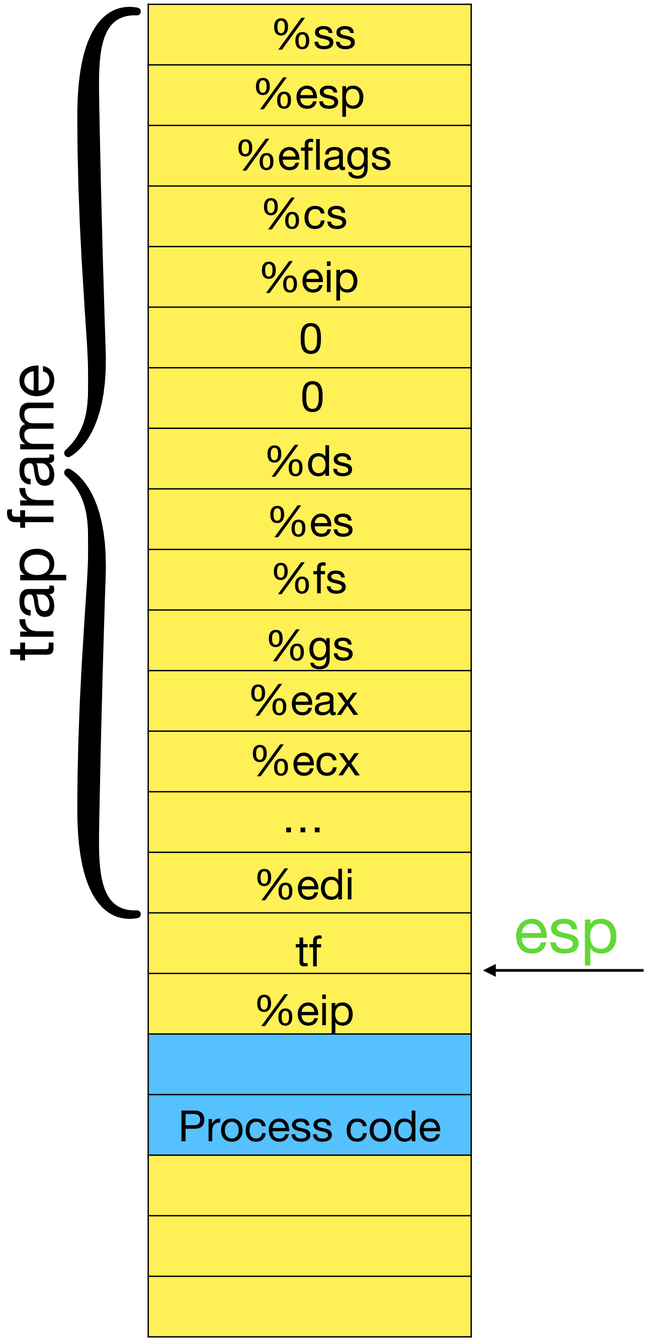

Interrupt handling with user process running

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trapasm.S

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  addl $4, %esp
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  popl %ds..
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eip

vectors.S

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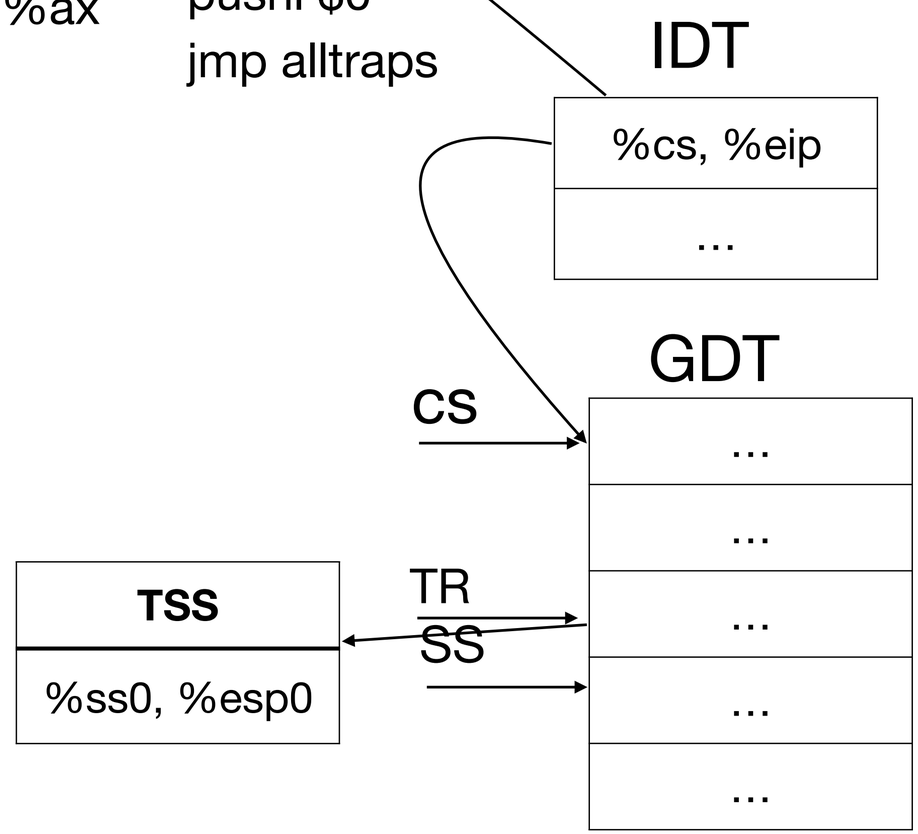

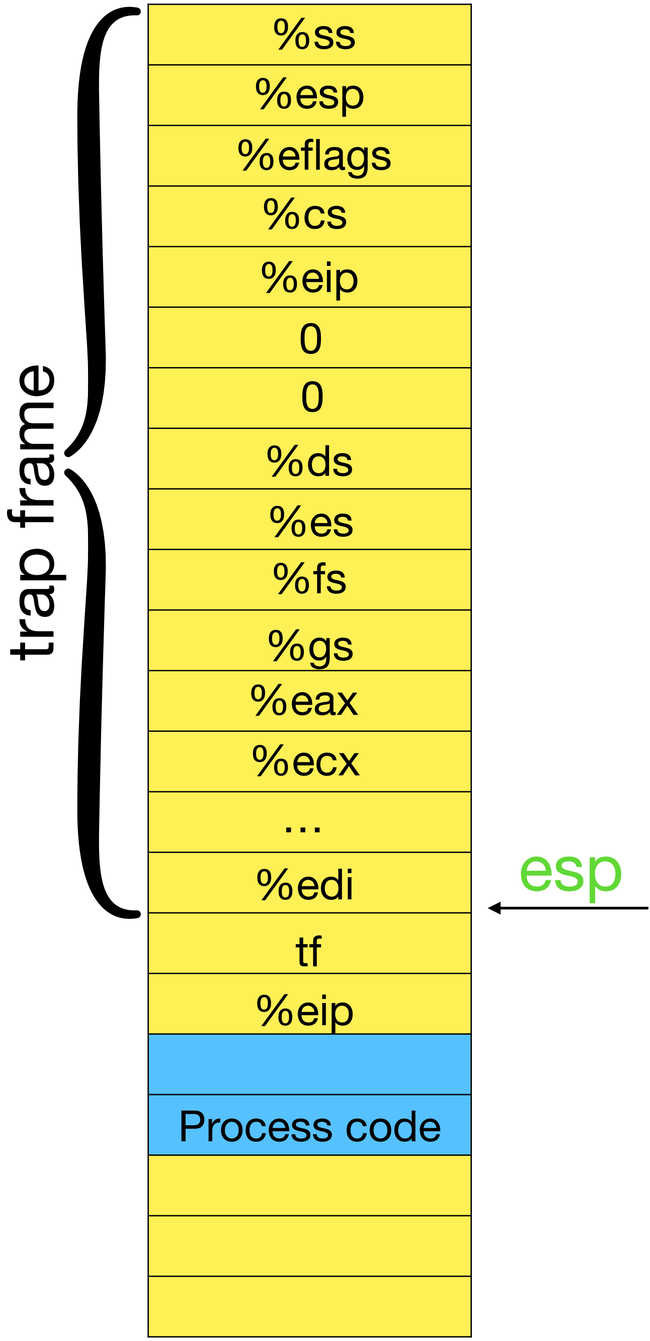

Interrupt handling with user process running

```
for(;;)
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```

trapasm.S

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

eip

vectors.S

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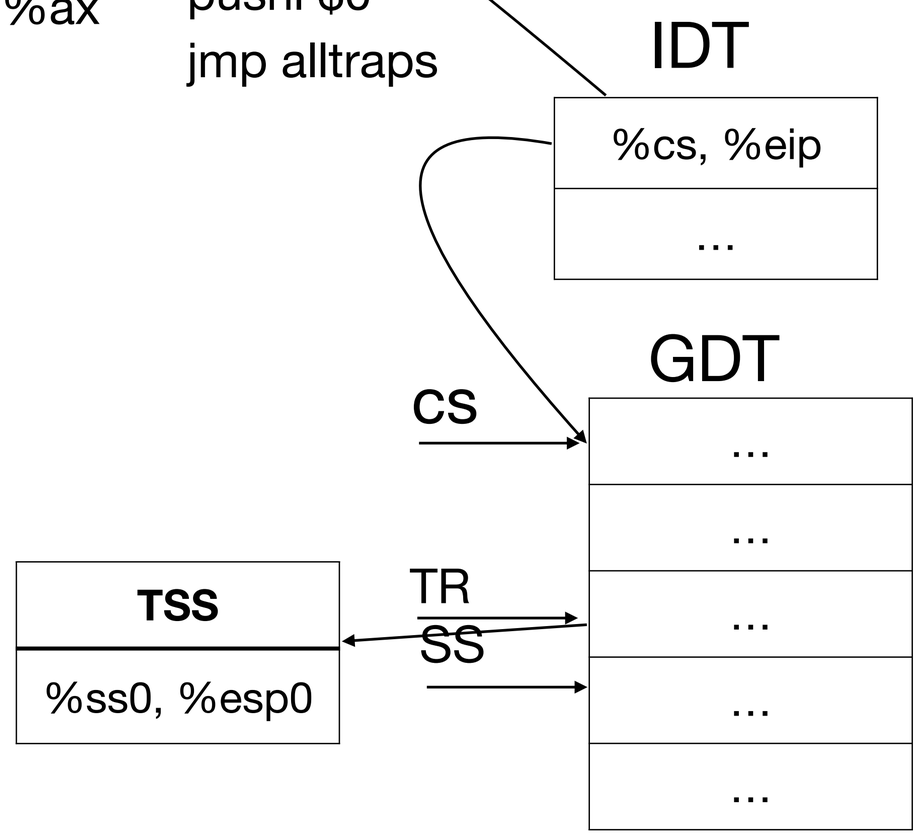

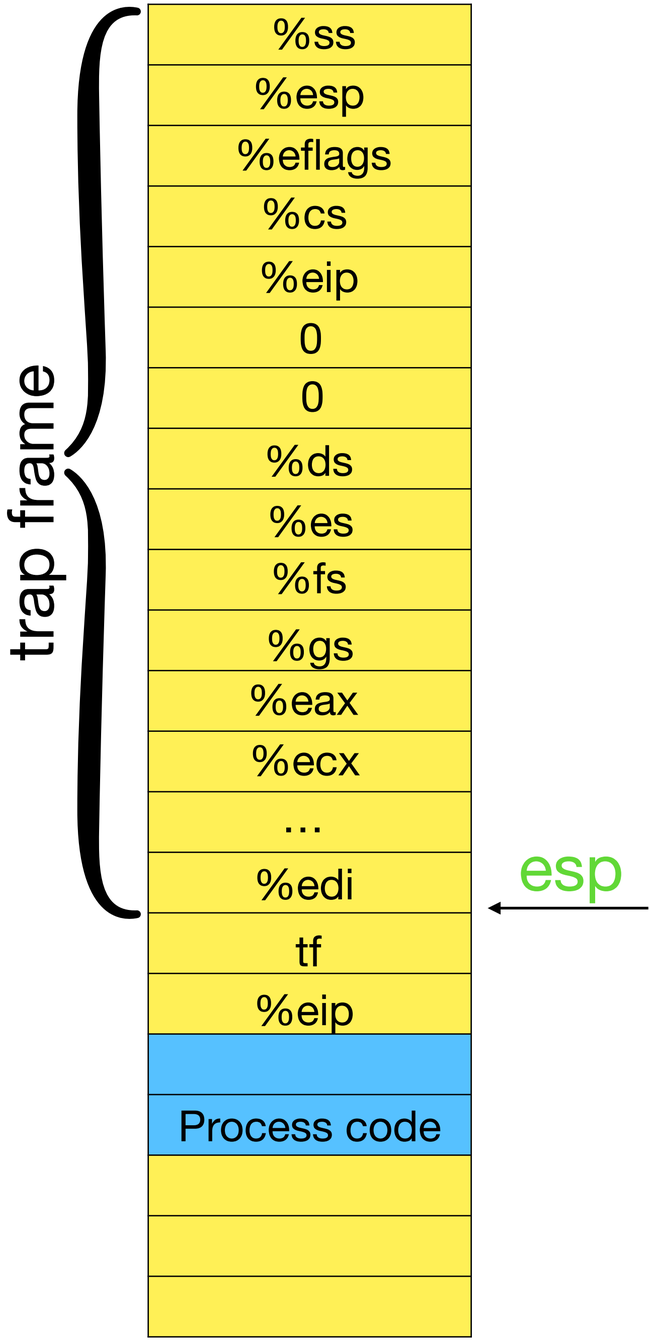

Interrupt handling with user process running

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```

trapasm.S

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

eip

vectors.S

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vector0:
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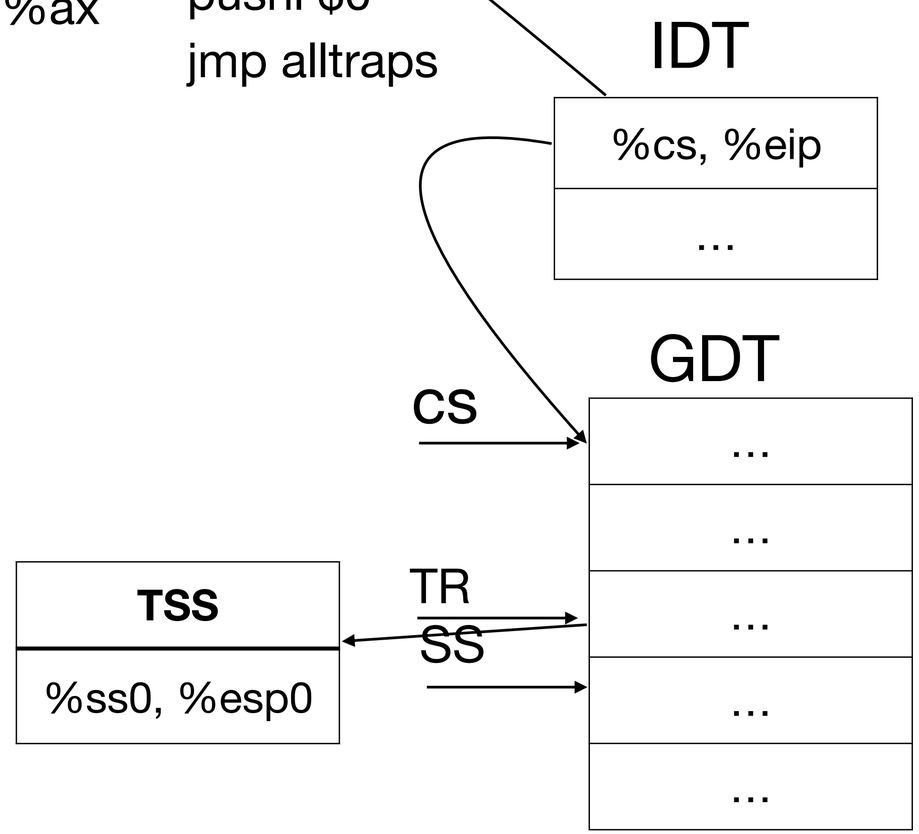

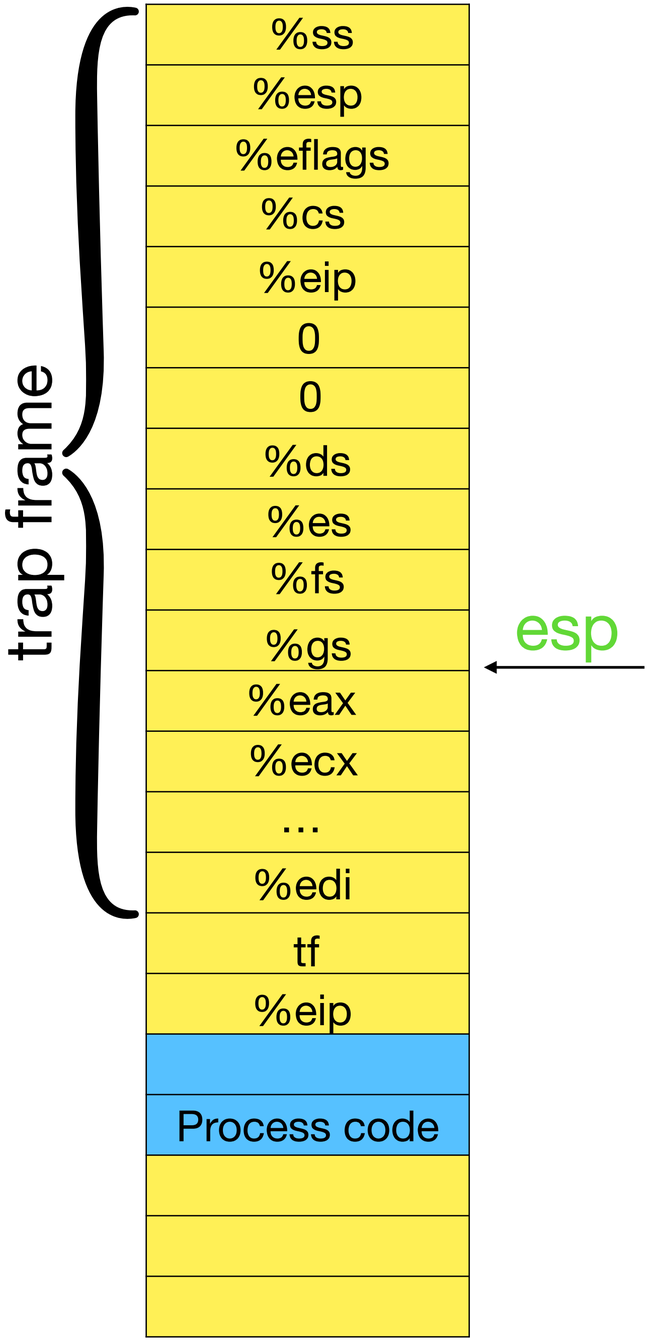

Interrupt handling with user process running

```
for(;;)
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```

trapasm.S

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

eip

vectors.S

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vector0:
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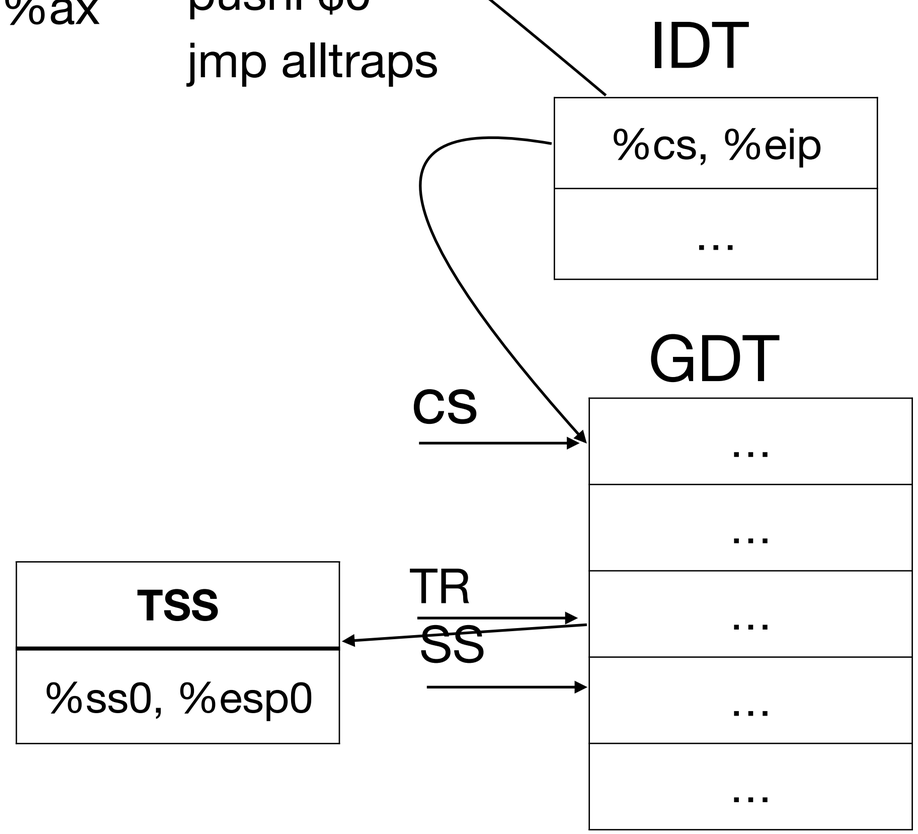

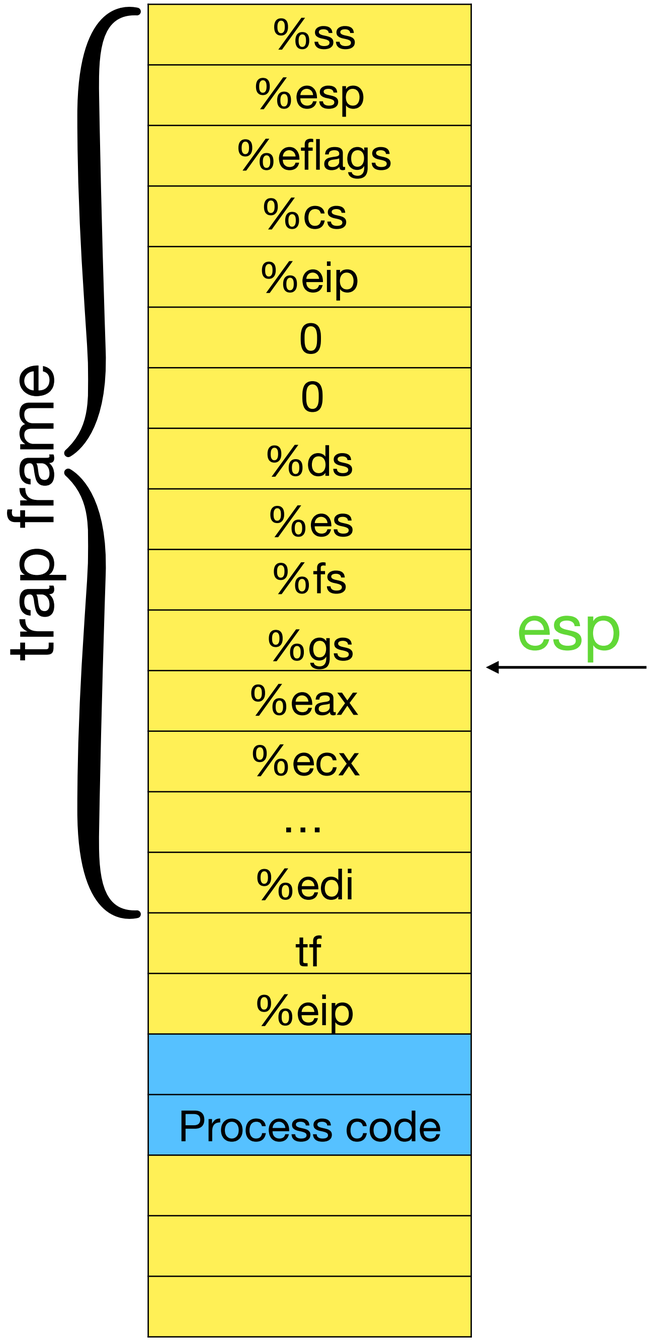

Interrupt handling with user process running

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trapasm.S

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  movw %ax, %ds..
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  addl $4, %esp
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eip

vectors.S

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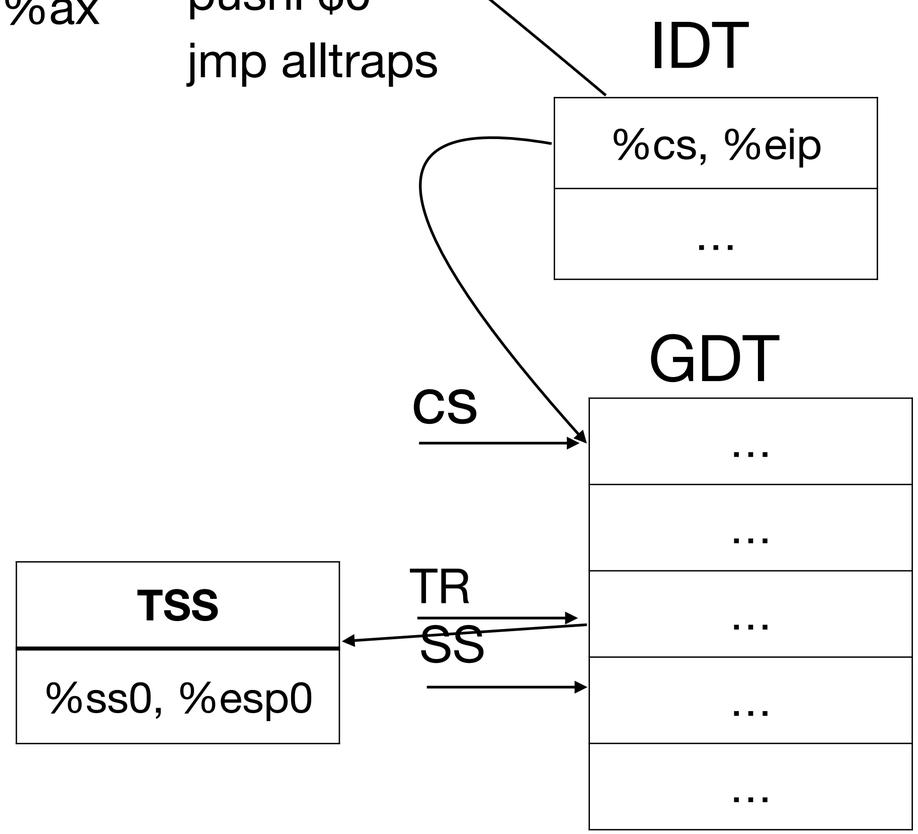

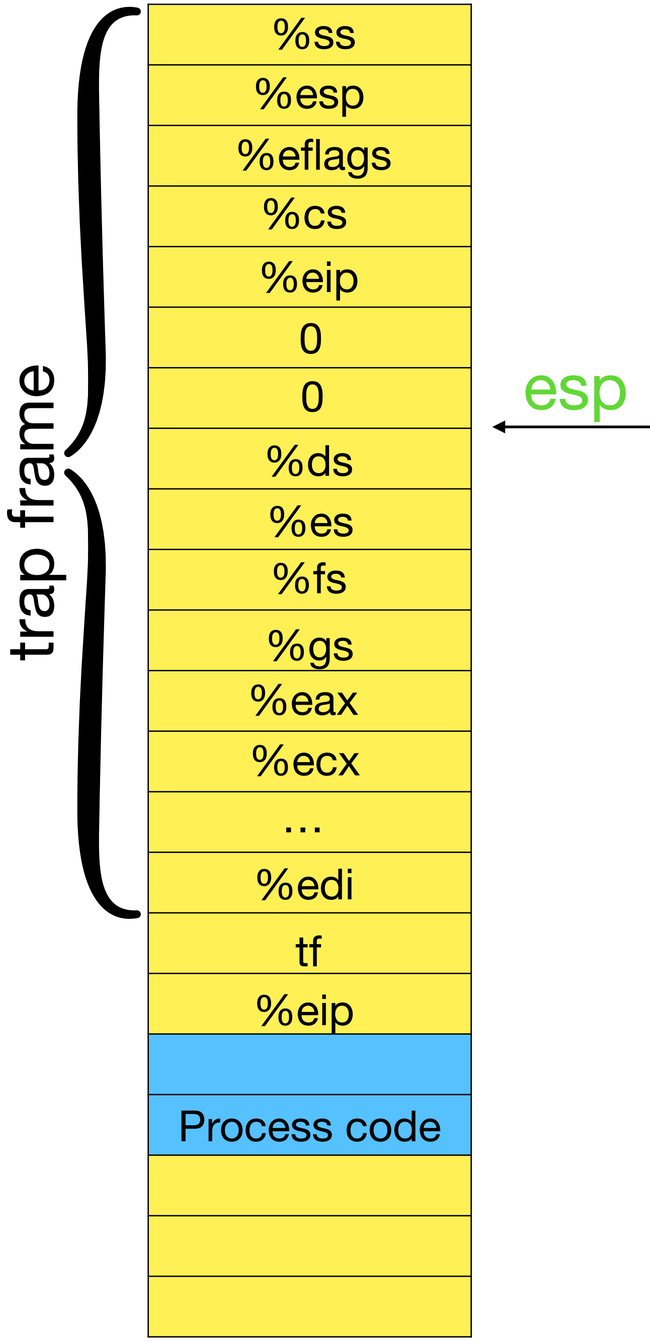

Interrupt handling with user process running

```
for(;;)
;
```

trapasm.S

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alltraps:
  pushl %ds..
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  movw $(SEG_KDATA<<3), %ax
  movw %ax, %ds..
  pushl %esp
  call trap
  addl $4, %esp
  popal
  popl %ds..
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eip

vectors.S

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vector0:
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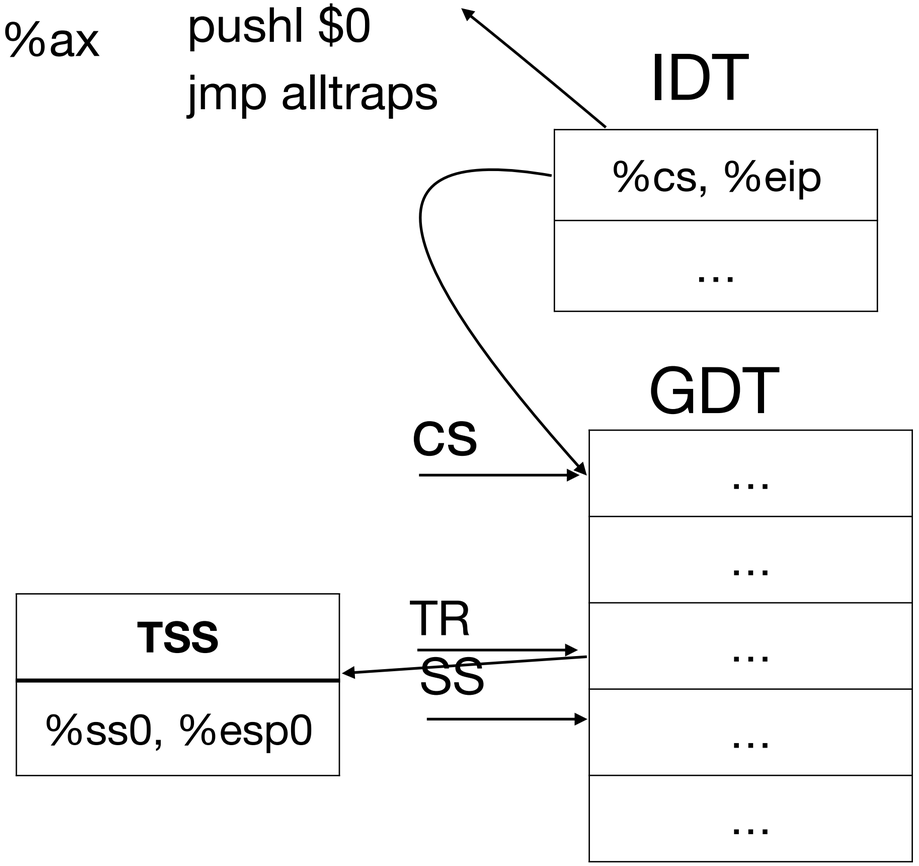

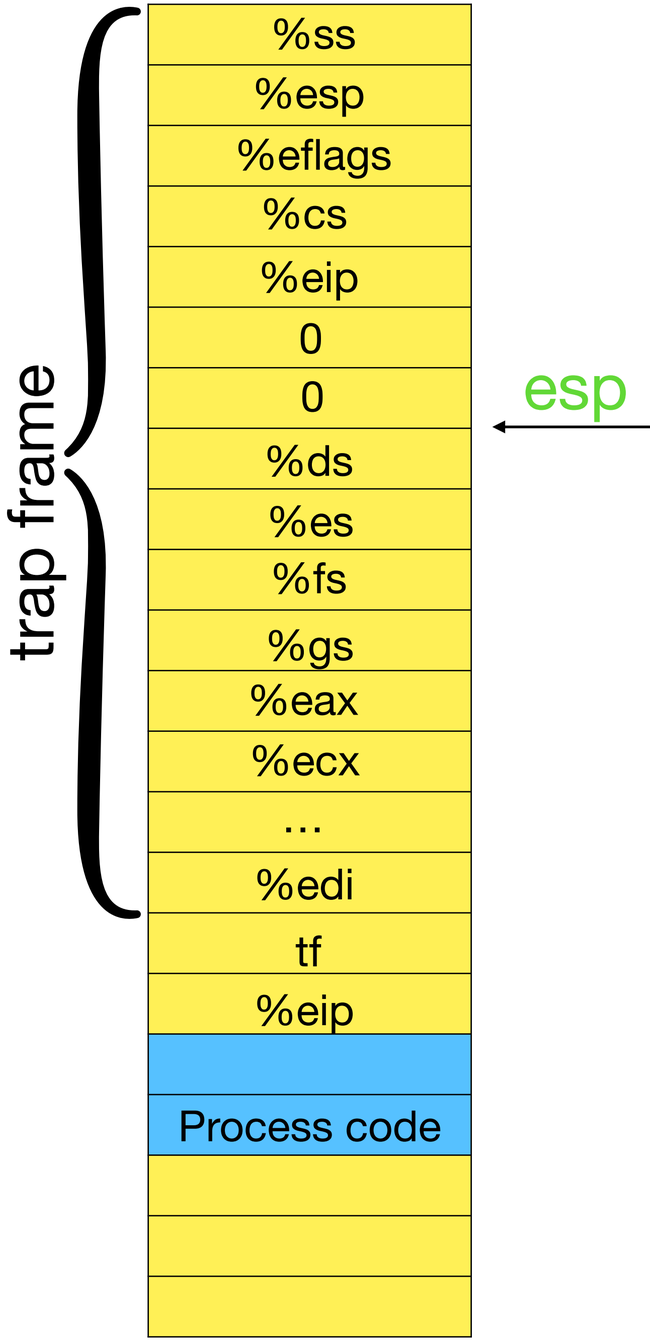

Interrupt handling with user process running

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for(;;)
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trapasm.S

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eip

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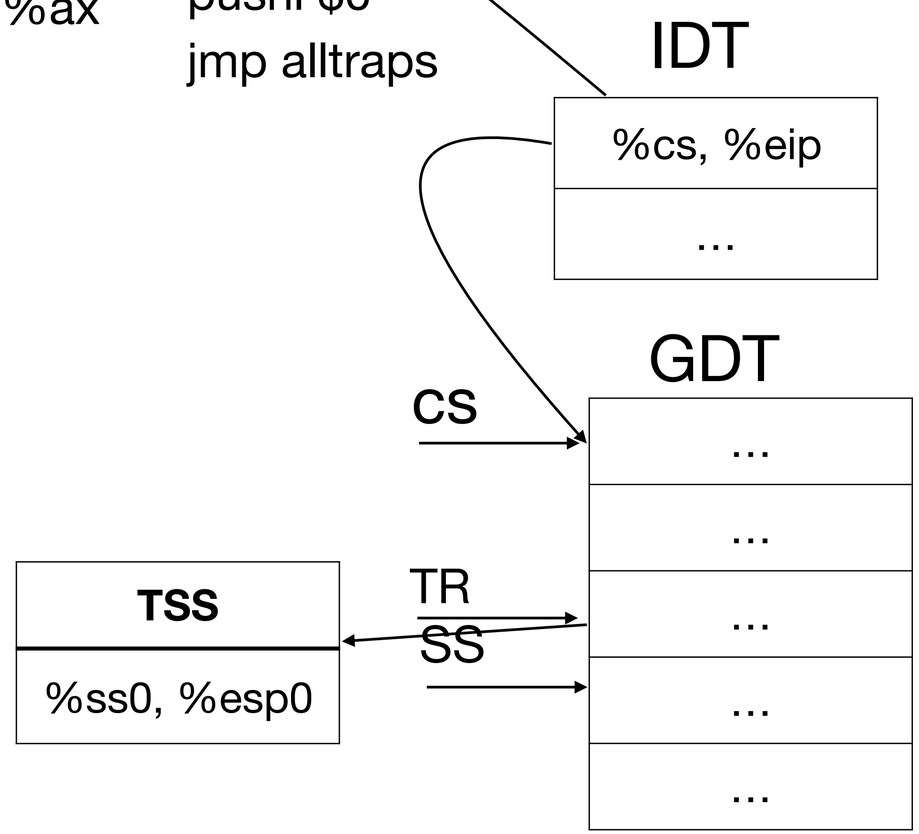

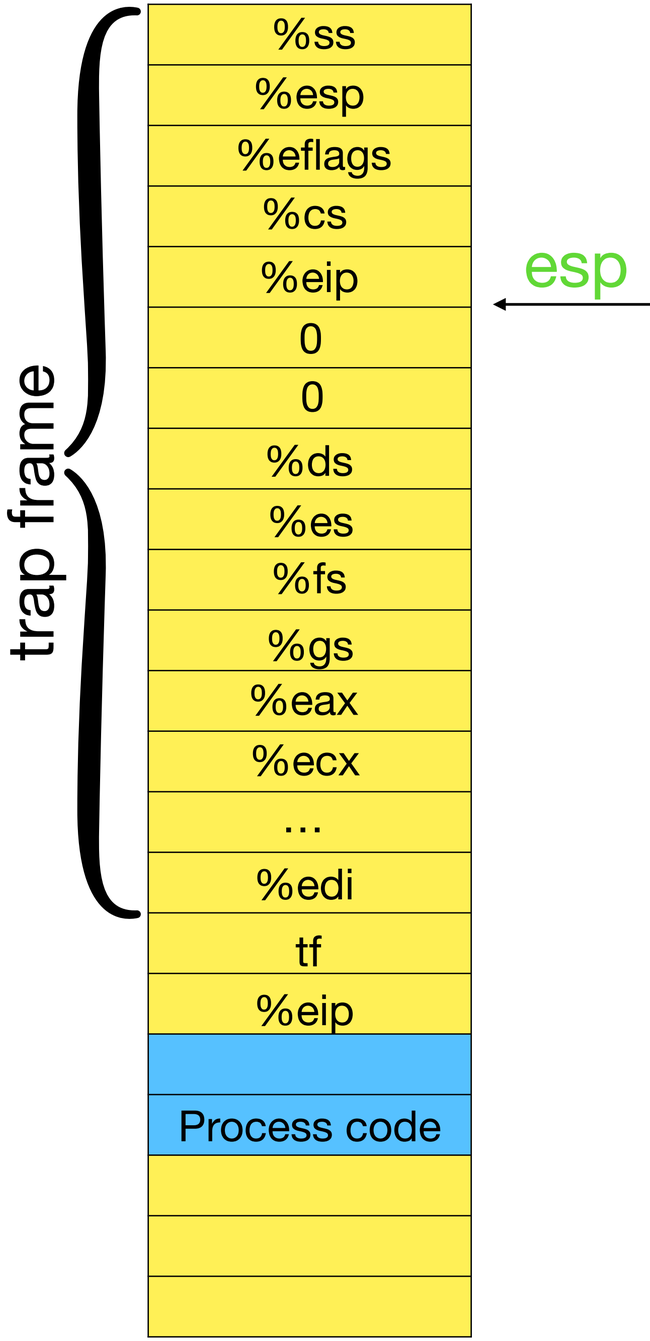

Interrupt handling with user process running

```
for(;;)
;
```

trapasm.S

```
alltraps:
  pushl %ds..
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  movw %ax, %ds..
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eip

vectors.S

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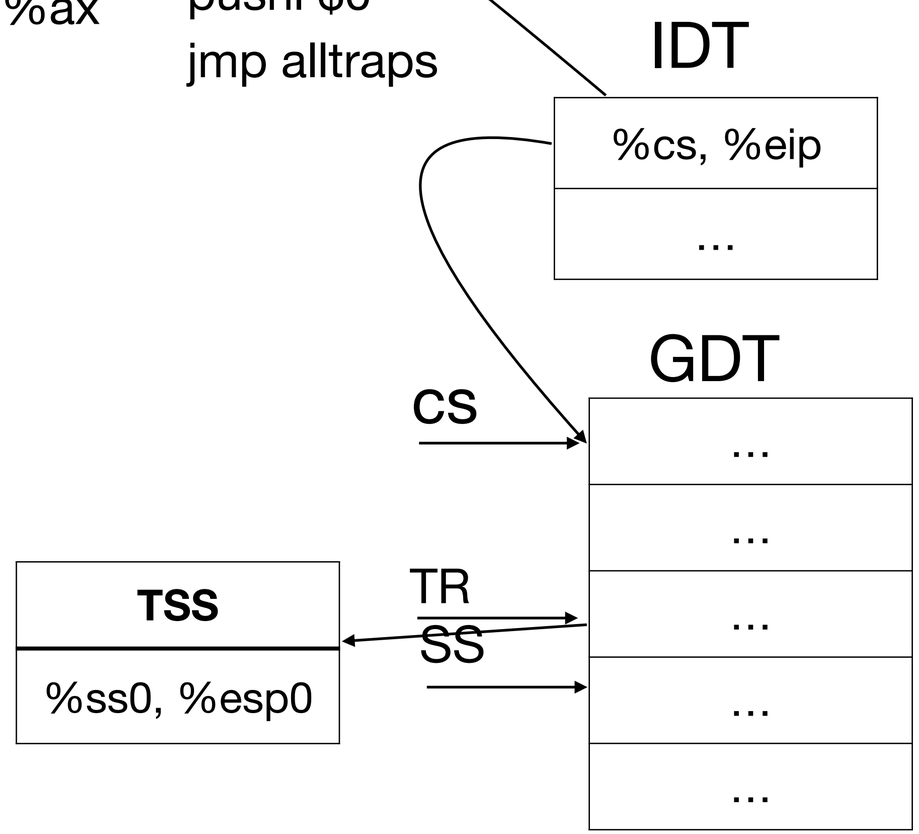

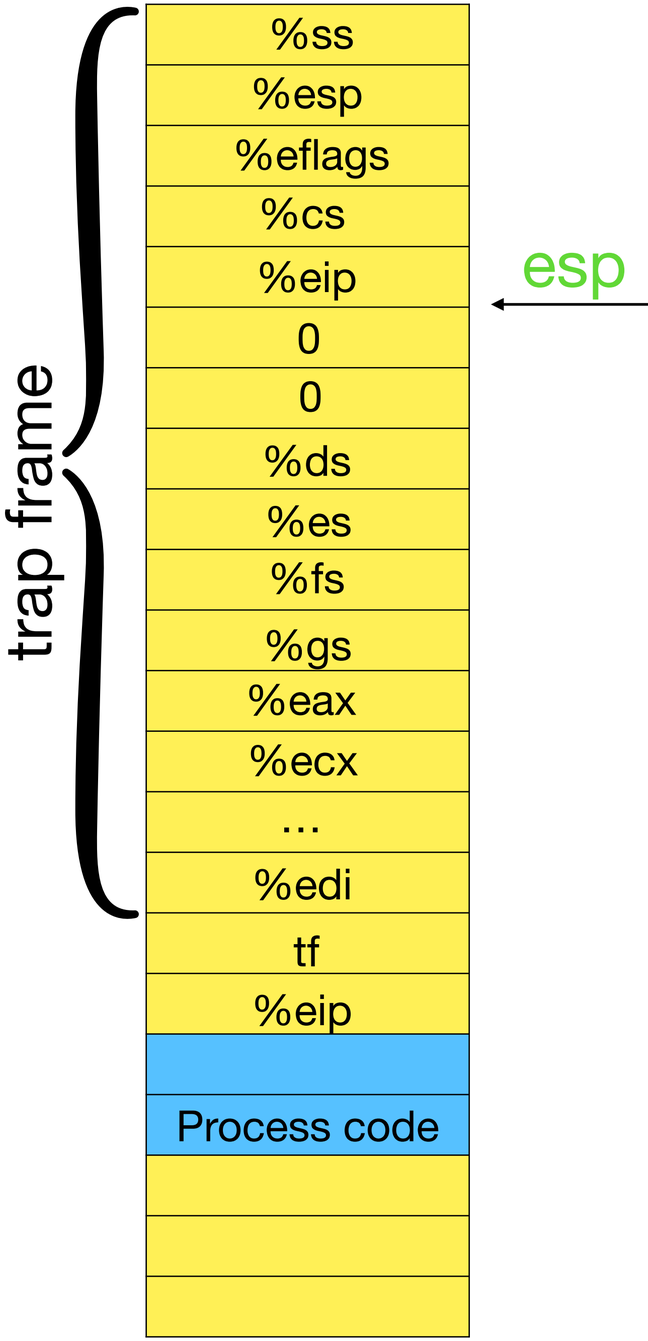

Interrupt handling with user process running

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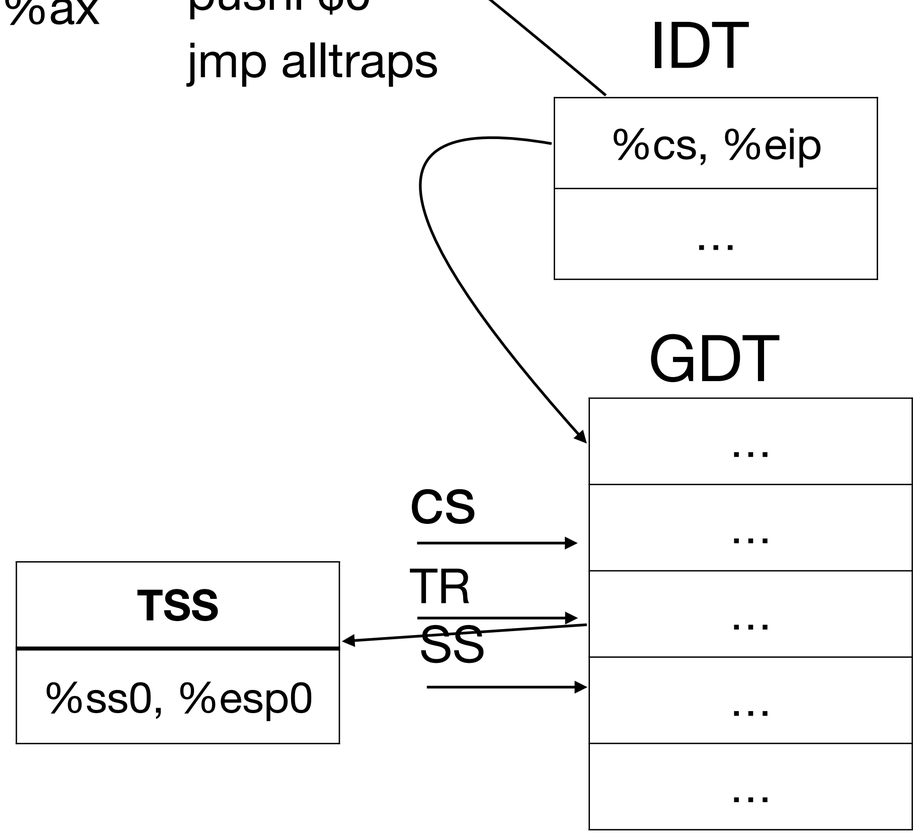

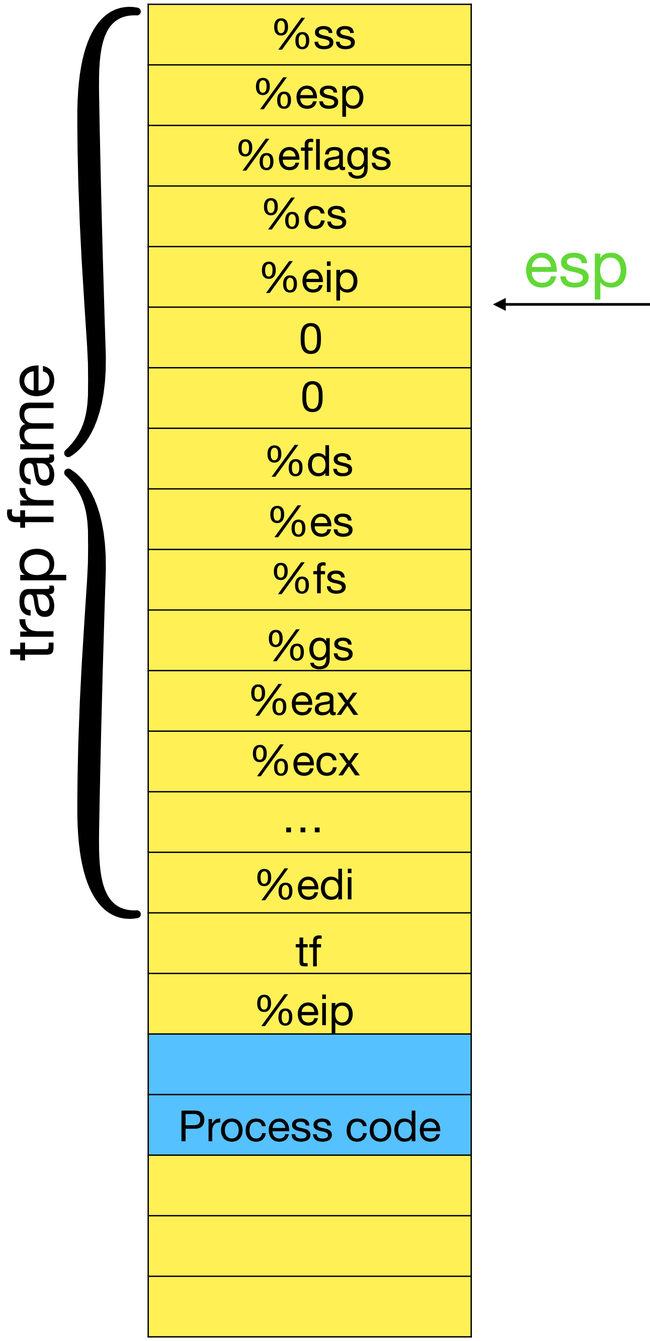

Interrupt handling with user process running

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for(;;)
;
```

trapasm.S

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alltraps:
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eip

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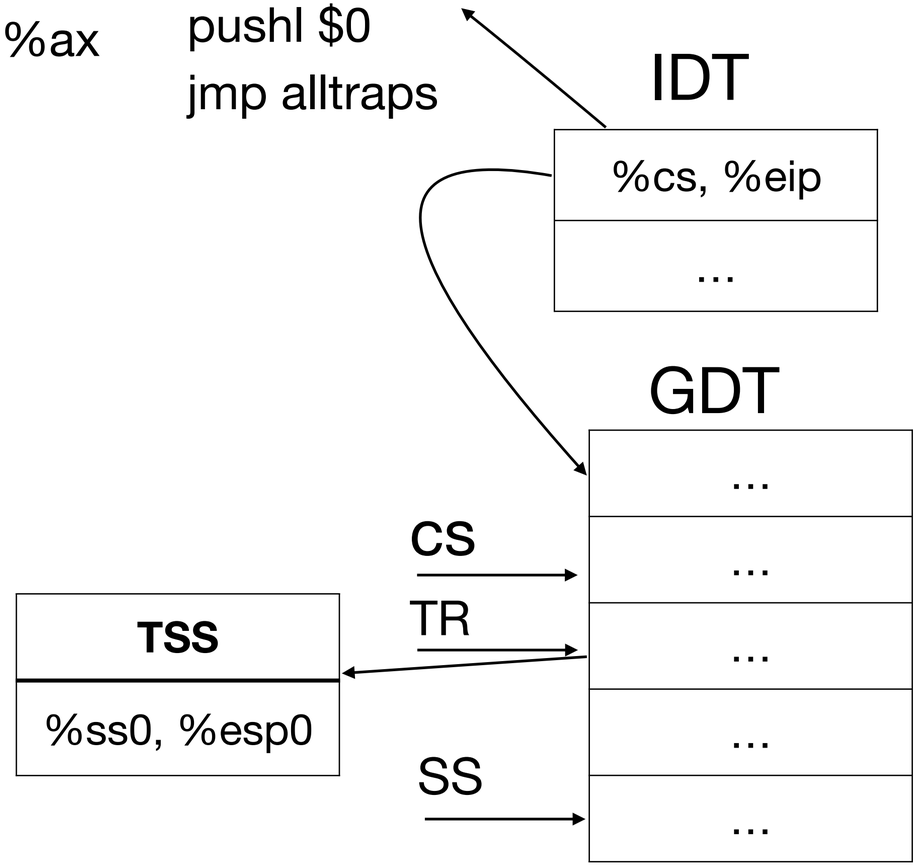

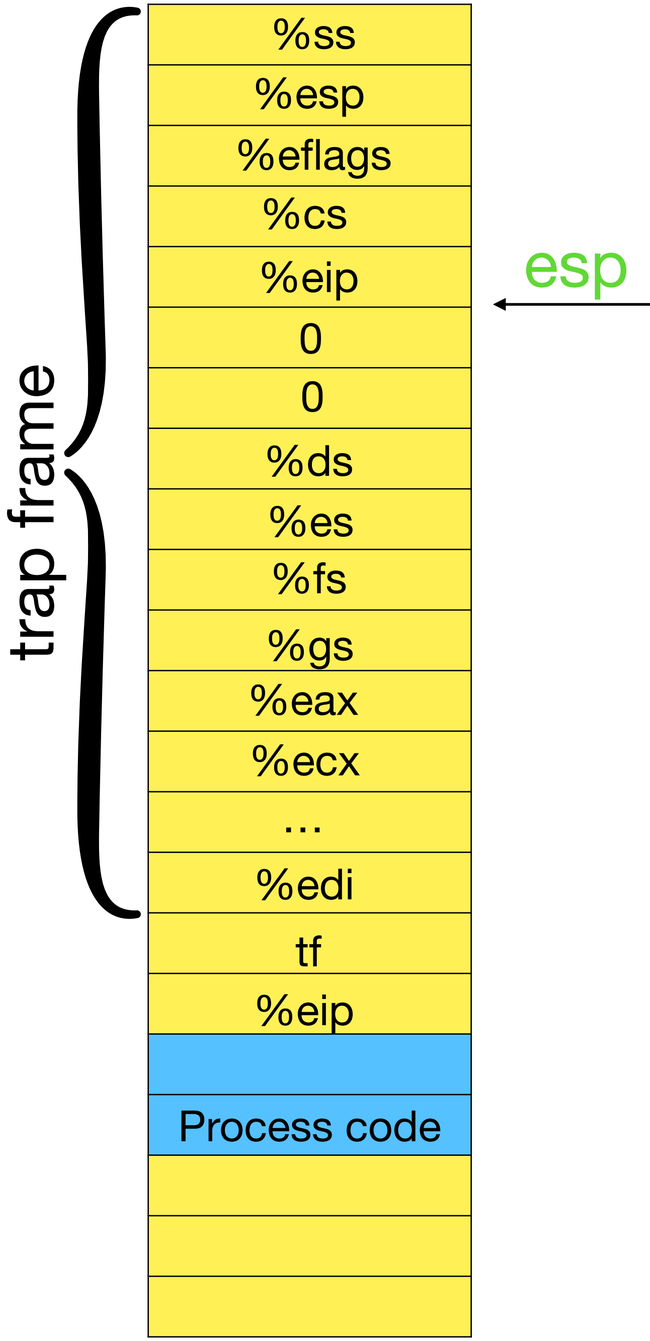

Interrupt handling with user process running

```
for(;;)
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```

trapasm.S

```
alltraps:
  pushl %ds..
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  pushl %esp
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  popl %ds..
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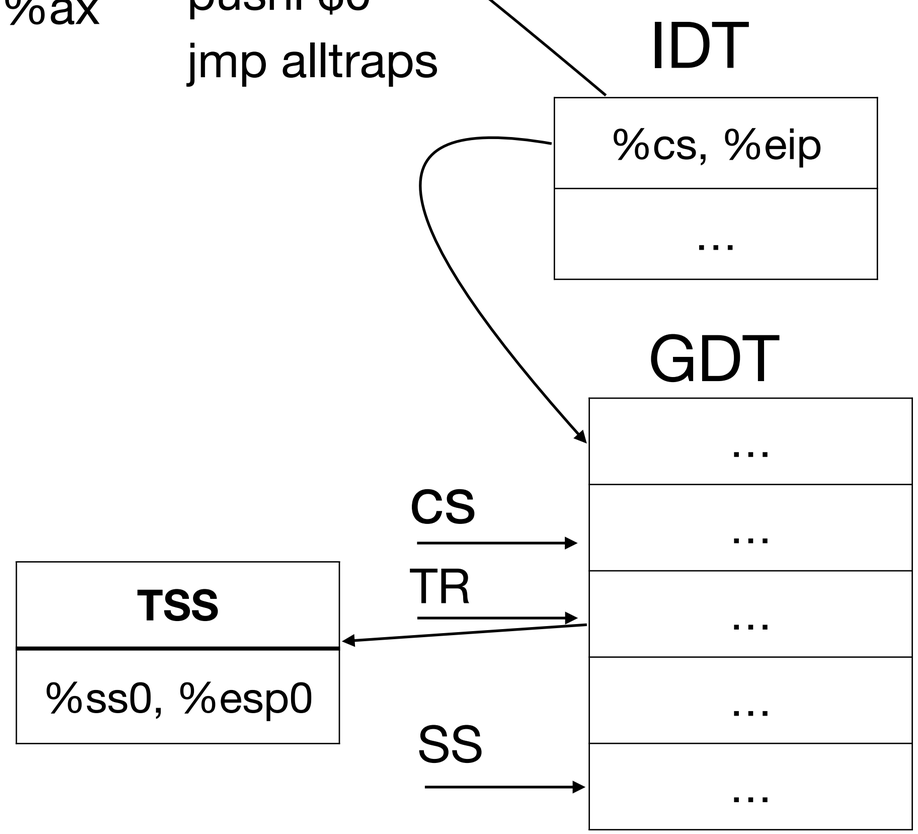
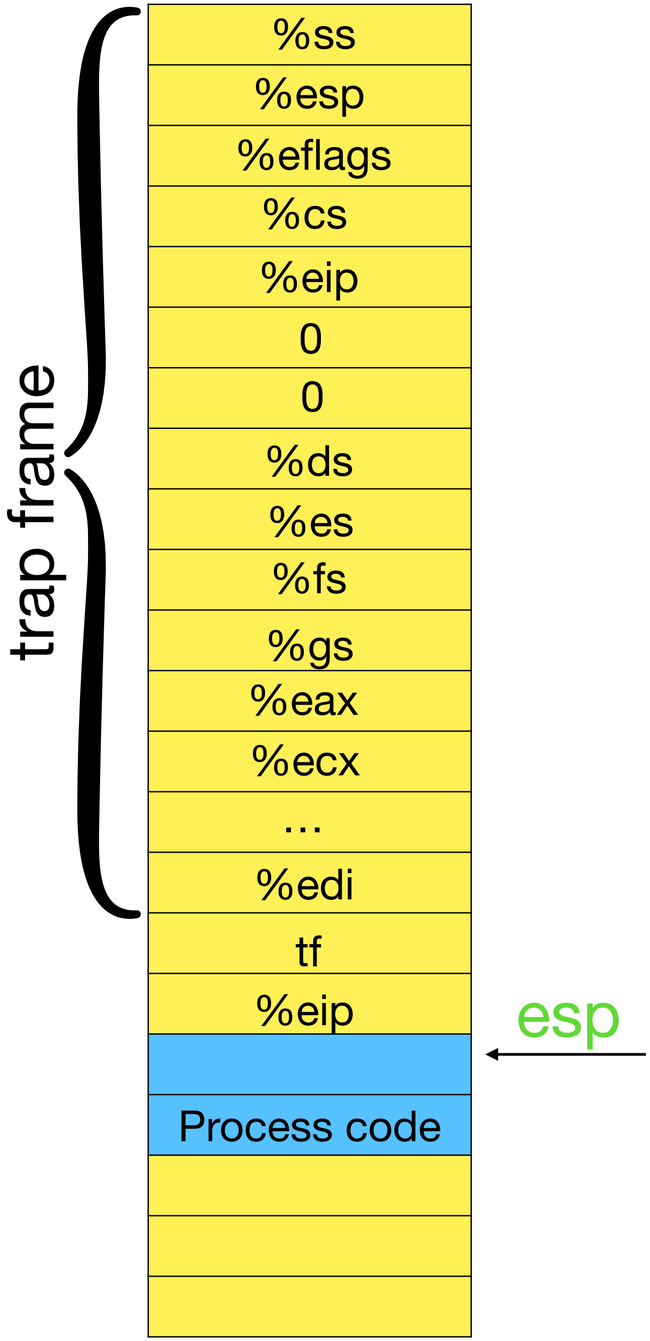
```

eip

vectors.S

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





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

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vector0:
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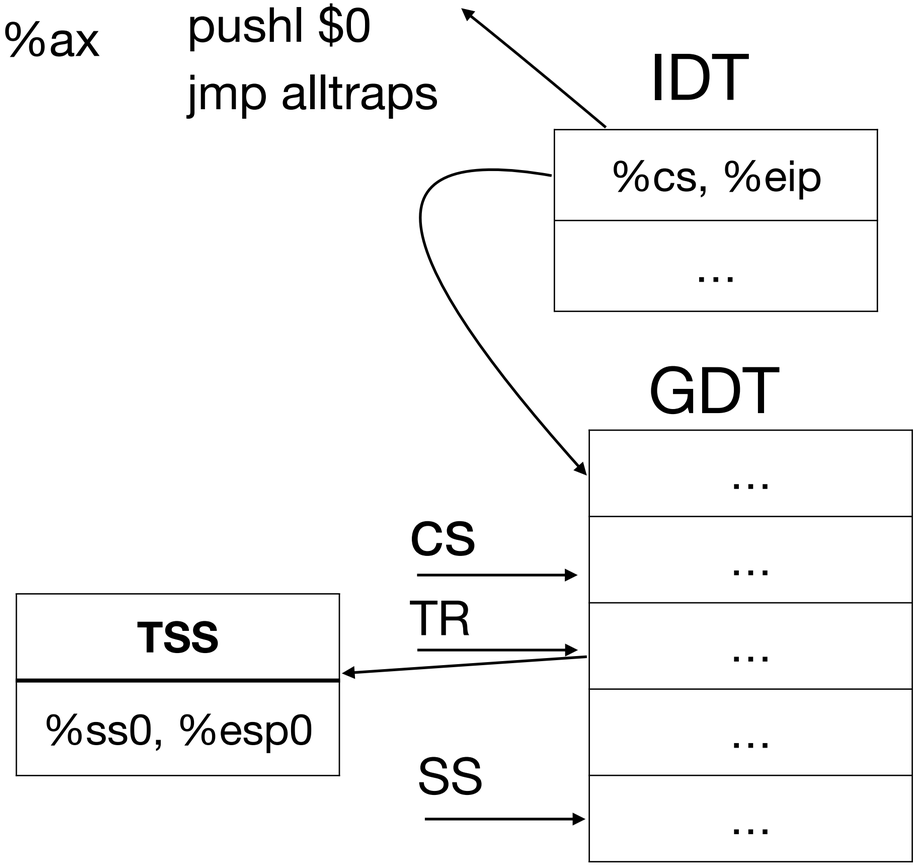

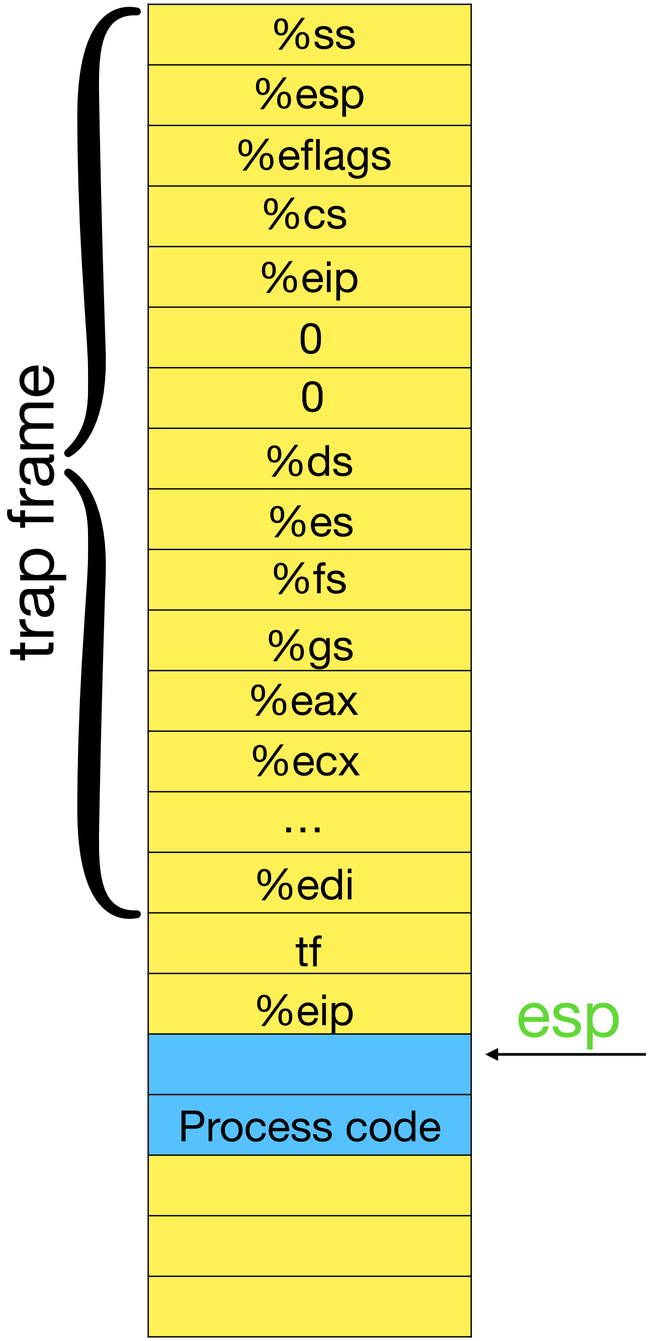

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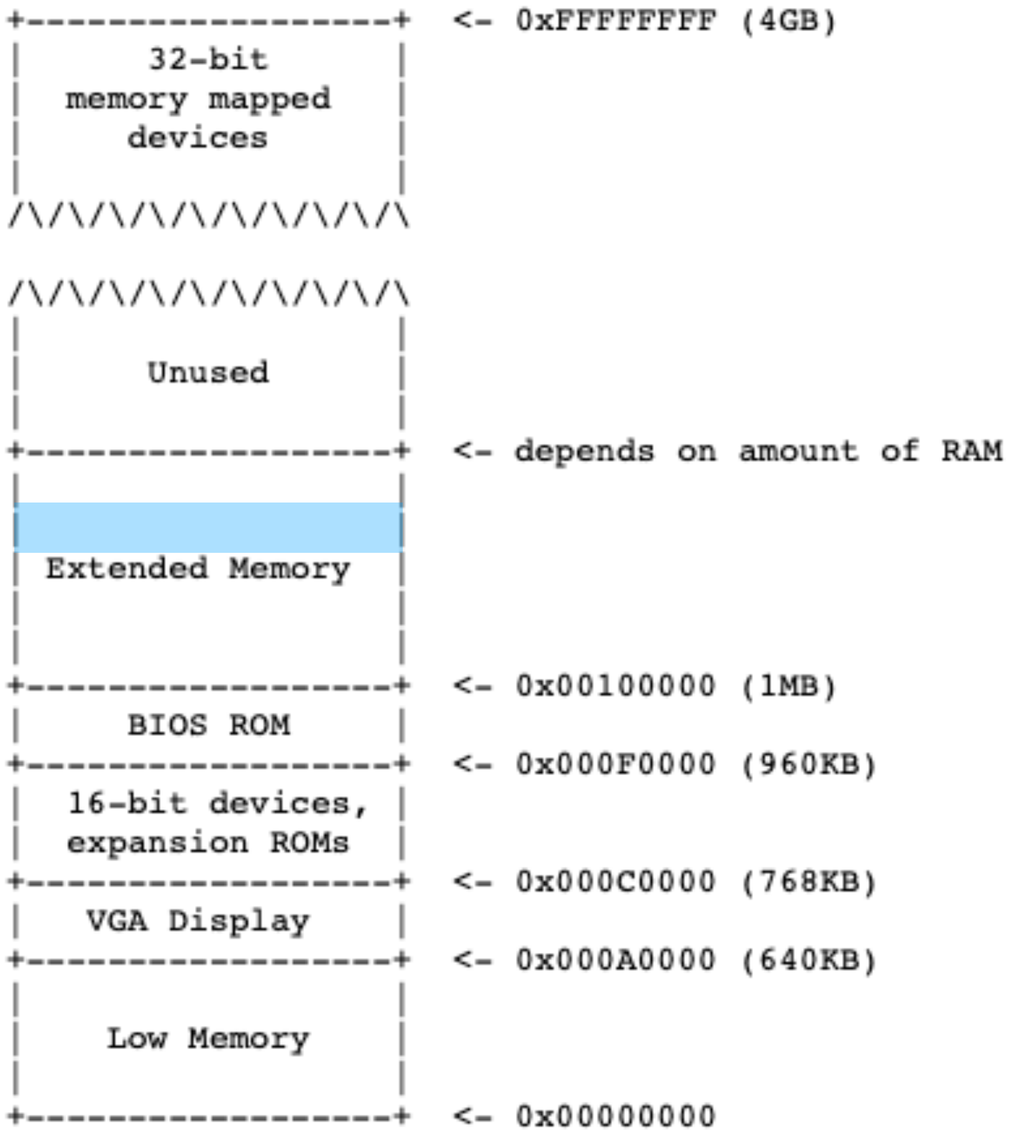
  - Not directly. It can change only via trap handling mechanism. OS code runs upon a trap. Trap handling writes to kernel stack.
- Can process run away with the CPU?
  - CPU will be snatched at the time of timer interrupt

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

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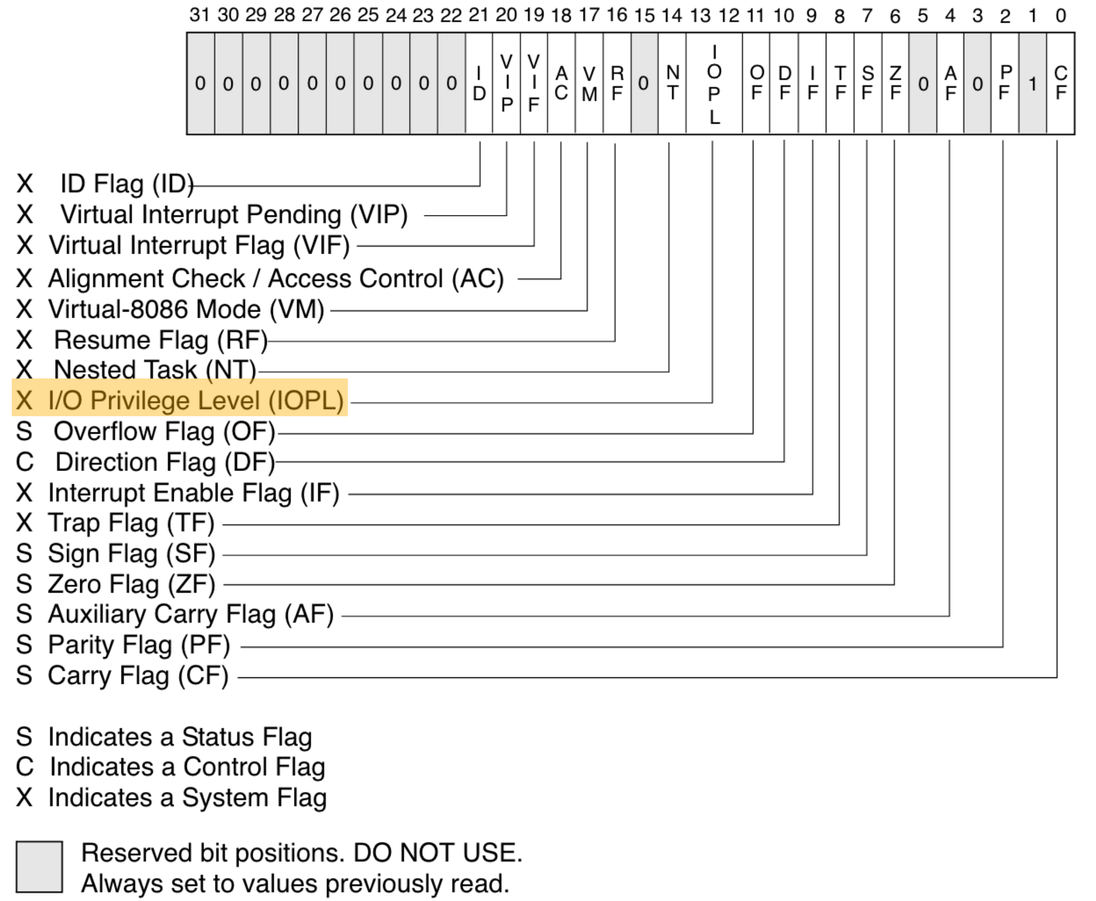

Figure 3-8. EFLAGS Register

Port-mapped IO protection

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```

- Option 1: Make in and out instruction privileged. Processes must do IO via kernel.
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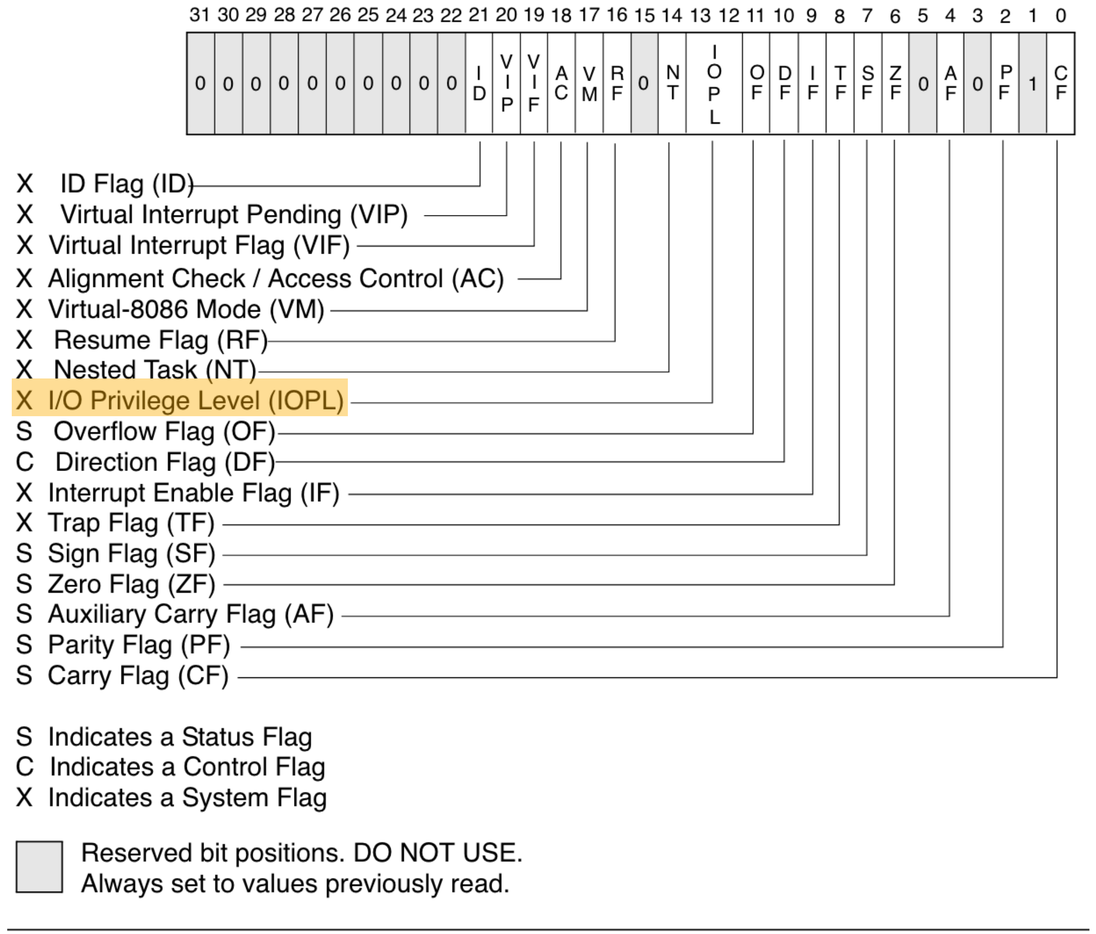
  - Processes (CPL=3) cannot modify EFLAGS.IOPL



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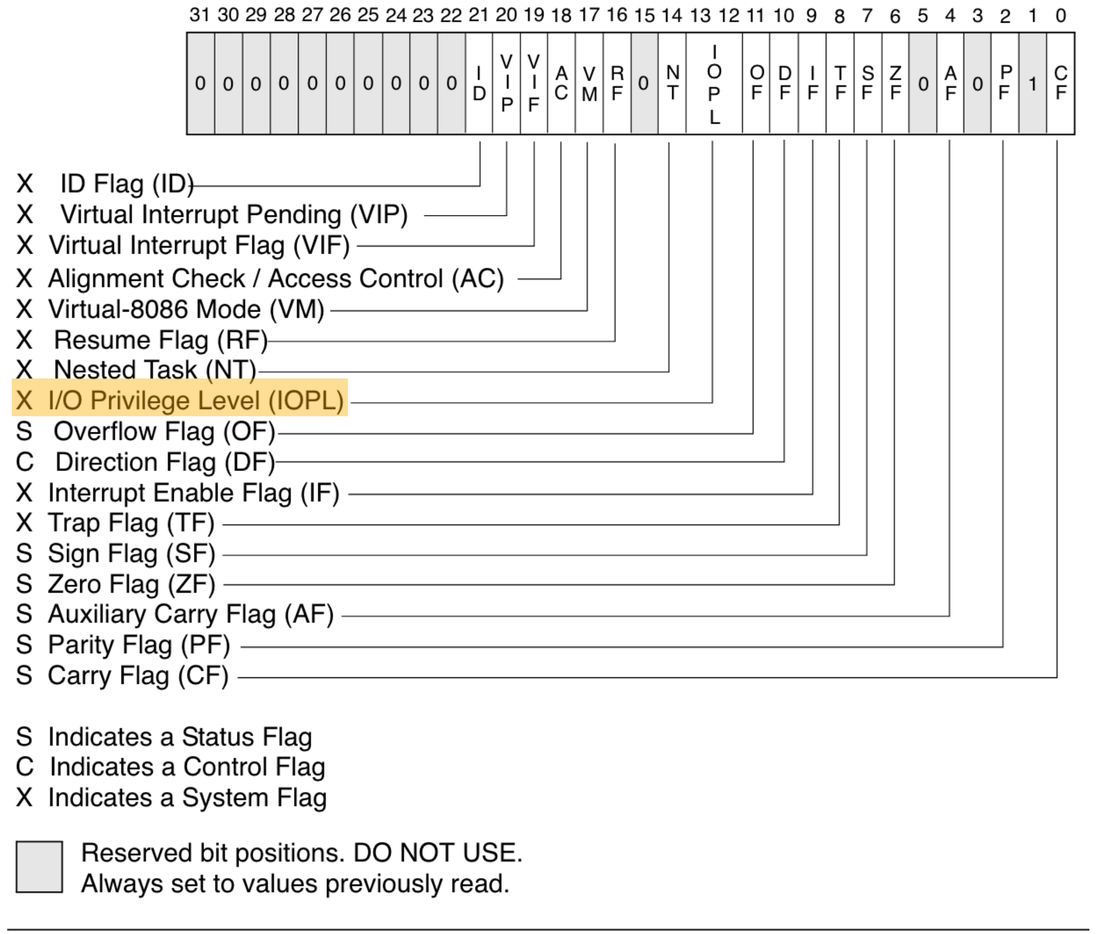
- Option 1: Make in and out instruction privileged. Processes must do IO via kernel.
  - Expensive user mode-kernel mode transitions for IO intensive processes.
- Option 2: Set EFLAGS.IOPL = 3
  - Processes (CPL=3) cannot modify EFLAGS.IOPL
  - Gives permission to access all IO ports



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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
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ESP0			4
Reserved	Previous Task Link		0

Reserved bits. Set to 0.

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

Port-mapped IO protection (2)

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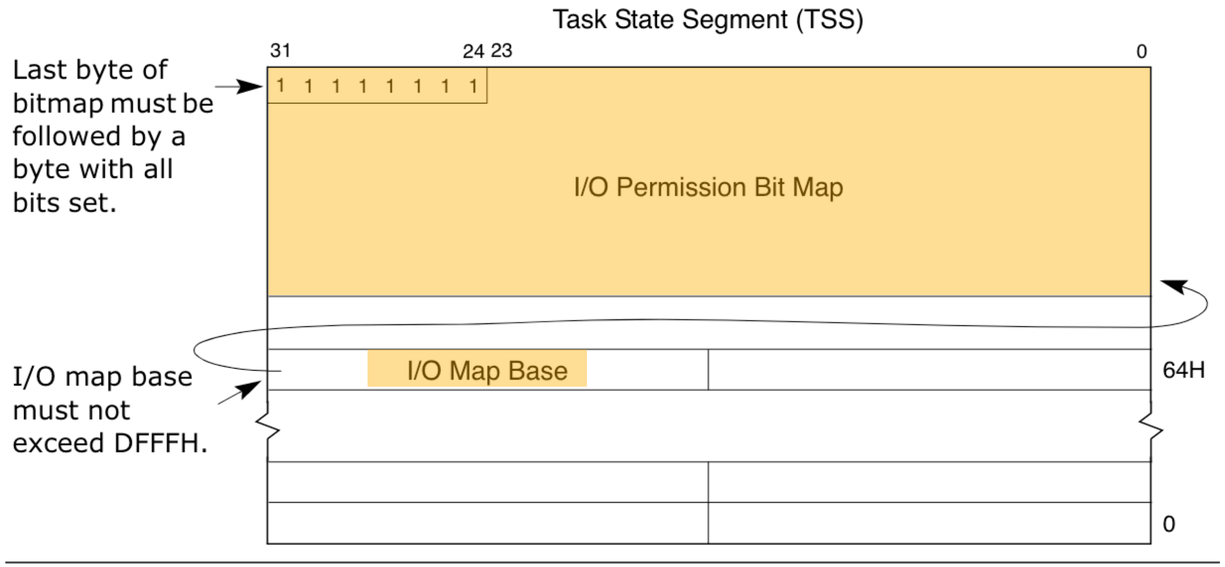

Figure 18-2. I/O Permission Bit Map

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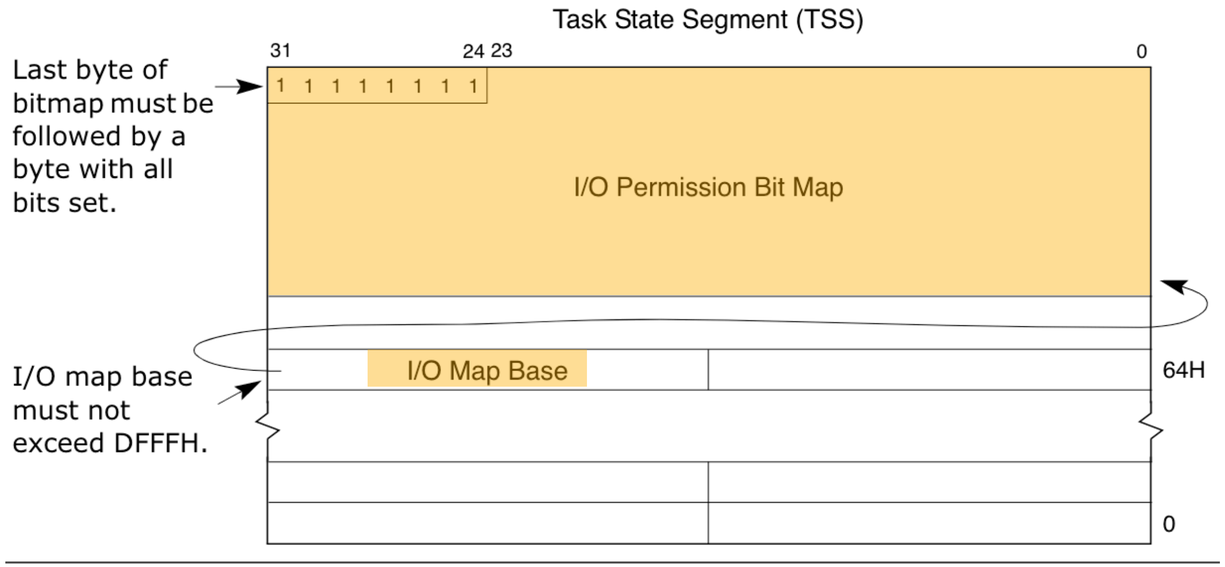

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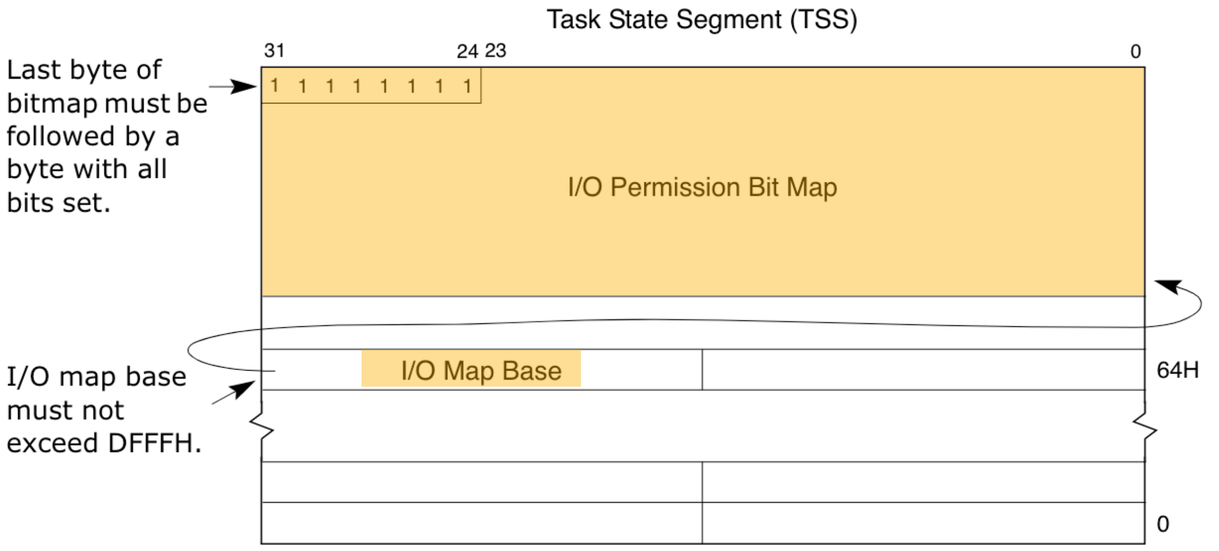
Port-mapped IO protection (2)

- 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



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  - PIO: Running in and out instructions will generate a trap (jump to OS)

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```
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);
}
```

System calls

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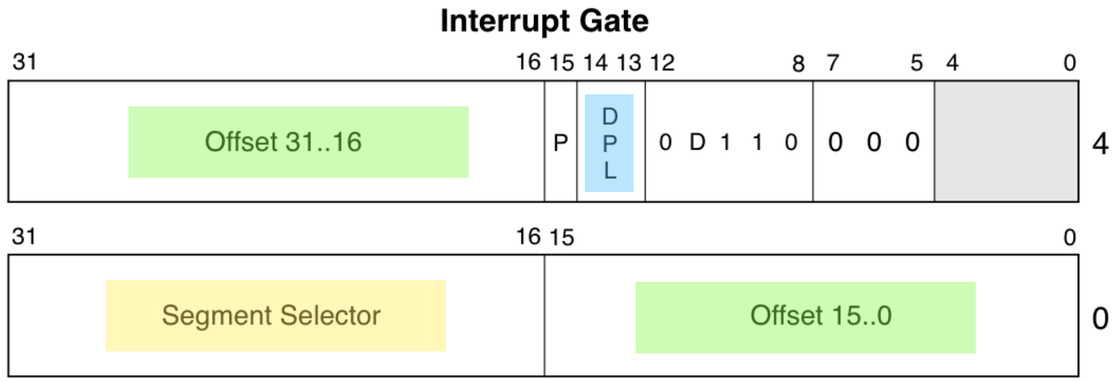
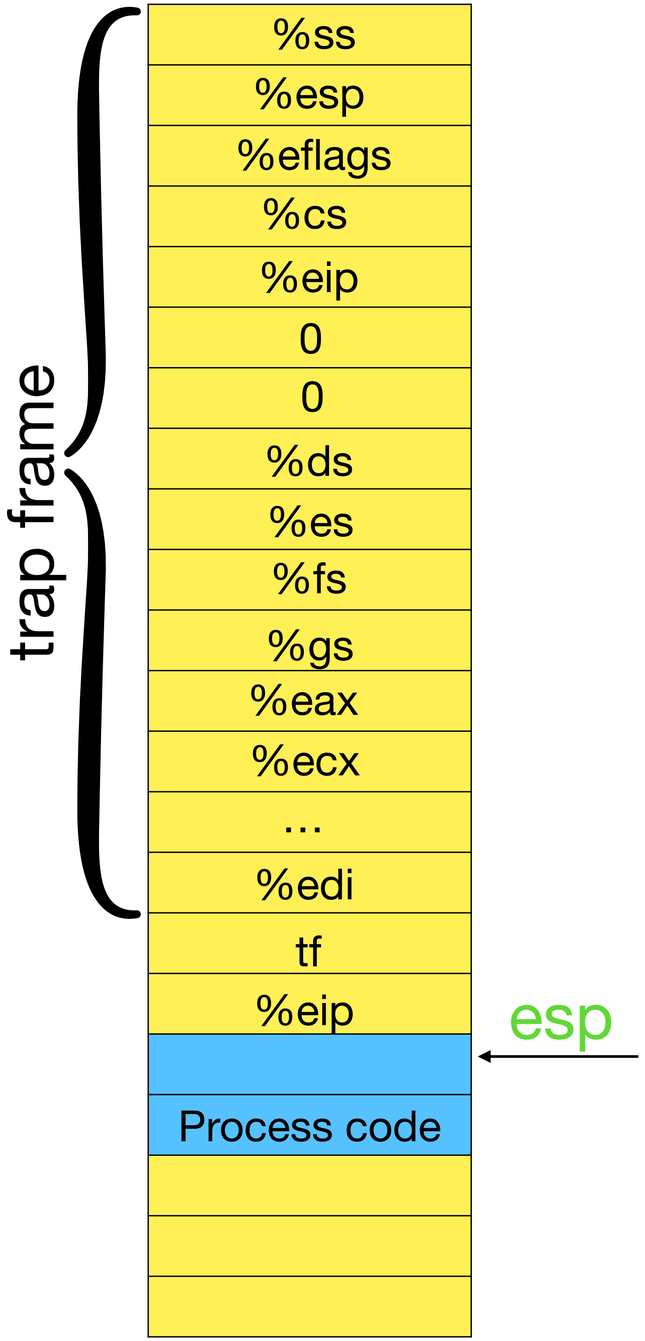


- Process wants OS to work on its behalf
  - Run INT xx instruction to trigger interrupt number xx
  - INT xx is allowed if CPL <= DPL for the xx interrupt vector

Code walkthrough p19-syscall

- trap.c
  - tvinit sets DPL of IDT entry for T_SYSCALL to 3
  - trap calls syscall if interrupt vector is T_SYSCALL
- syscall.c
  - syscall reads eax from trap frame to find which syscall is made and calls that particular call
  - Return value of sys call is set in trap frame's eax
- initproc.S
  - Calls three system calls: open "console" file, write "hello world", close



Visualising syscall handling p19-syscall

```
# sys_open("console", O_WRONLY)
eip → pushl $1
      pushl $console
      pushl $0
      movl $SYS_open, %eax
      int $T_SYSCALL
      pushl %eax
```

```
int sys_open(void) {
  int fd, omode;
  if(argint(1, &omode) < 0) {
    return -1;
  }
  ..
  return fd;
}
```

```
int fetchint(uint addr, int *ip) {
  if(addr >= p->sz || addr+4 > p->sz)
    return -1;
  *ip = *(int*)(addr + p->offset);
}

int argint(int n, int *ip) {
  return fetchint((myproc()->tf->esp)
                  + 4 + 4*n, ip);
}
void syscall(void) {
  int num = curproc->tf->eax;
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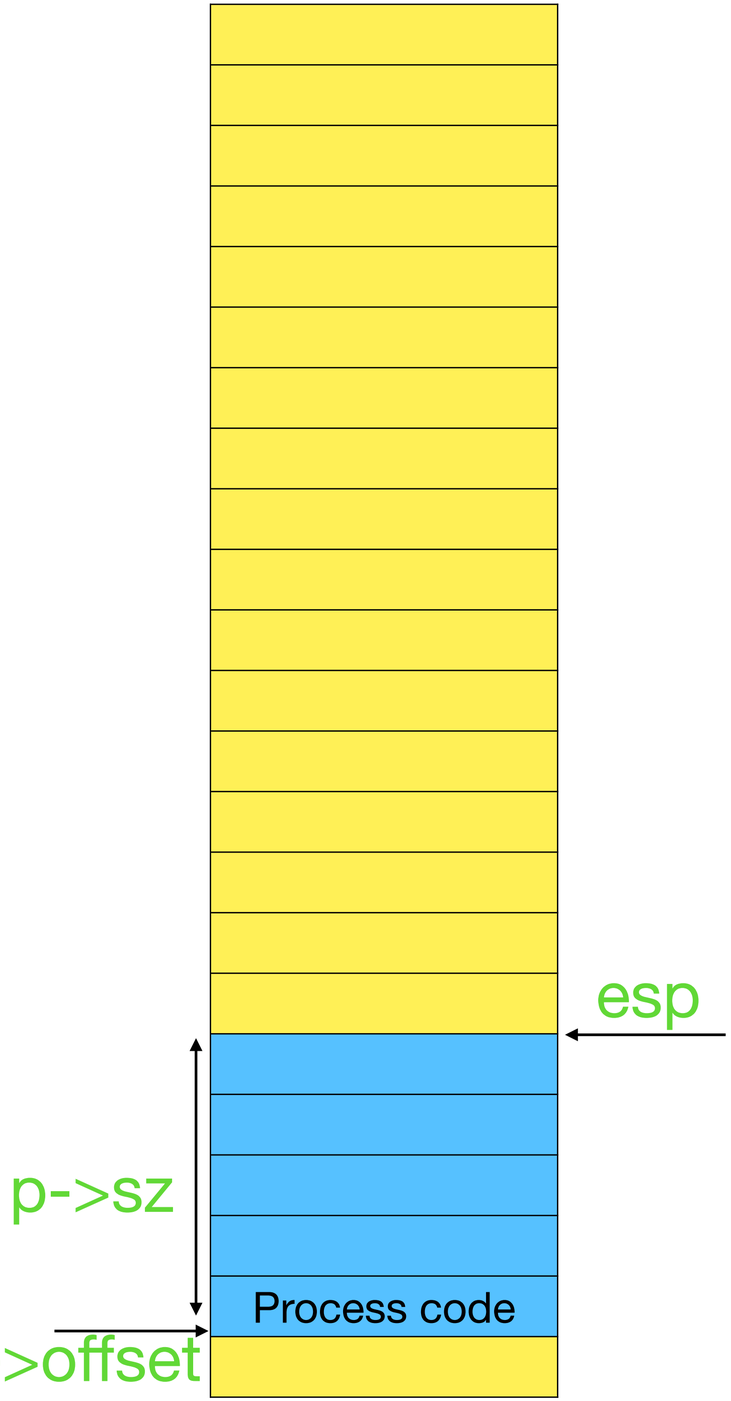

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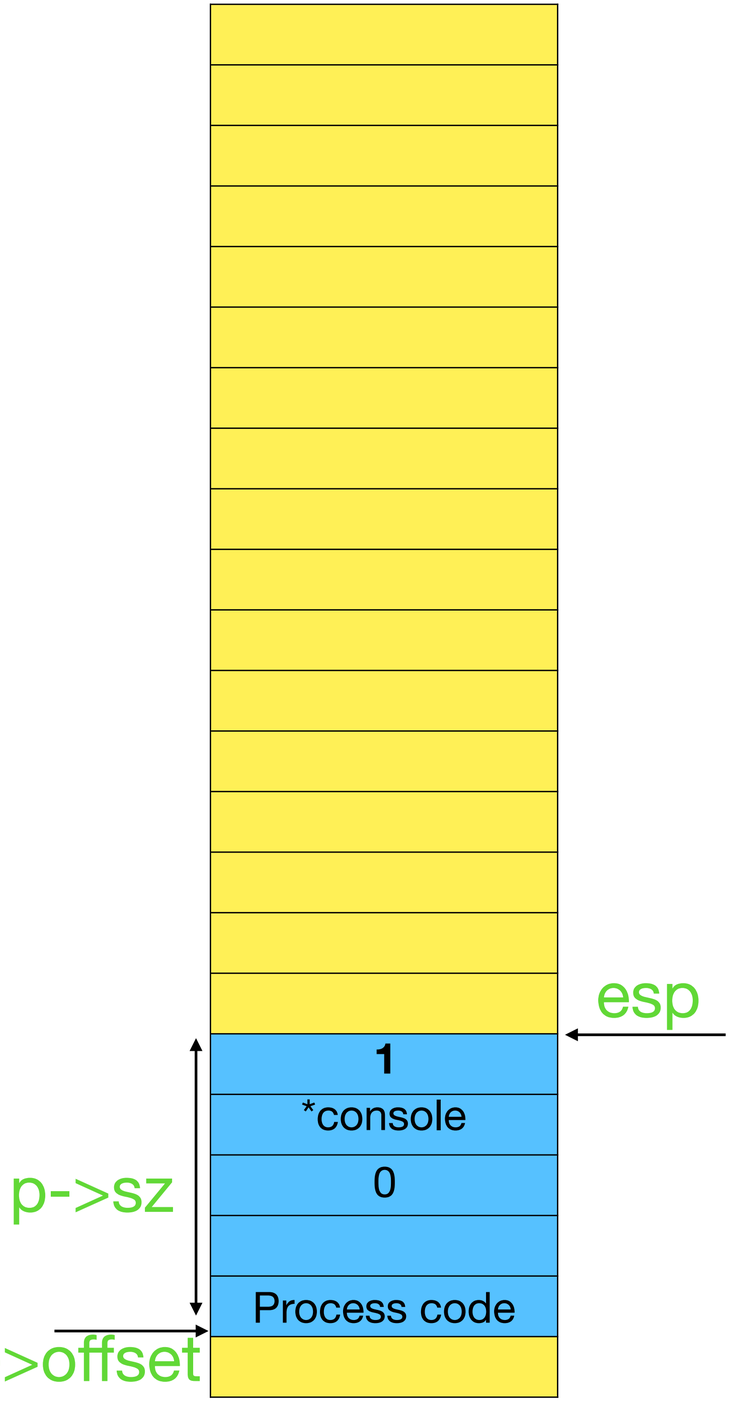

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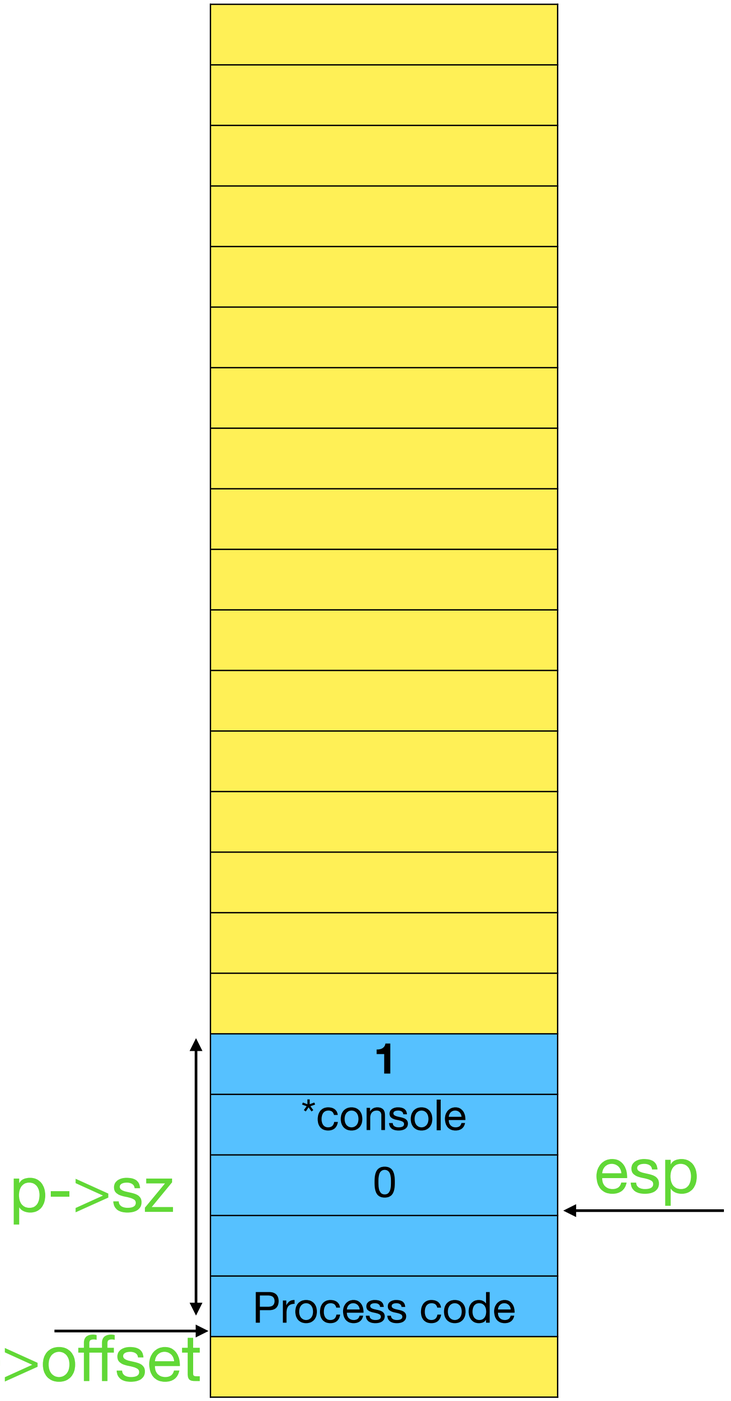

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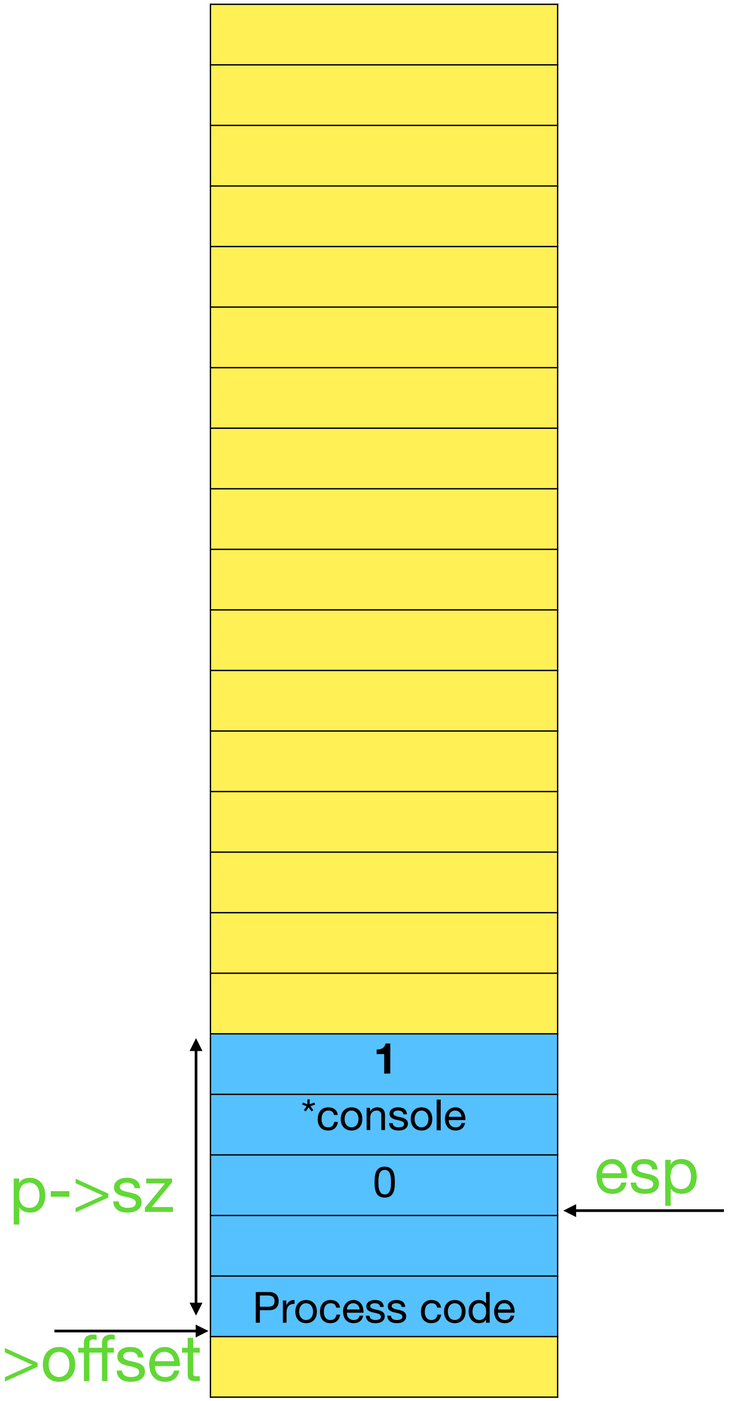

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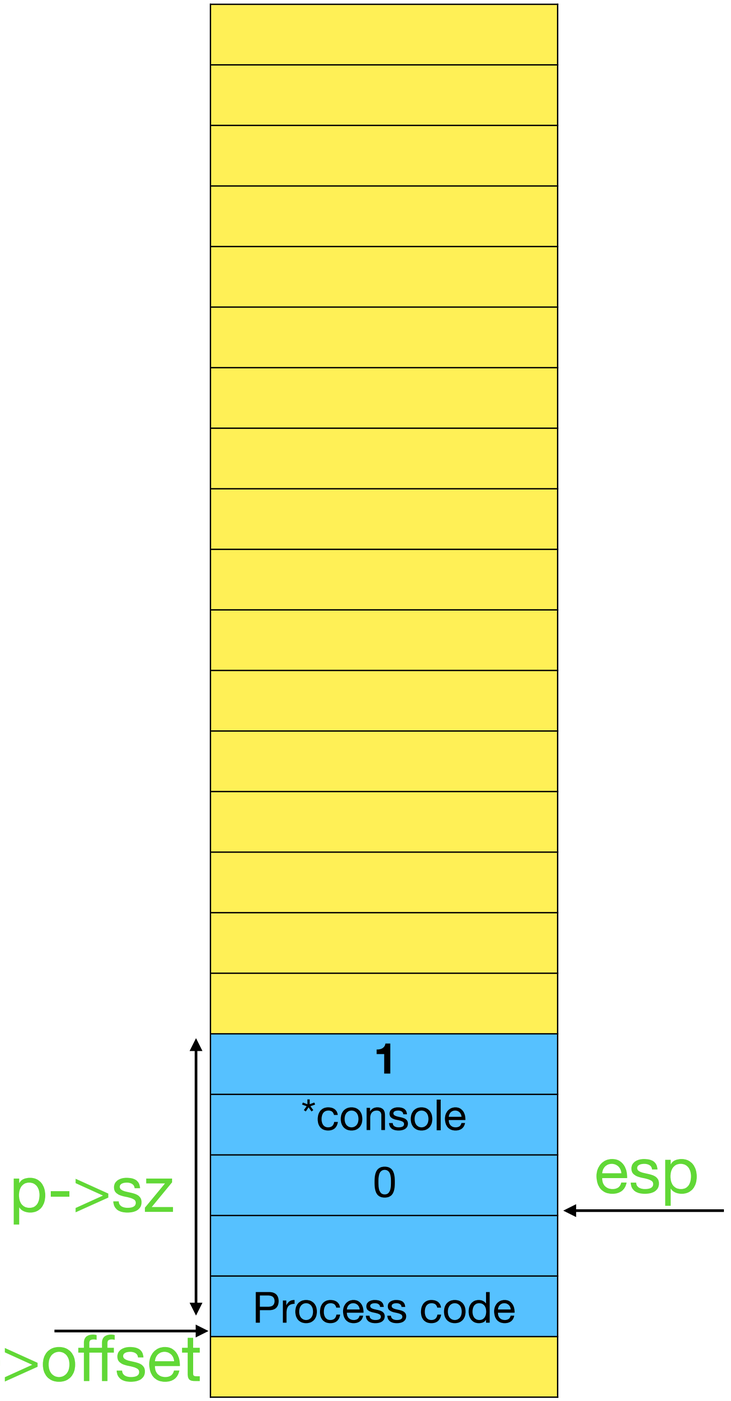

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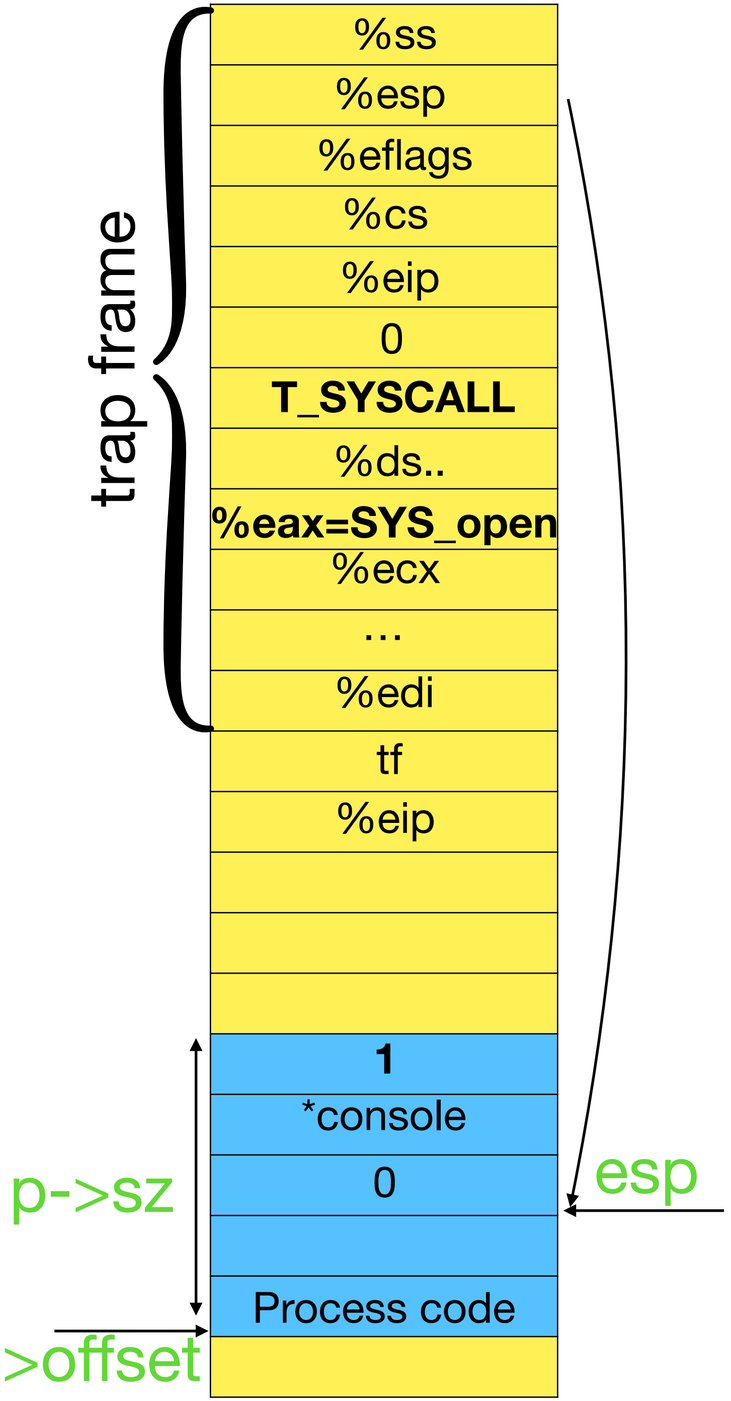

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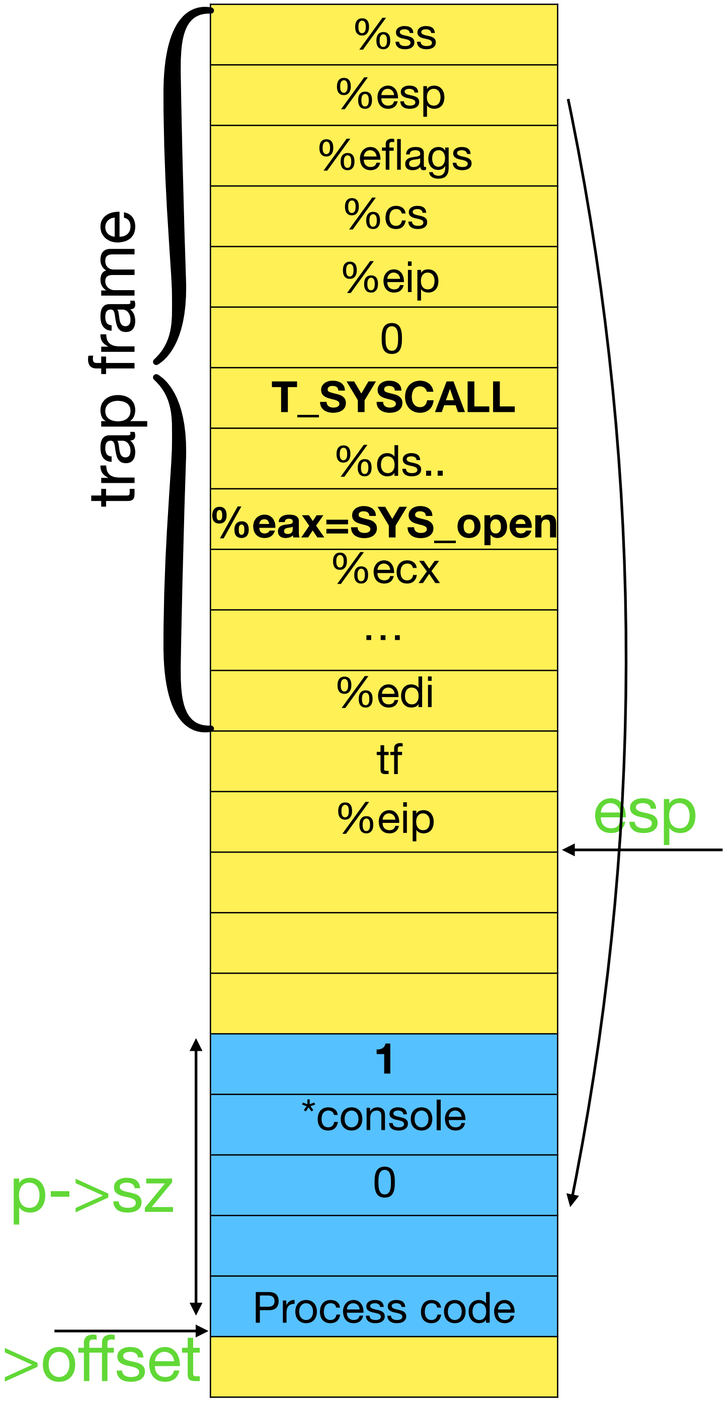

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        movl $SYS_open, %eax
        int $T_SYSCALL
        pushl %eax
```

```
int sys_open(void) {
  int fd, omode;
  if(argint(1, &omode) < 0) {
    return -1;
  }
  ..
  return fd;
}
```

eip

```
int fetchint(uint addr, int *ip) {
  if(addr >= p->sz || addr+4 > p->sz)
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  *ip = *(int*)(addr + p->offset);
}

int argint(int n, int *ip) {
  return fetchint((myproc()->tf->esp)
                  + 4 + 4*n, ip);
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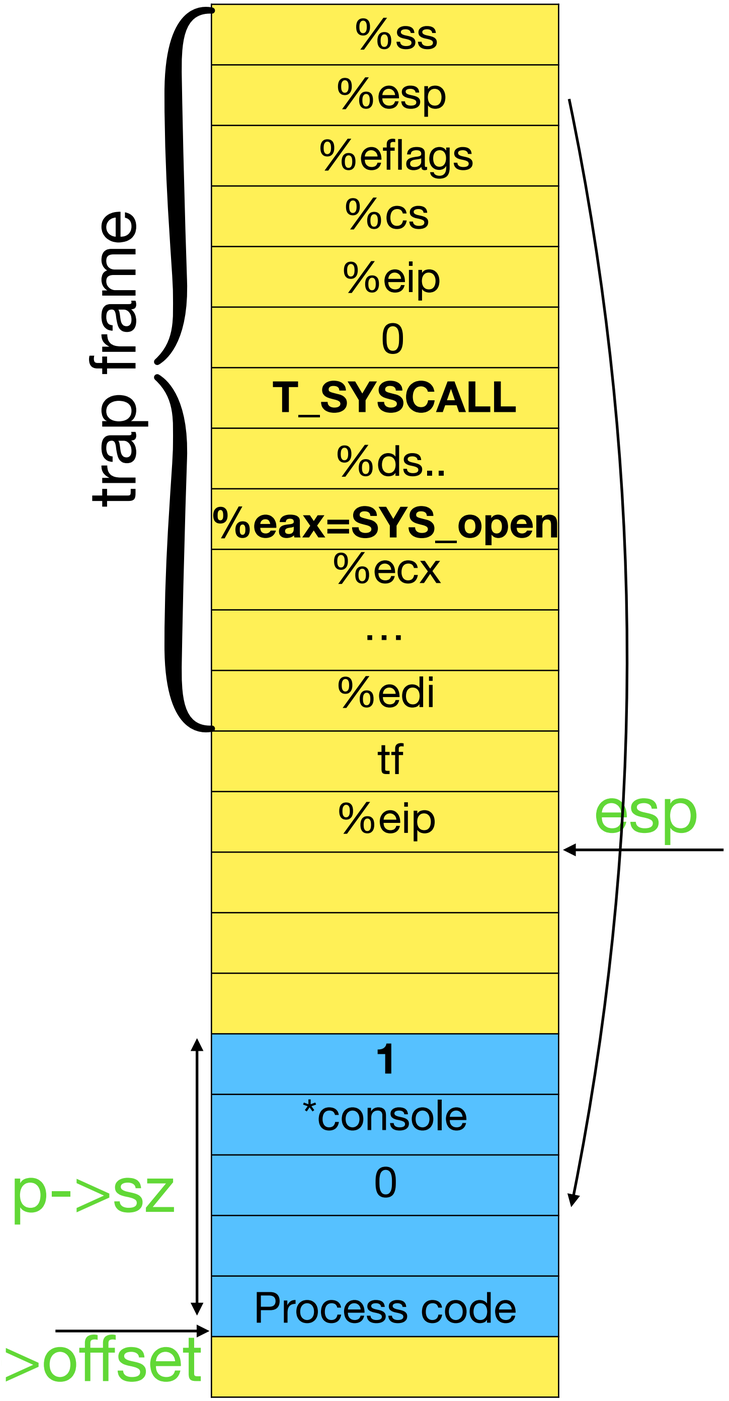

Visualising syscall handling p19-syscall

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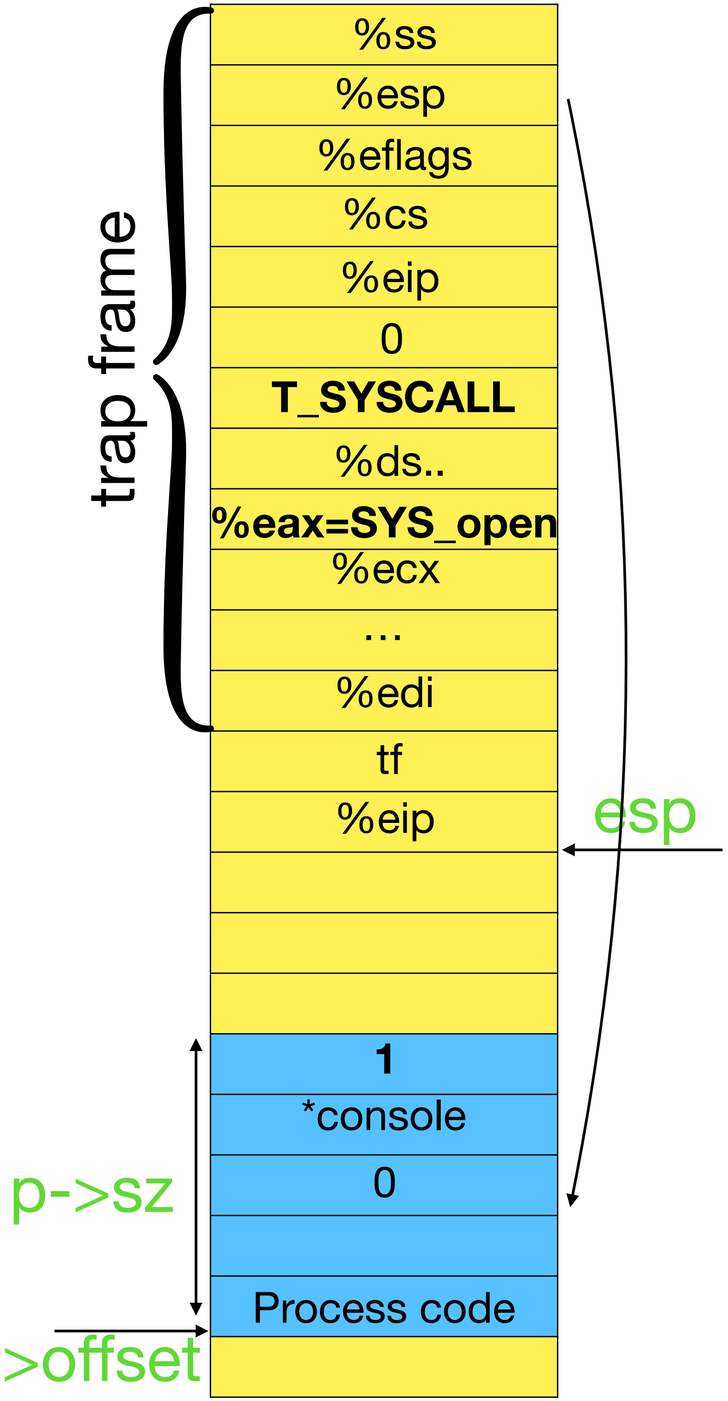

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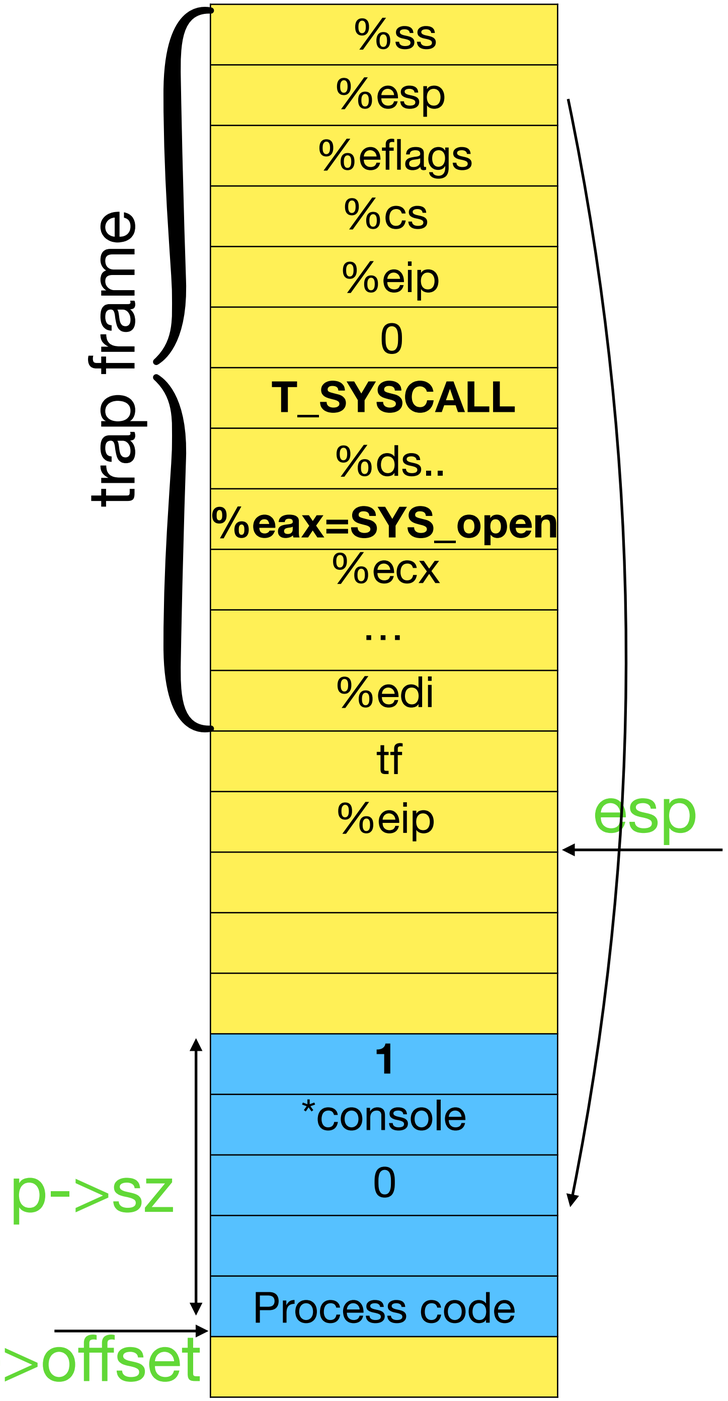

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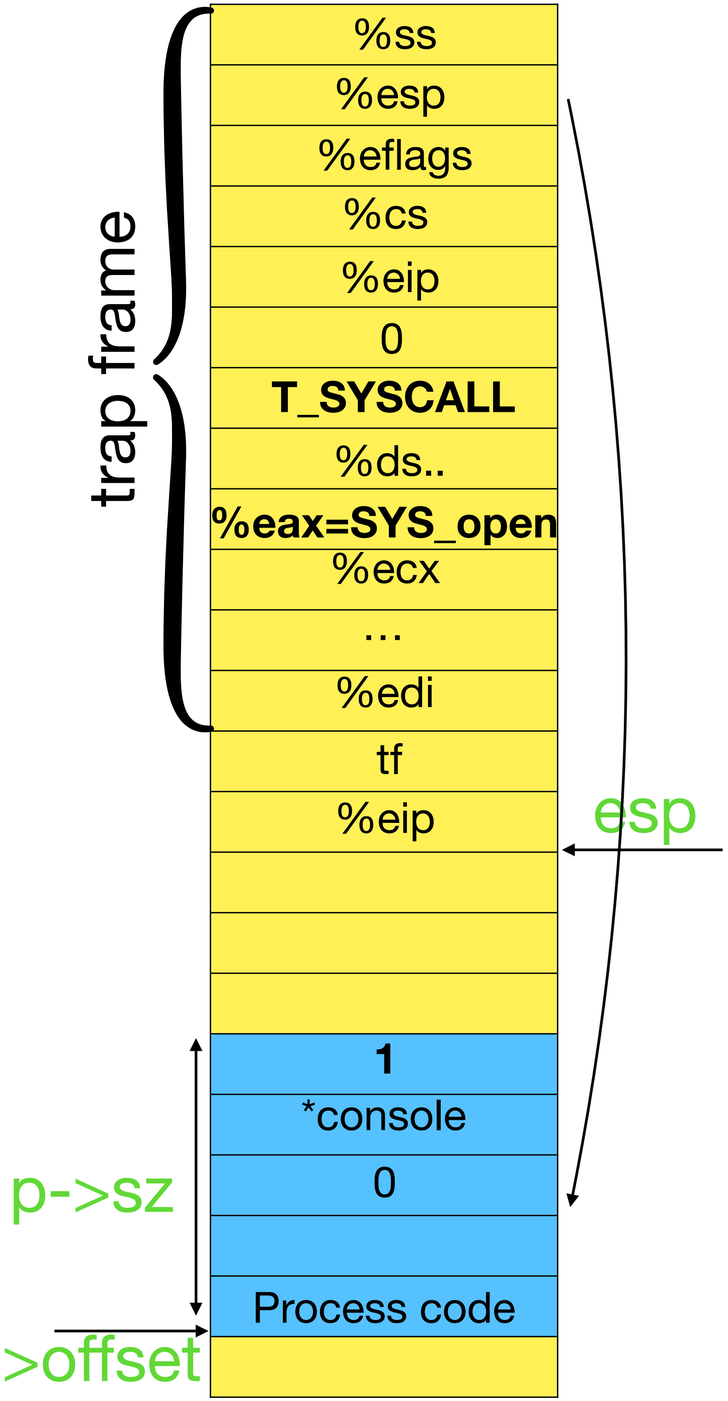

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eip

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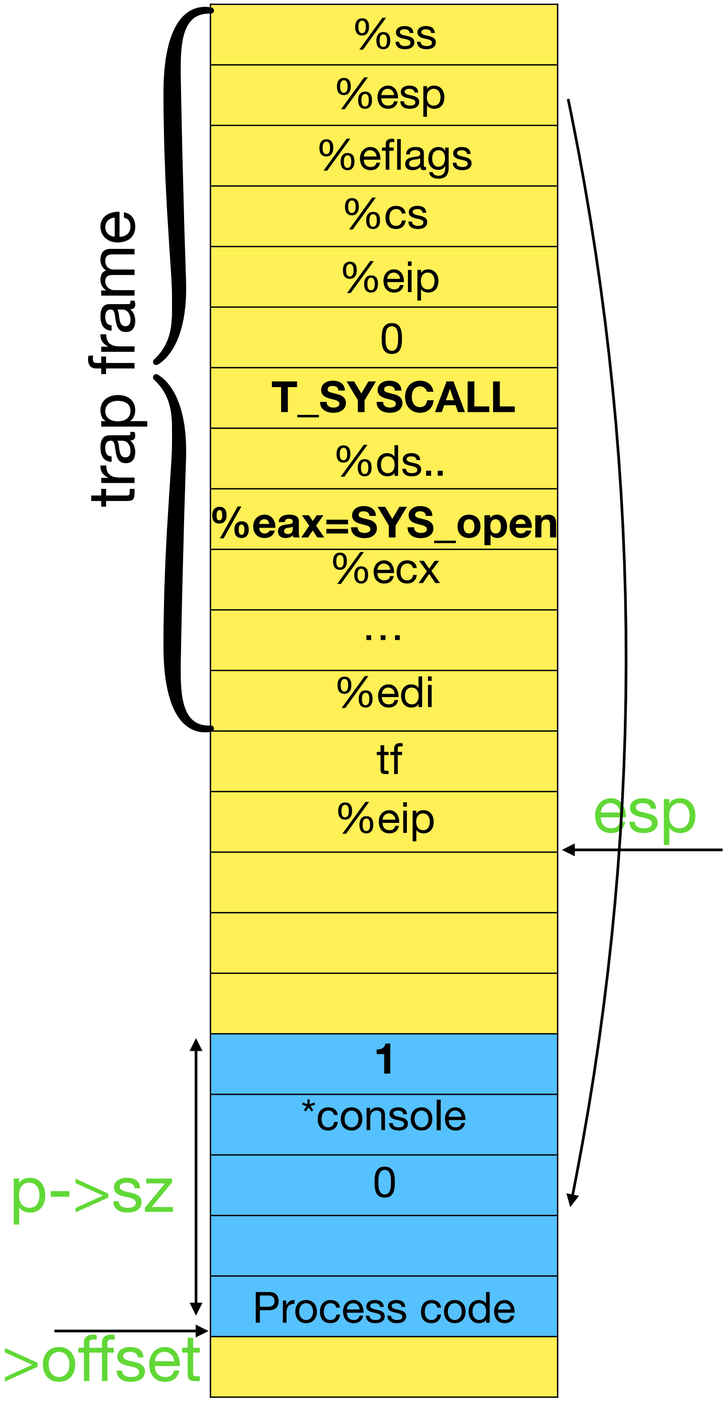

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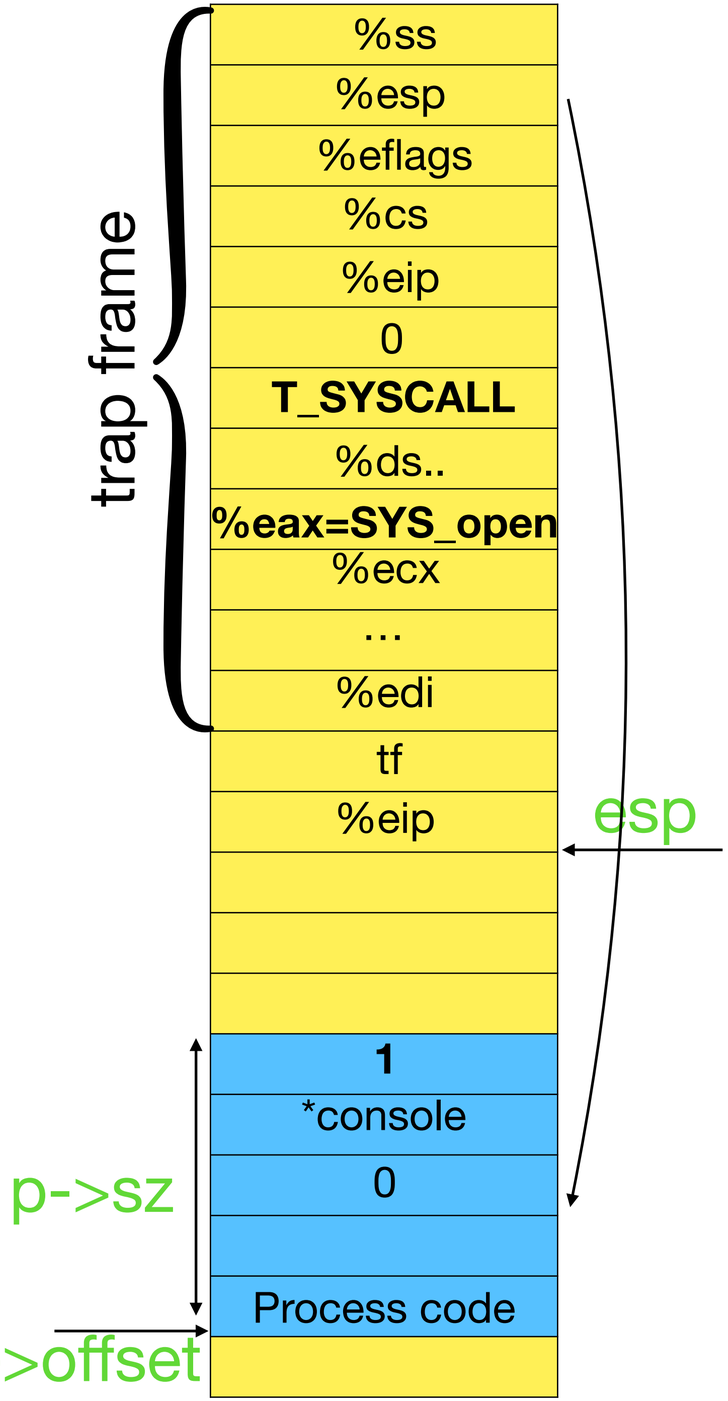

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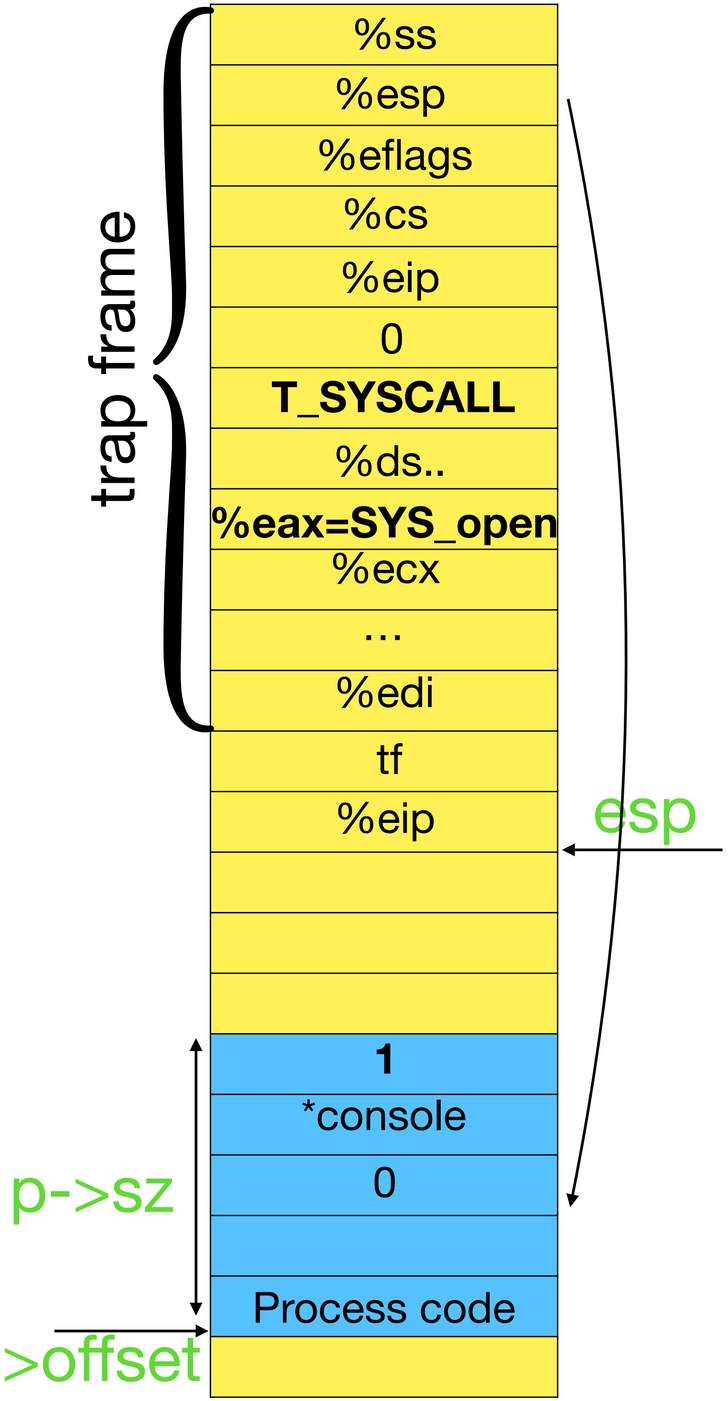

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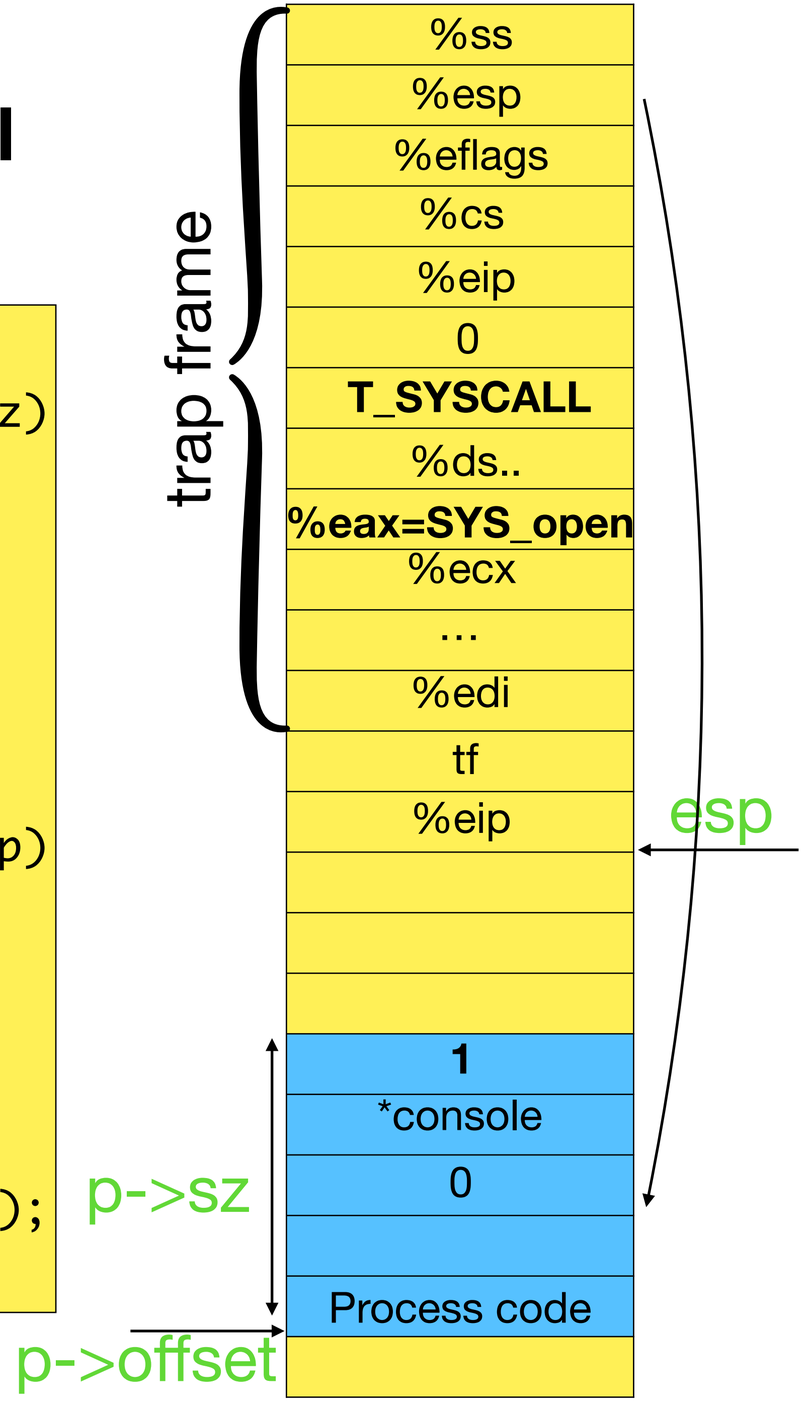

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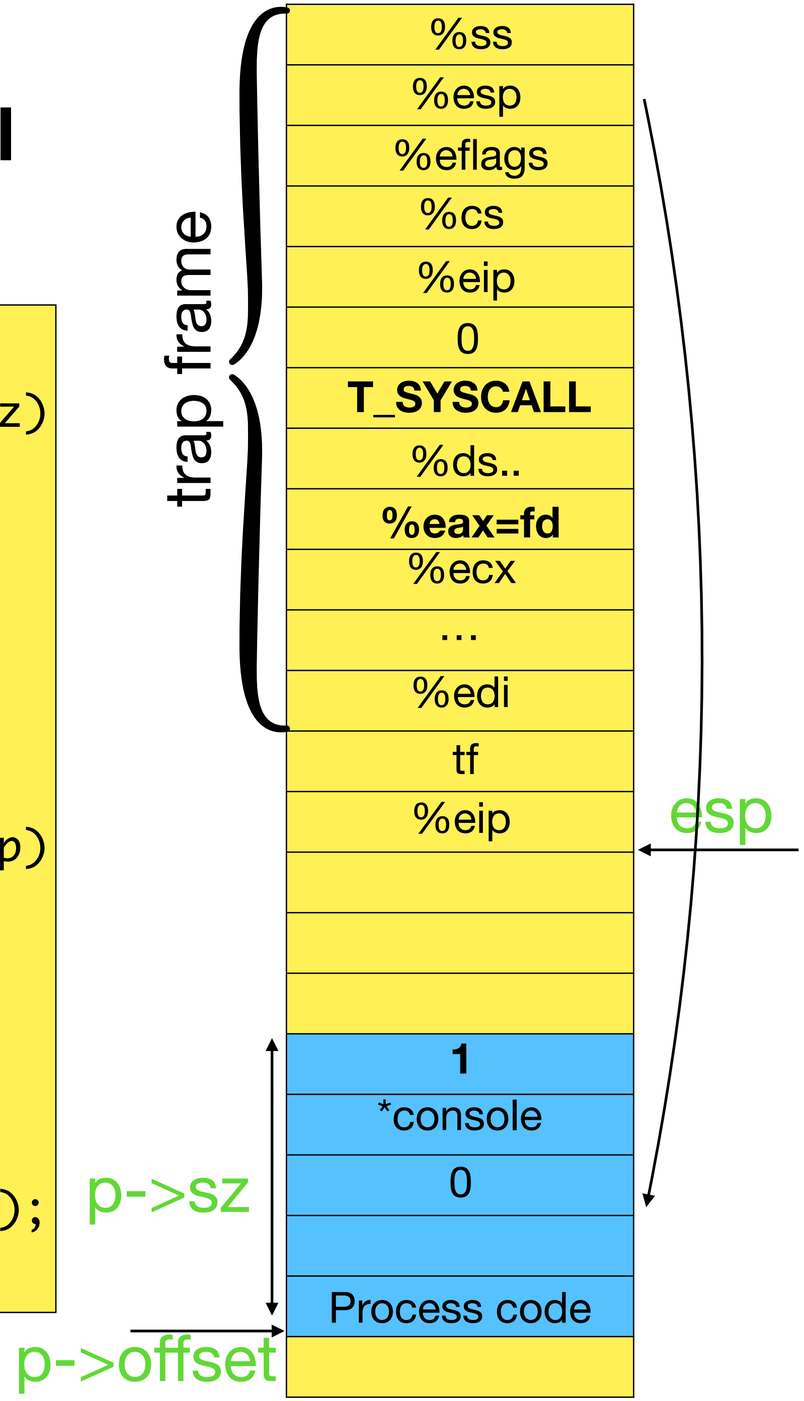
eip



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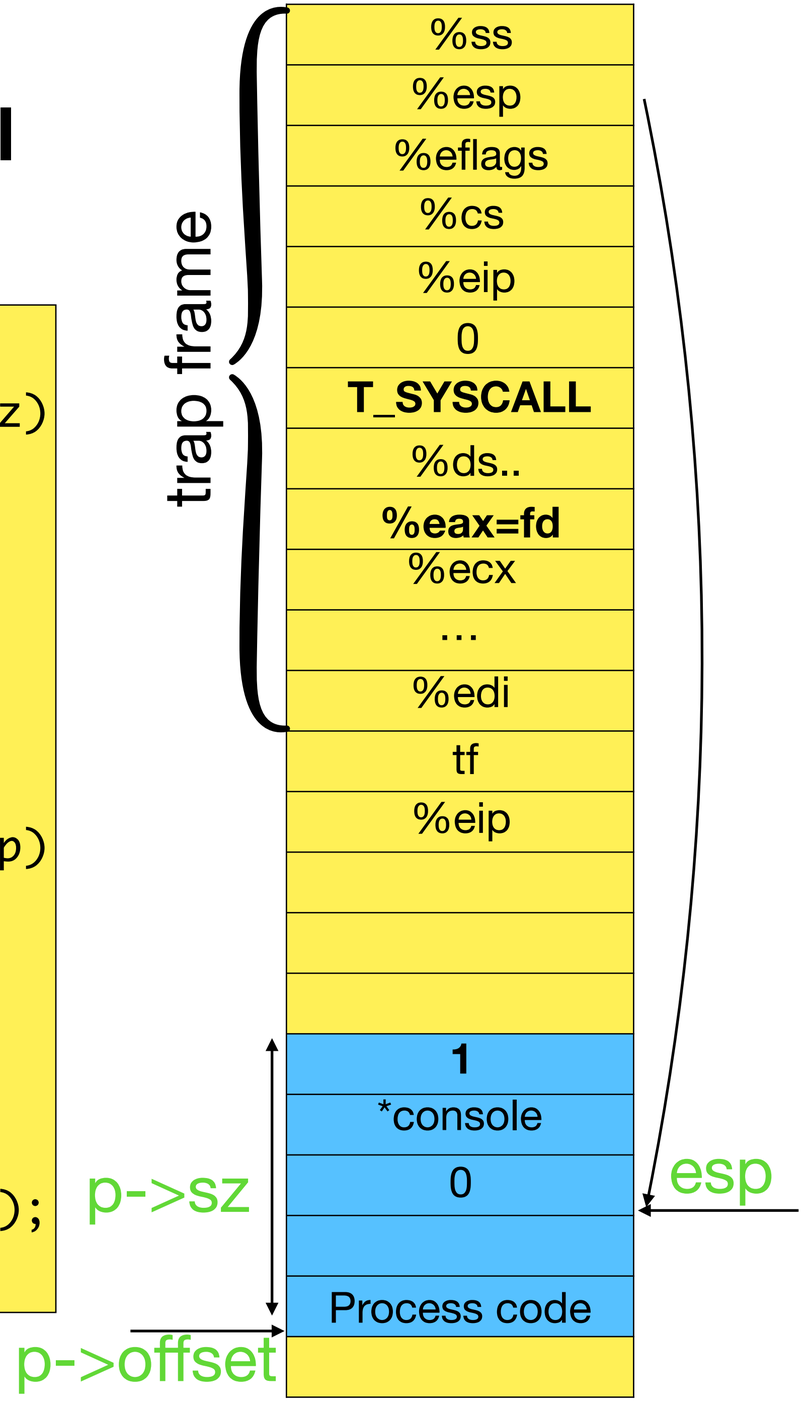
```

eip



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eip →   pushl %eax
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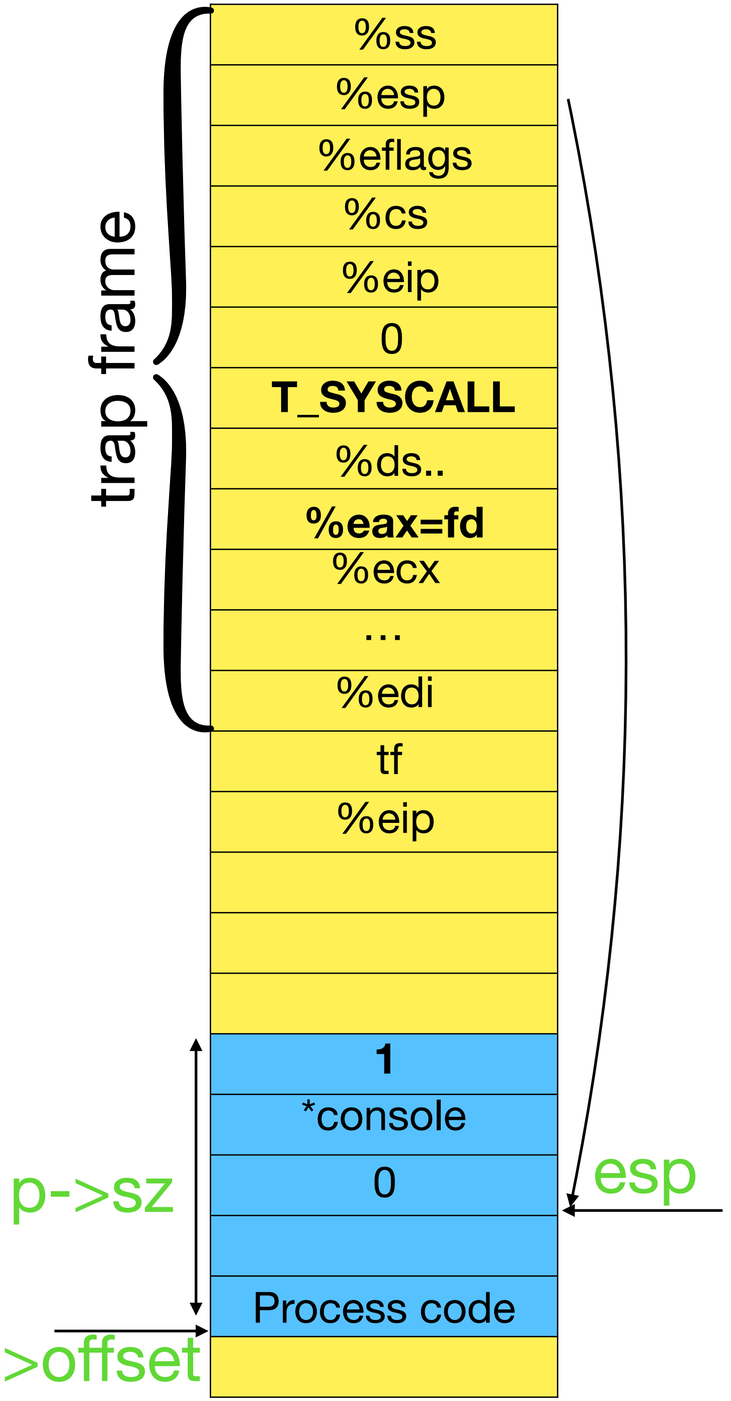

Syscall parameter checking and translation

```
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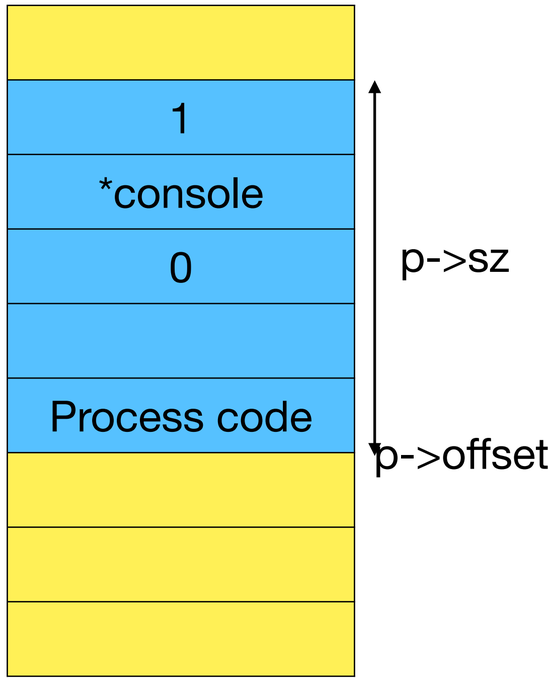

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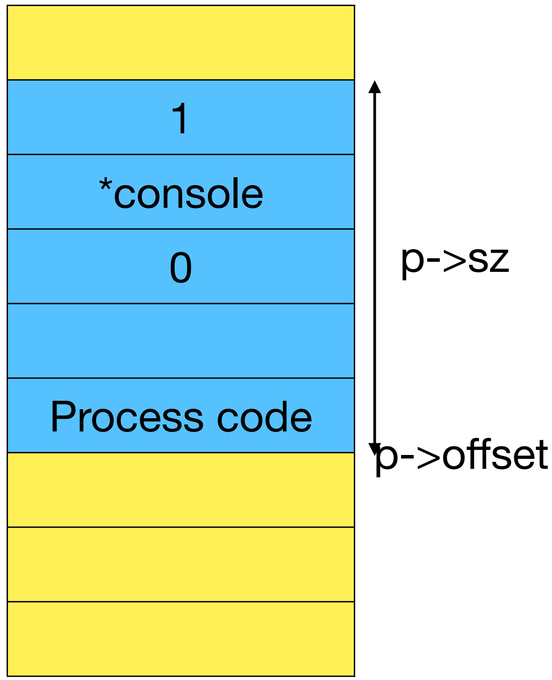
- Syscall parameters must be in process' address space:



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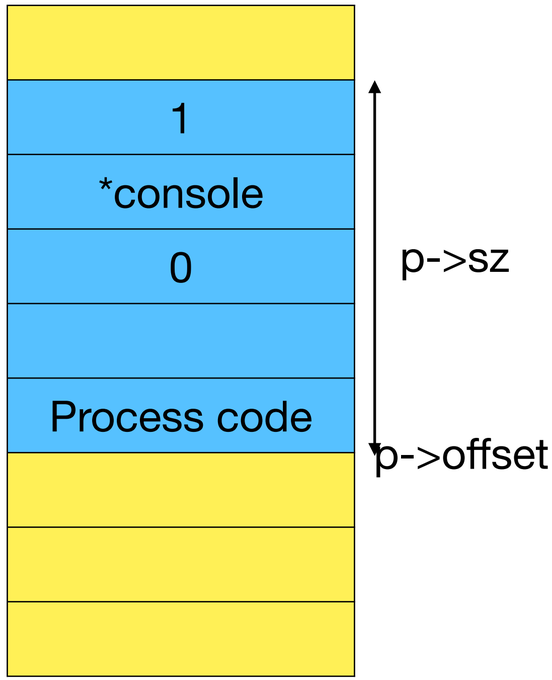
  - Check virtual address (VA) is within limit



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- Syscall parameters must be in process' address space:
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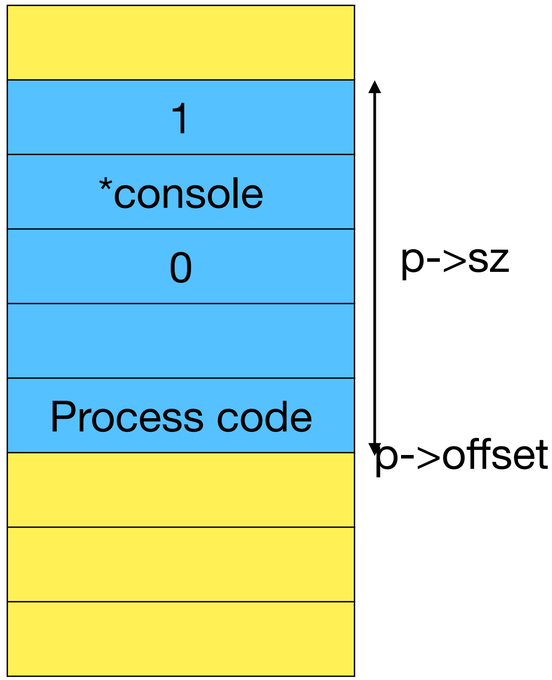

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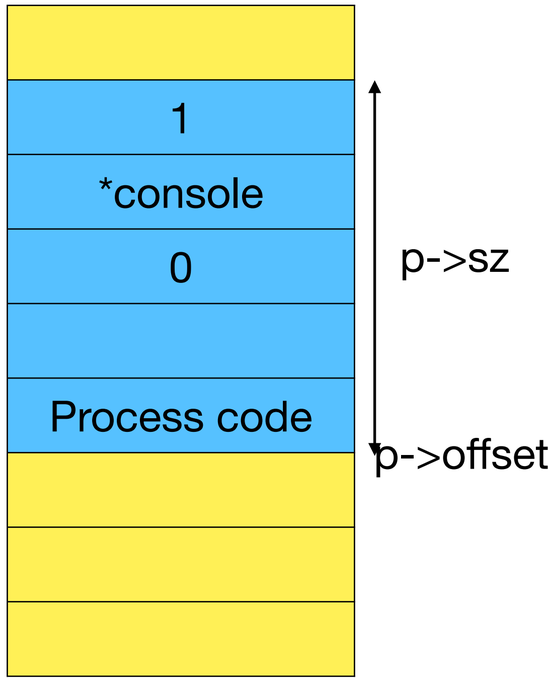

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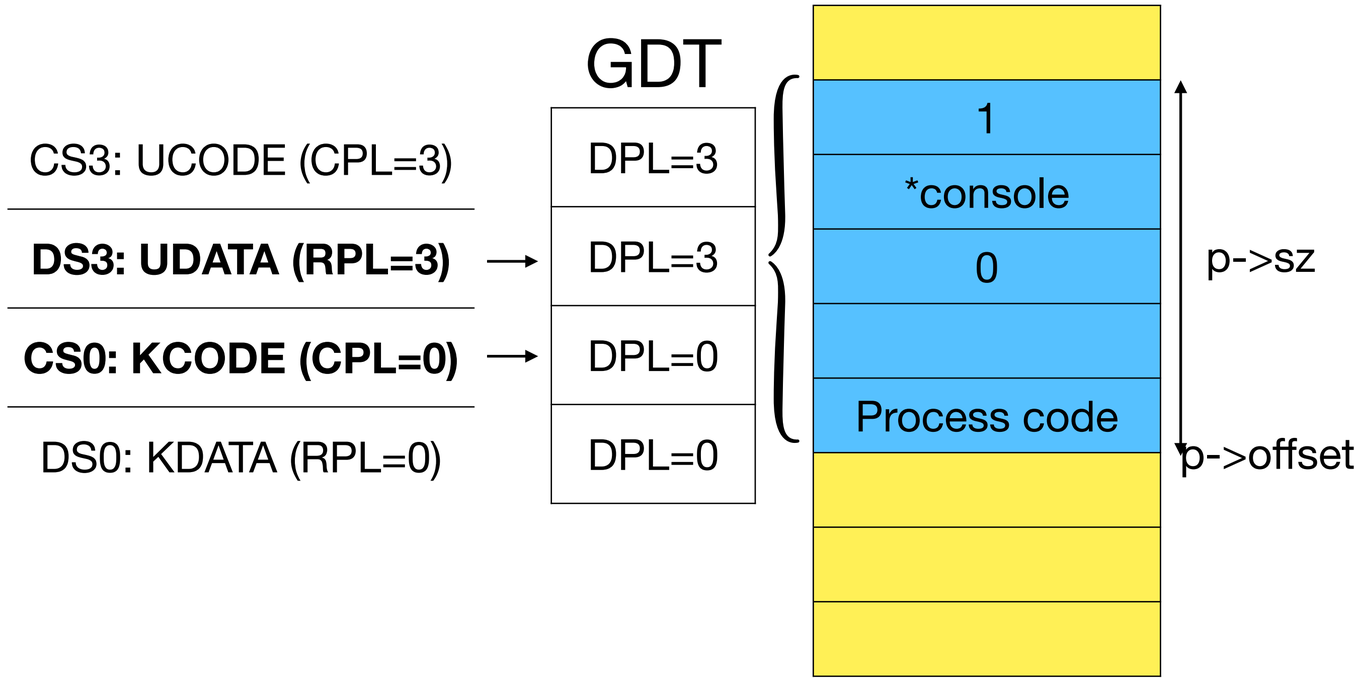

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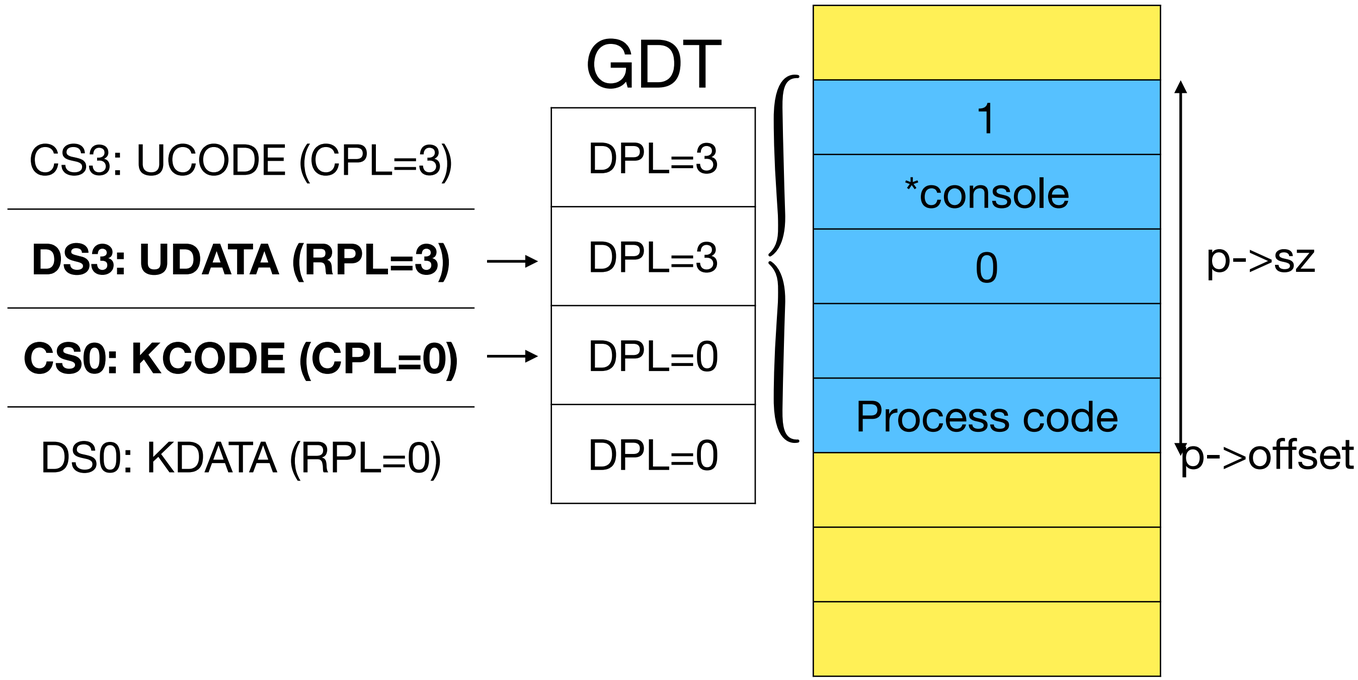
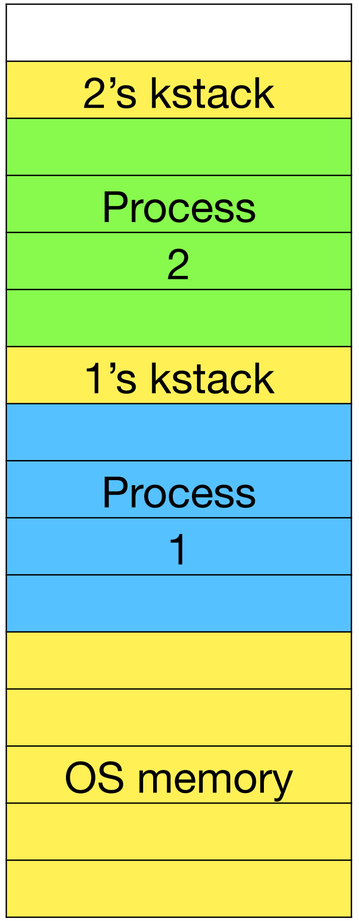
  - CPL <= DPL and RPL <= DPL



Code walkthrough: Setting up multiple processes

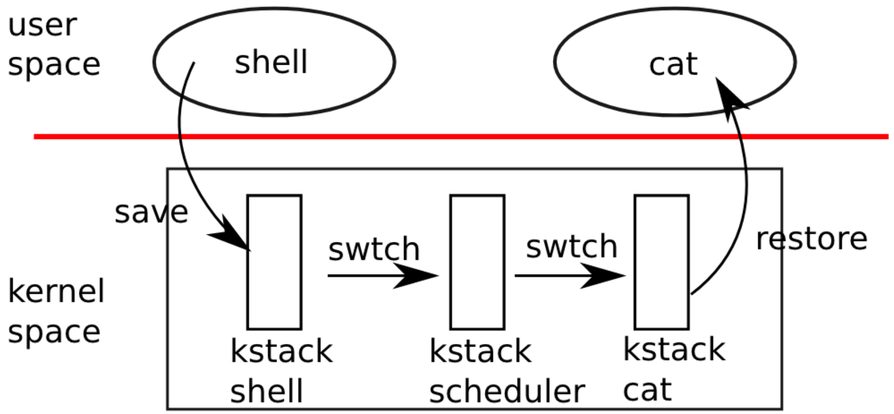
p18-sched

- main.c
  - Calls pinit twice to start two processes and then calls scheduler
- proc.c
  - pinit calls allocproc which sets up processes like earlier with the added difference that it calls kalloc to find empty 1MB of space
- kalloc.c
  - Maintains free list in chunks of 1MB. kalloc returns the first element from free list. There is no coalescing and splitting since our OS always asks for 1MB.



Code walkthrough: context switching

p18-sched



- main.c
  - Calls scheduler to run the first RUNNABLE process. When giving control, we also remember “scheduler context” to come back to scheduler. Earlier, we were only running one process and were never coming back to the scheduler.
- trap.c
  - Calls yield when timer interrupt happens
- proc.c
  - yield calls sched which switches control from the process to the scheduler
  - scheduler looks for the next RUNNABLE process and switches to it

Context switching in action: giving control

p18-sched

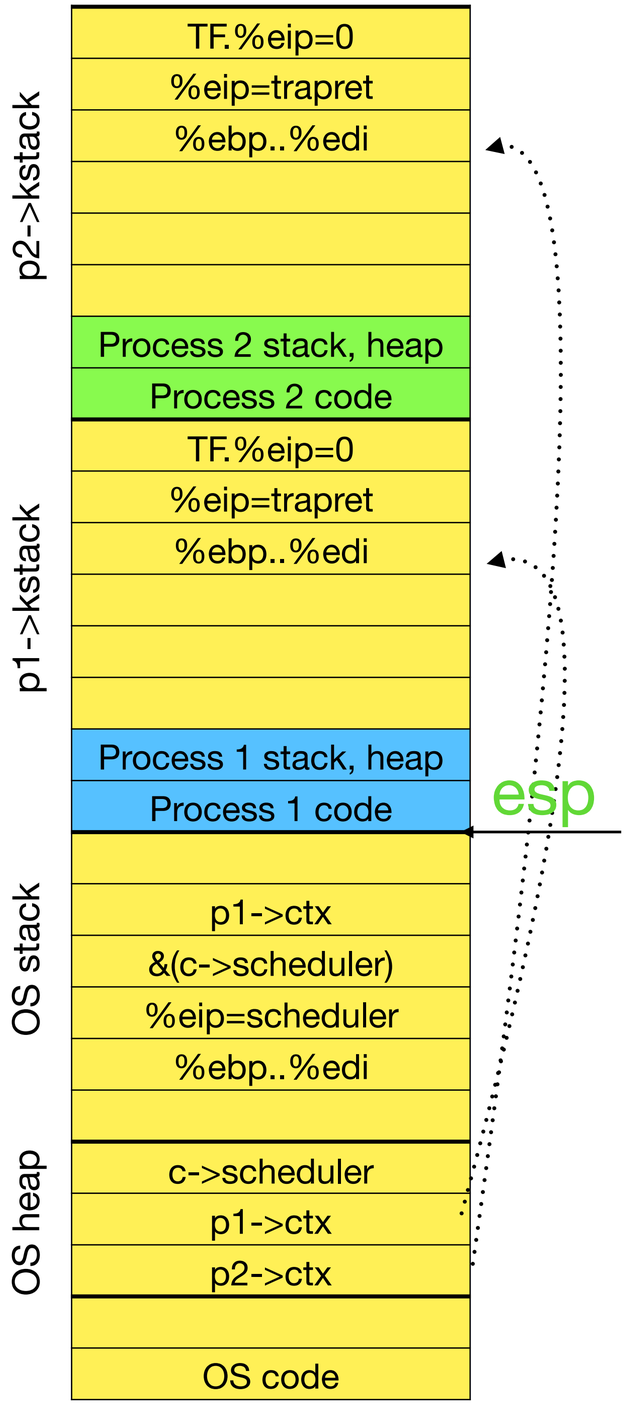
```
.globl swtch
swtch:
  movl 4(%esp), %eax
  movl 8(%esp), %edx
  pushl %ebp
  pushl %ebx
  pushl %esi
  pushl %edi
  movl %esp, (%eax)
  movl %edx, %esp
  popl %edi
  popl %esi
  popl %ebx
  popl %ebp
  ret
```

eip →

```
void scheduler(void) {
  struct proc *p;  struct cpu *c = mycpu();
  for(;;){
   for(p = ptable.proc; p < &ptable.proc[NPROC]; p++){
      if(p->state != RUNNABLE)
        continue;
      p->state = RUNNING;
      switchuvm(p);
      swtch(&(c->scheduler), p->context);
    }
  }
}
```

```
void yield(void) {
  struct proc *p = myproc();
  p->state = RUNNABLE;
  swtch(&p->context, c->scheduler);
}
```

```
void trap(struct trapframe *tf) {
  ..
  if(tf->trapno == T_IRQ0+IRQ_TIMER)
    yield();
}
```



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p18-sched

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     p->state = RUNNING;
     switchuvm(p);
     swtch(&(c->scheduler), p->context);
   }
  }
}
```

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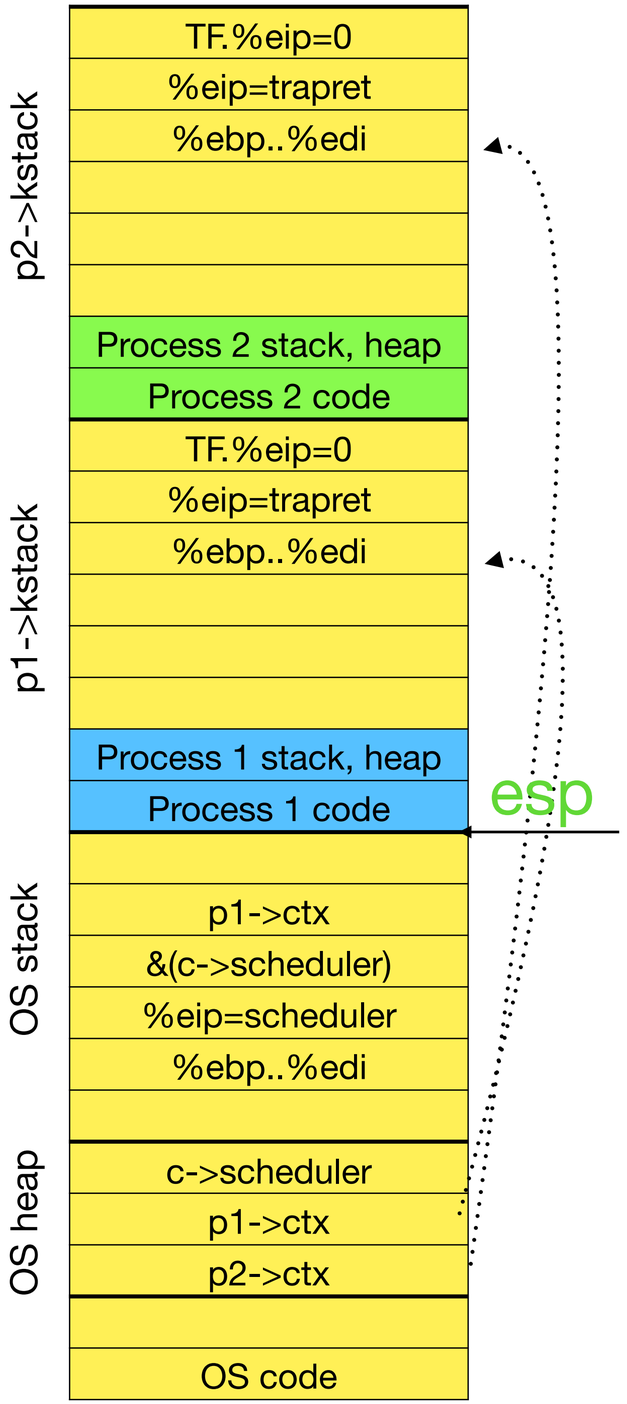

Context switching in action: giving control

p18-sched

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.globl swtch
swtch:
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  movl %esp, (%eax)
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  ret
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void scheduler(void) {
  struct proc *p;  struct cpu *c = mycpu();
  for(;;){
   for(p = ptable.proc; p < &ptable.proc[NPROC]; p++){
      if(p->state != RUNNABLE)
        continue;
      p->state = RUNNING;
      switchuvm(p);
      swtch(&(c->scheduler), p->context);
    }
  }
}
```

eip

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void yield(void) {
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void trap(struct trapframe *tf) {
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  if(tf->trapno == T_IRQ0+IRQ_TIMER)
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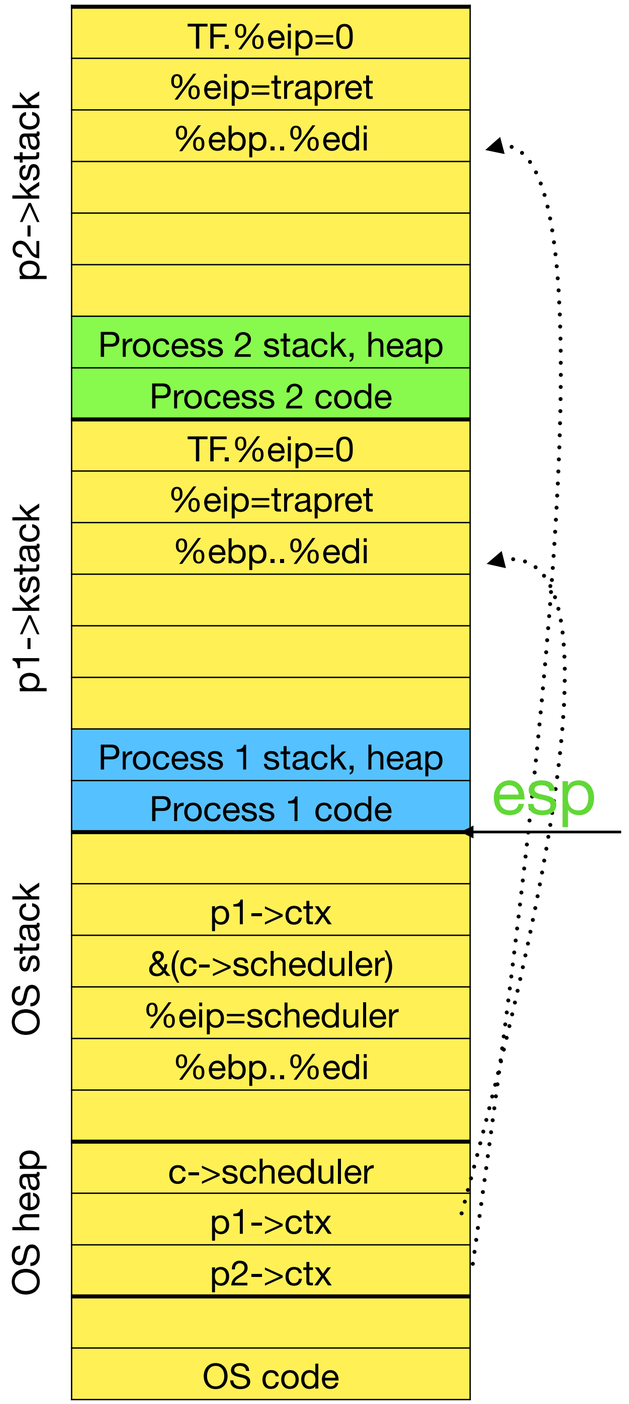

Context switching in action: giving control

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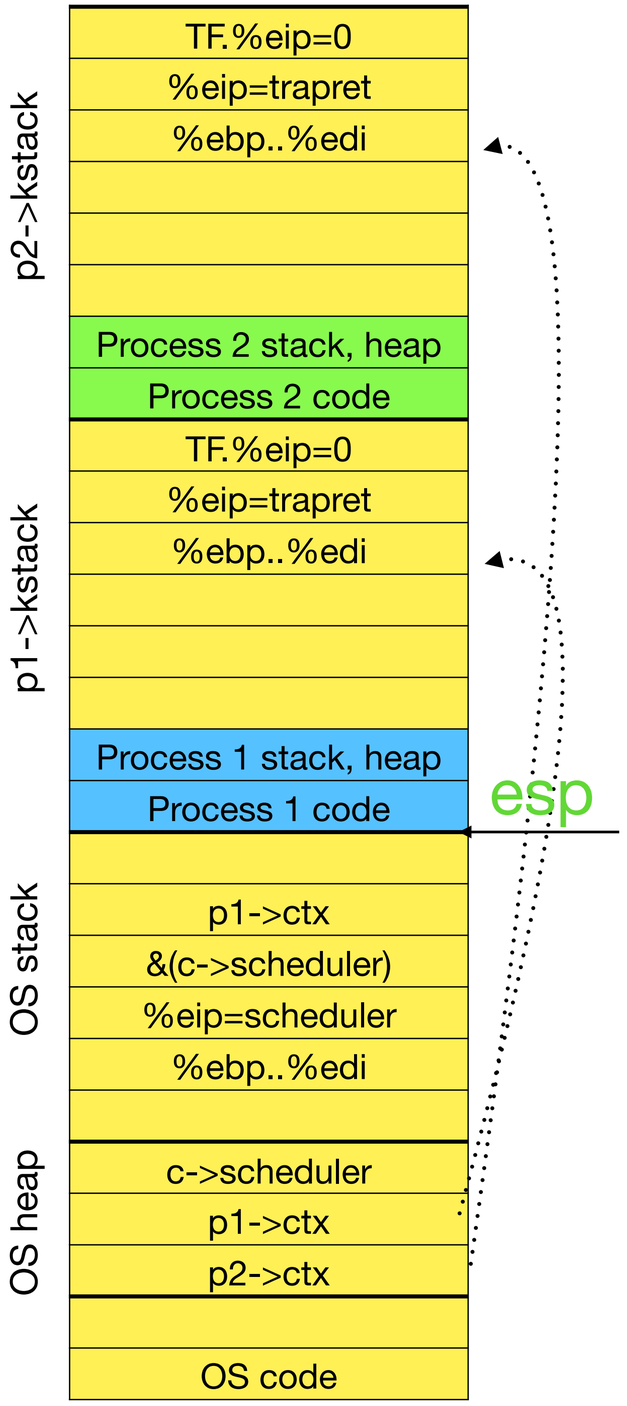

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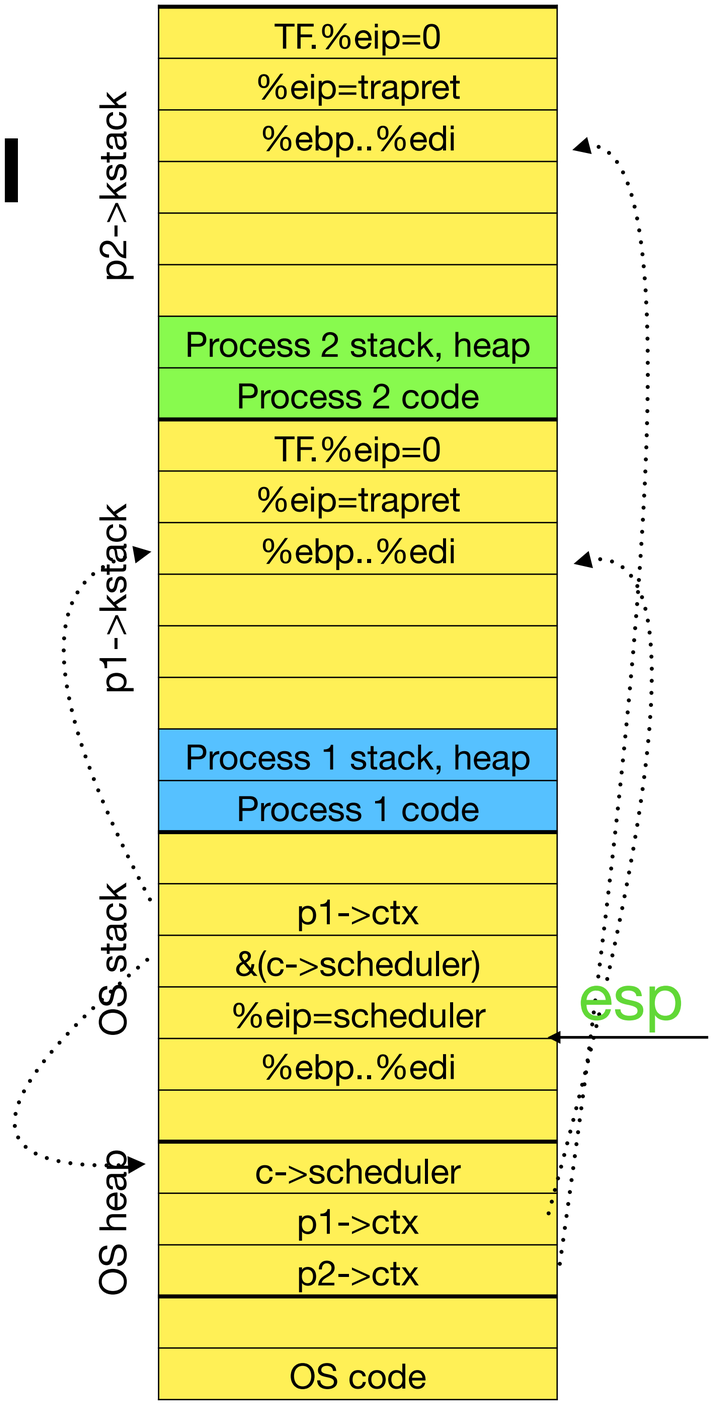

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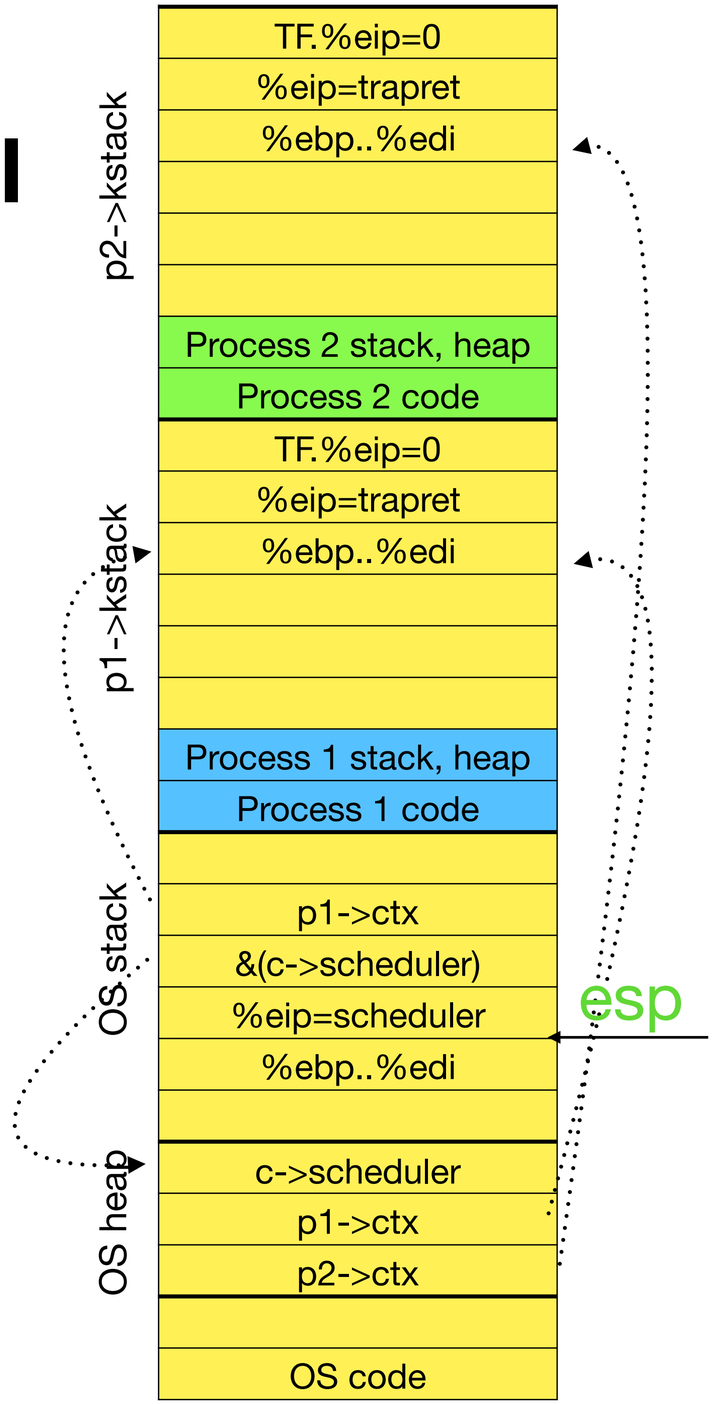

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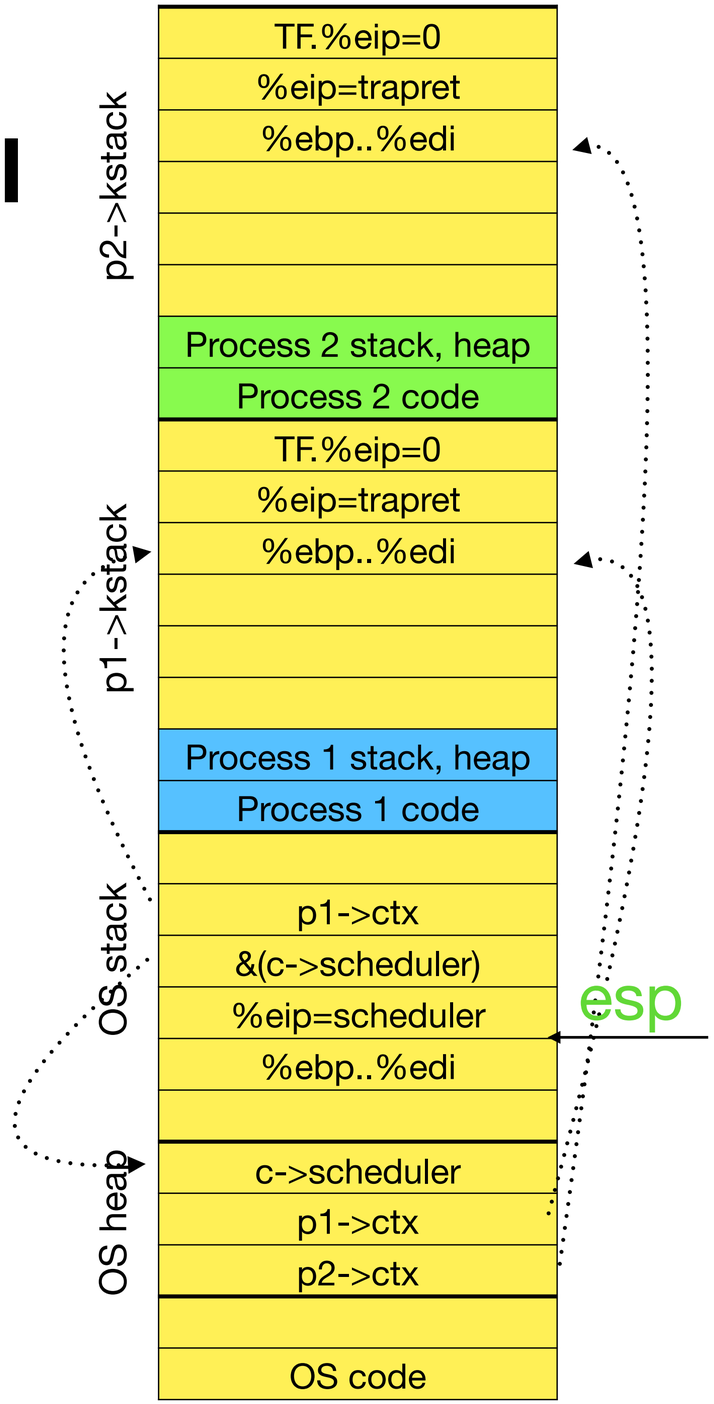

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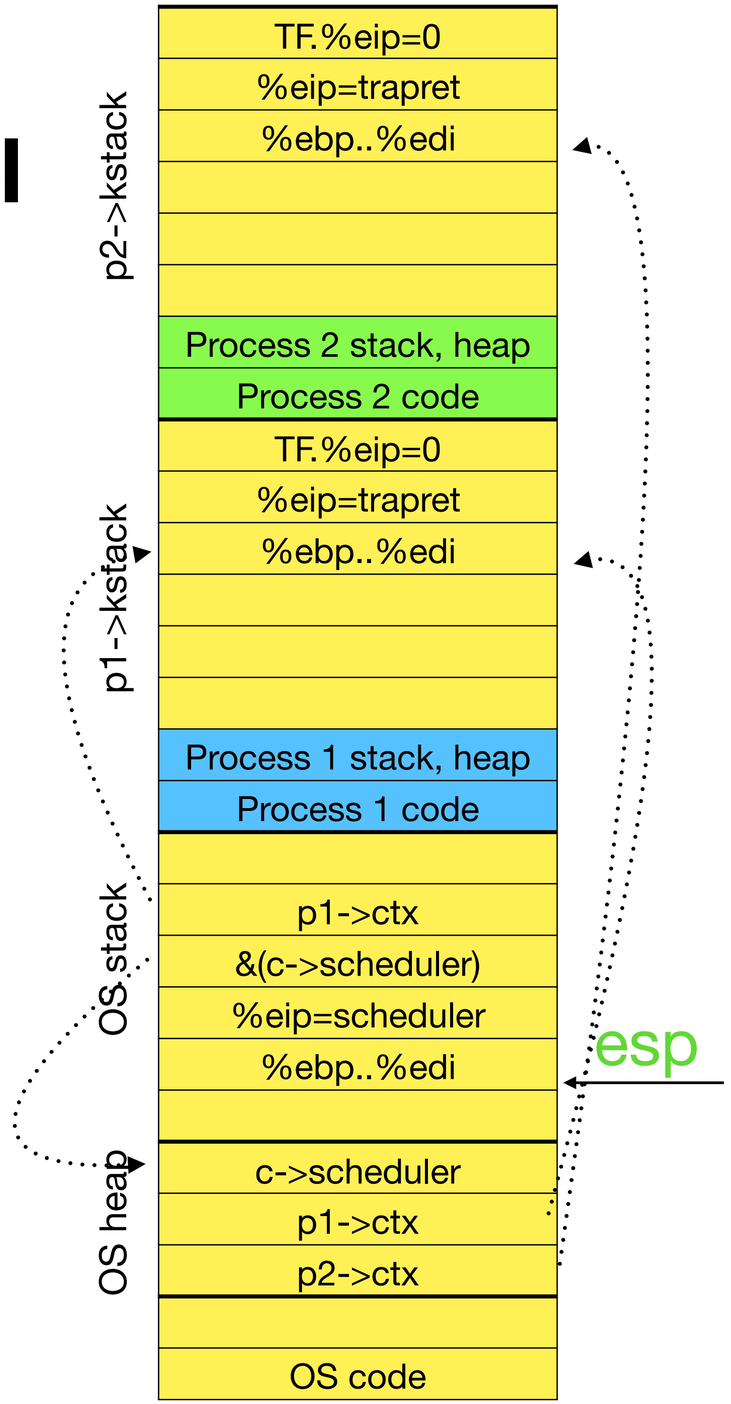

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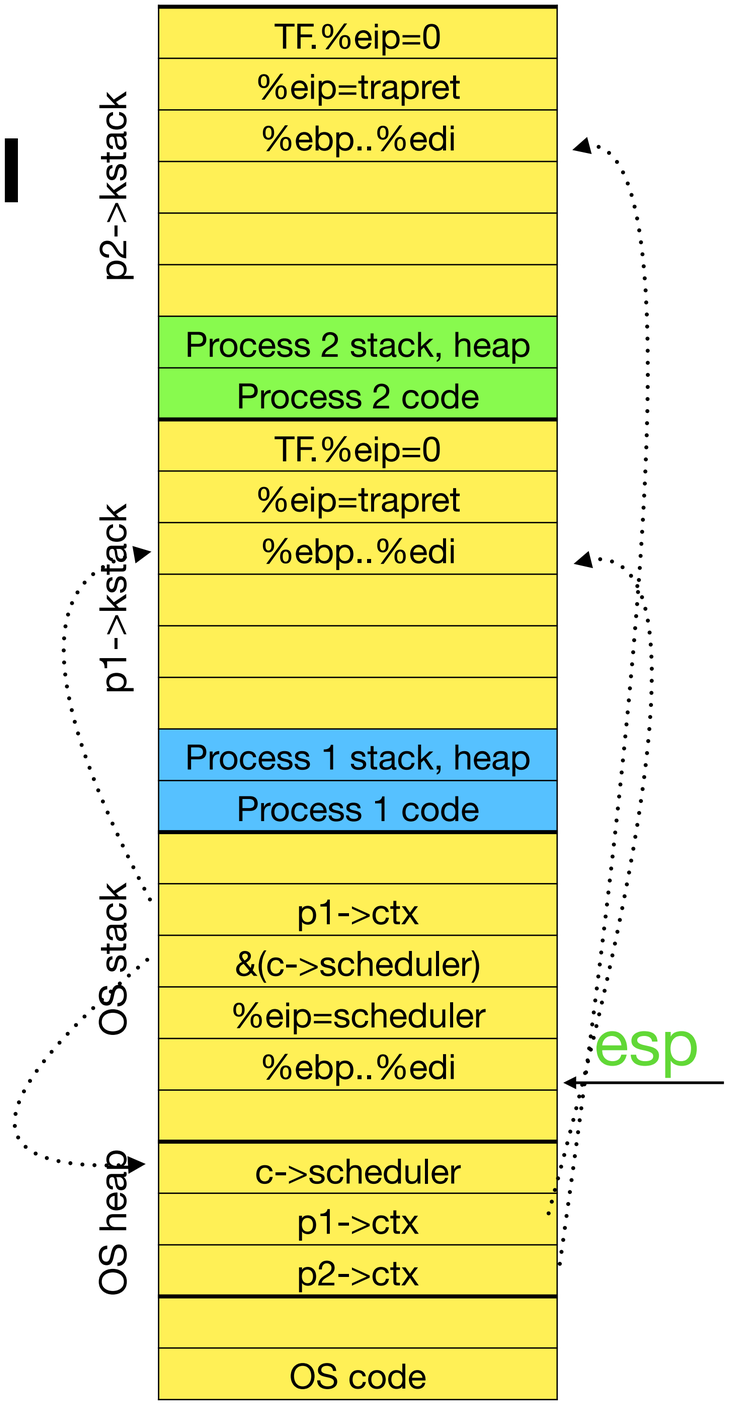

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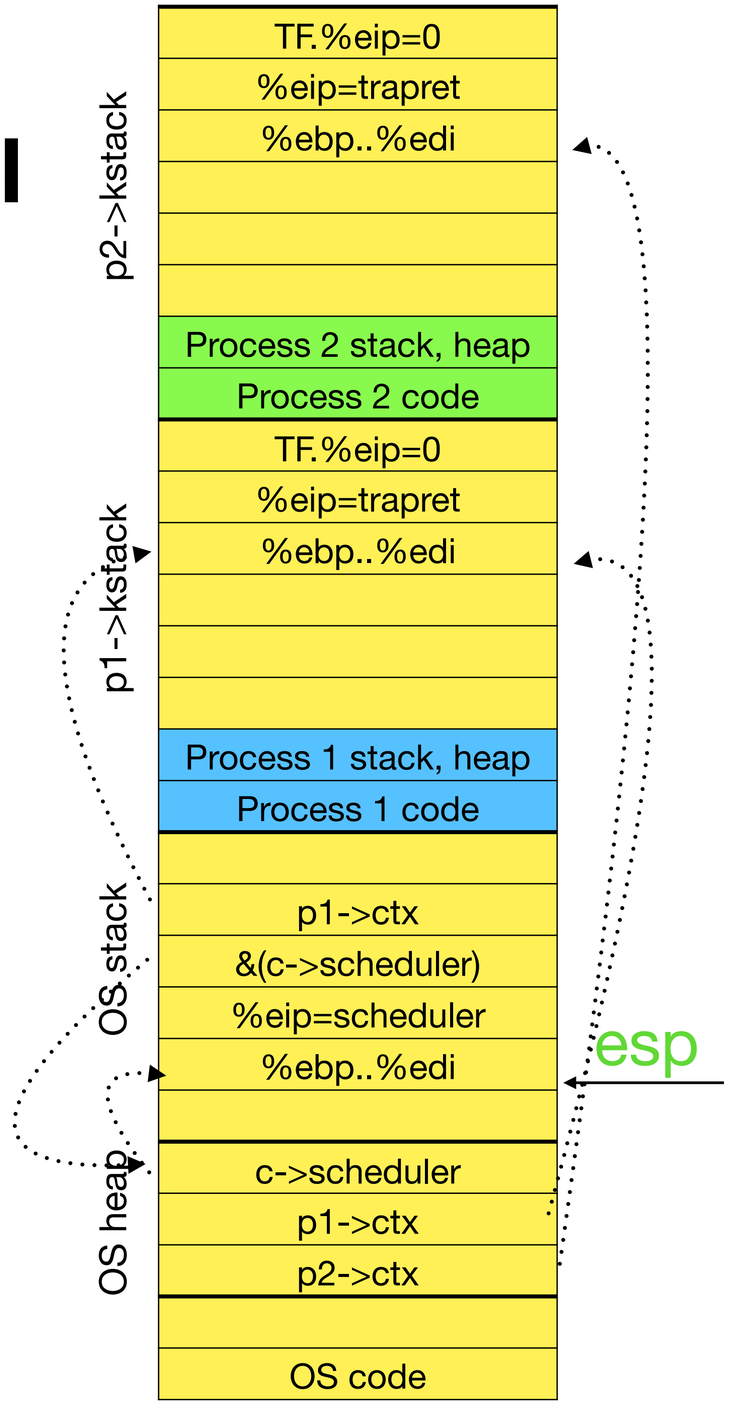

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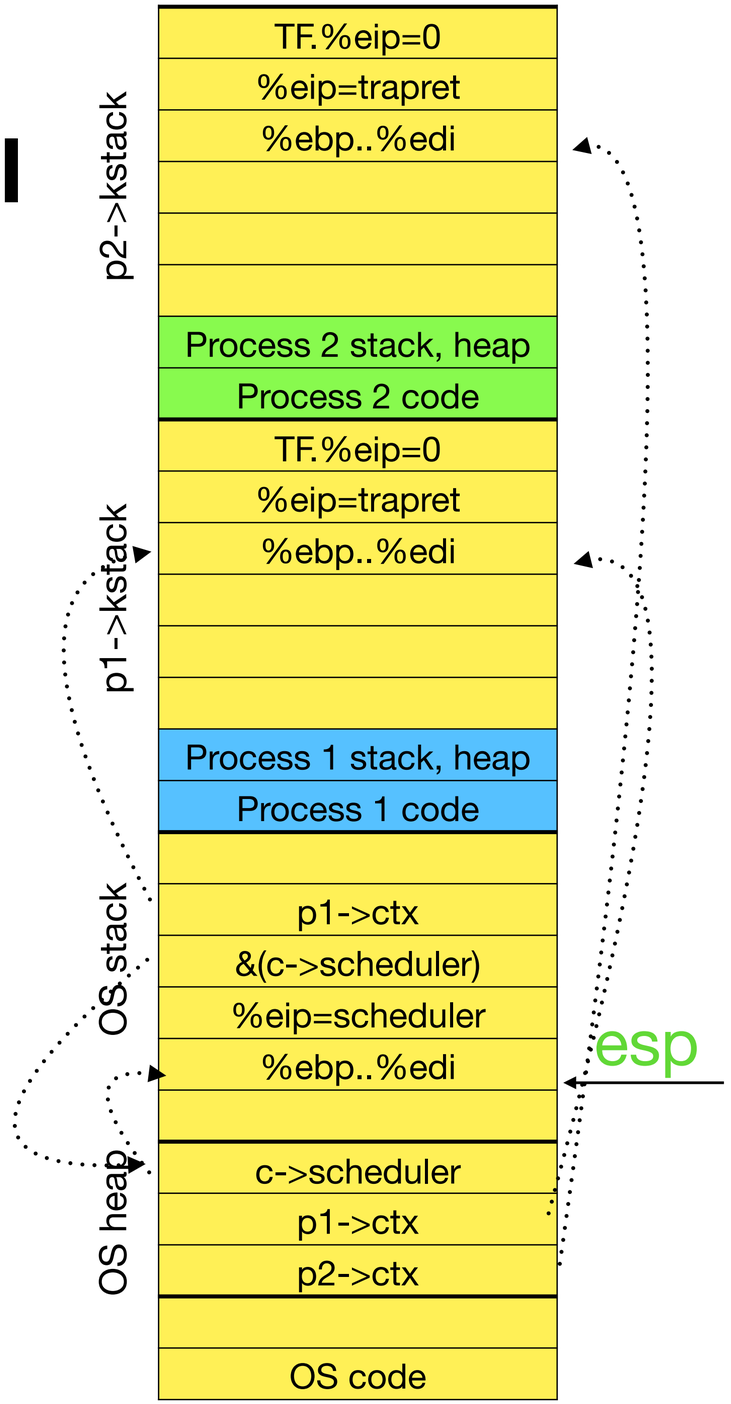

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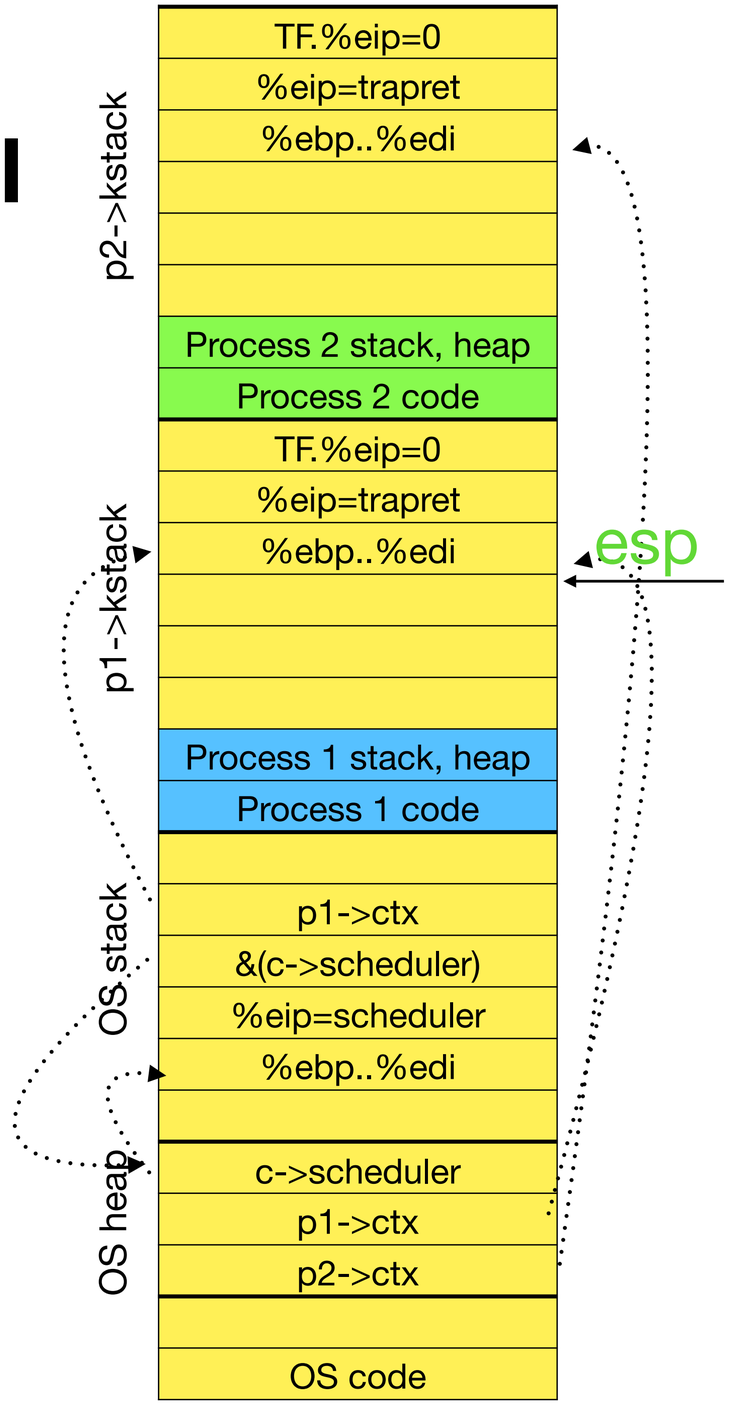

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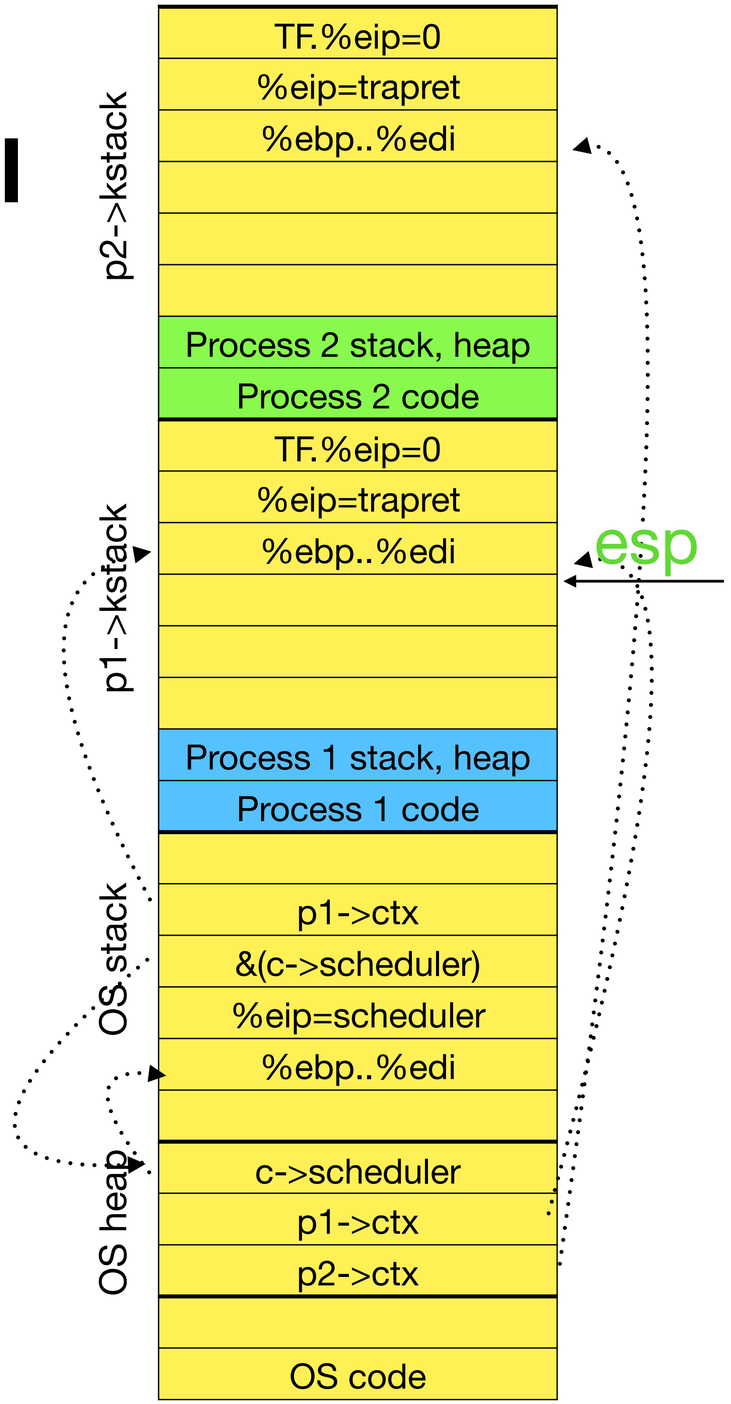

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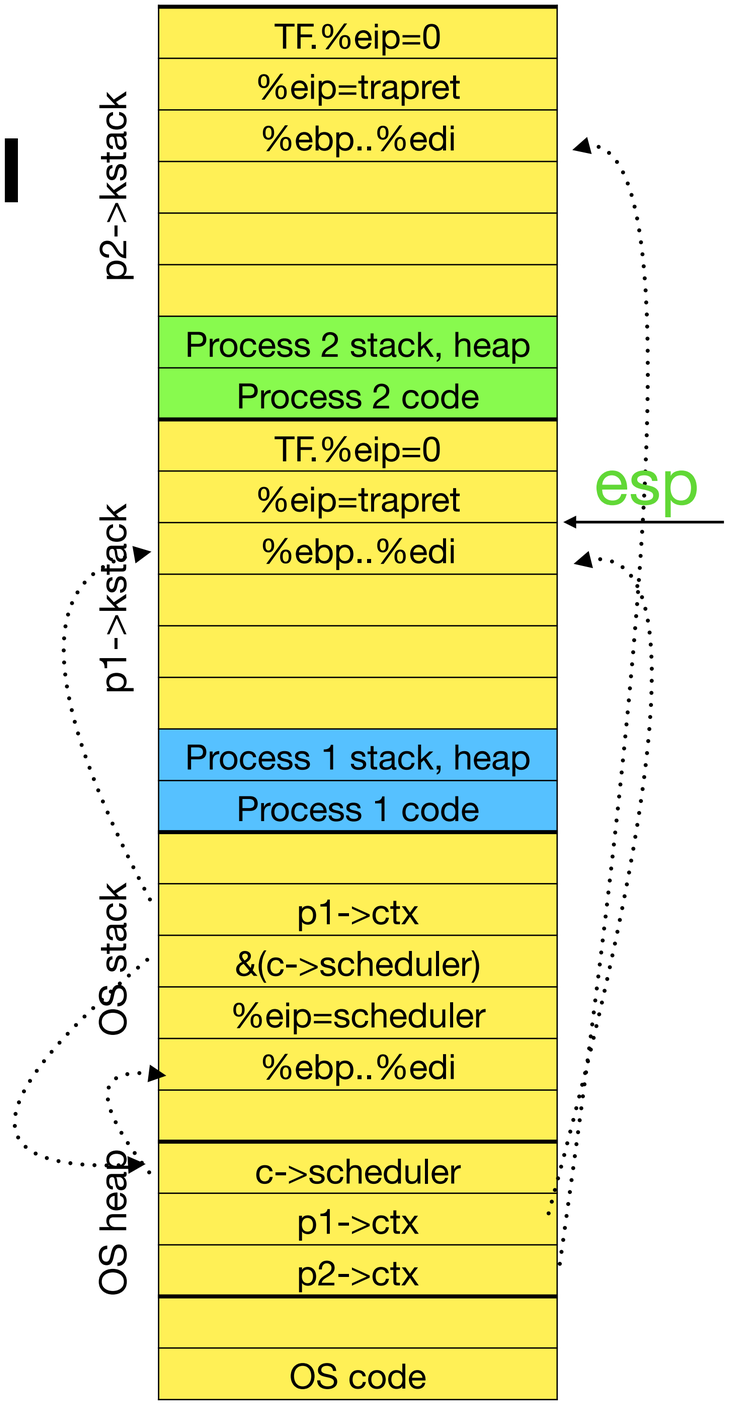

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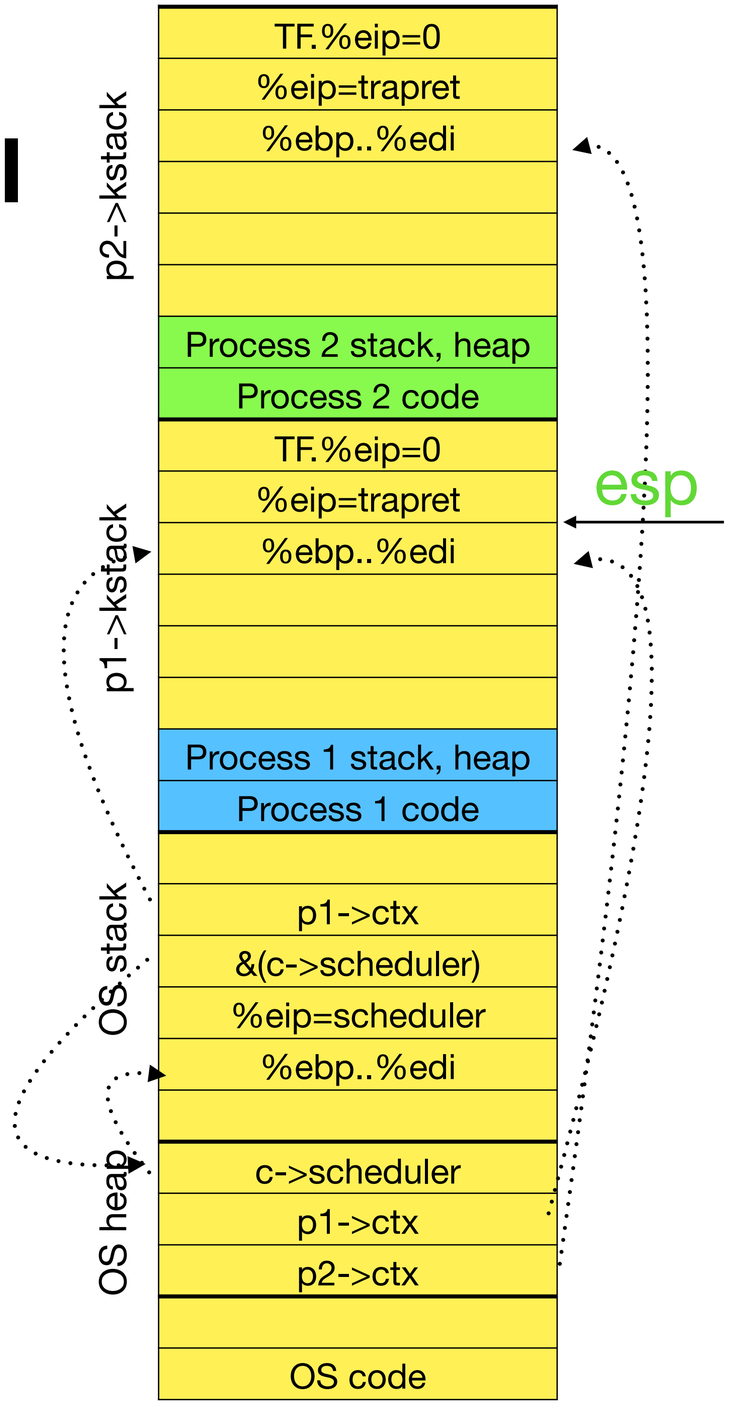

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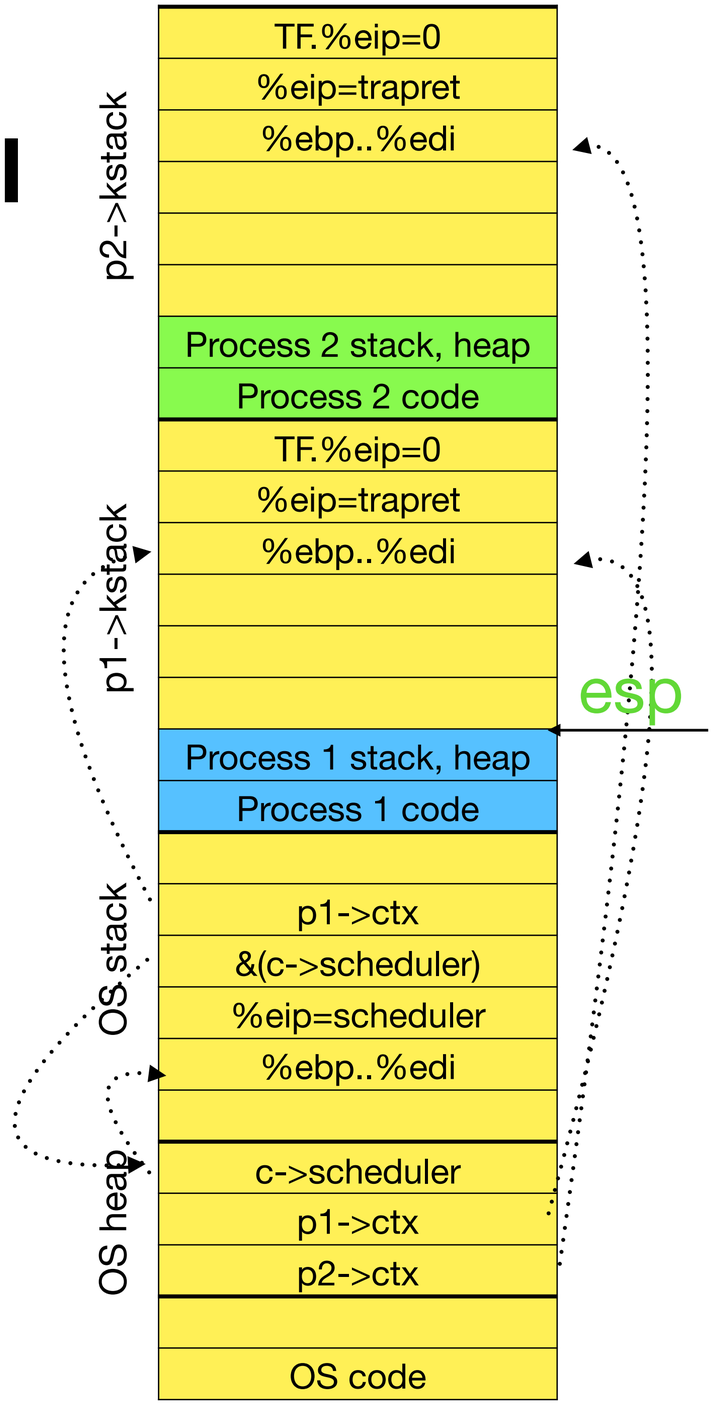

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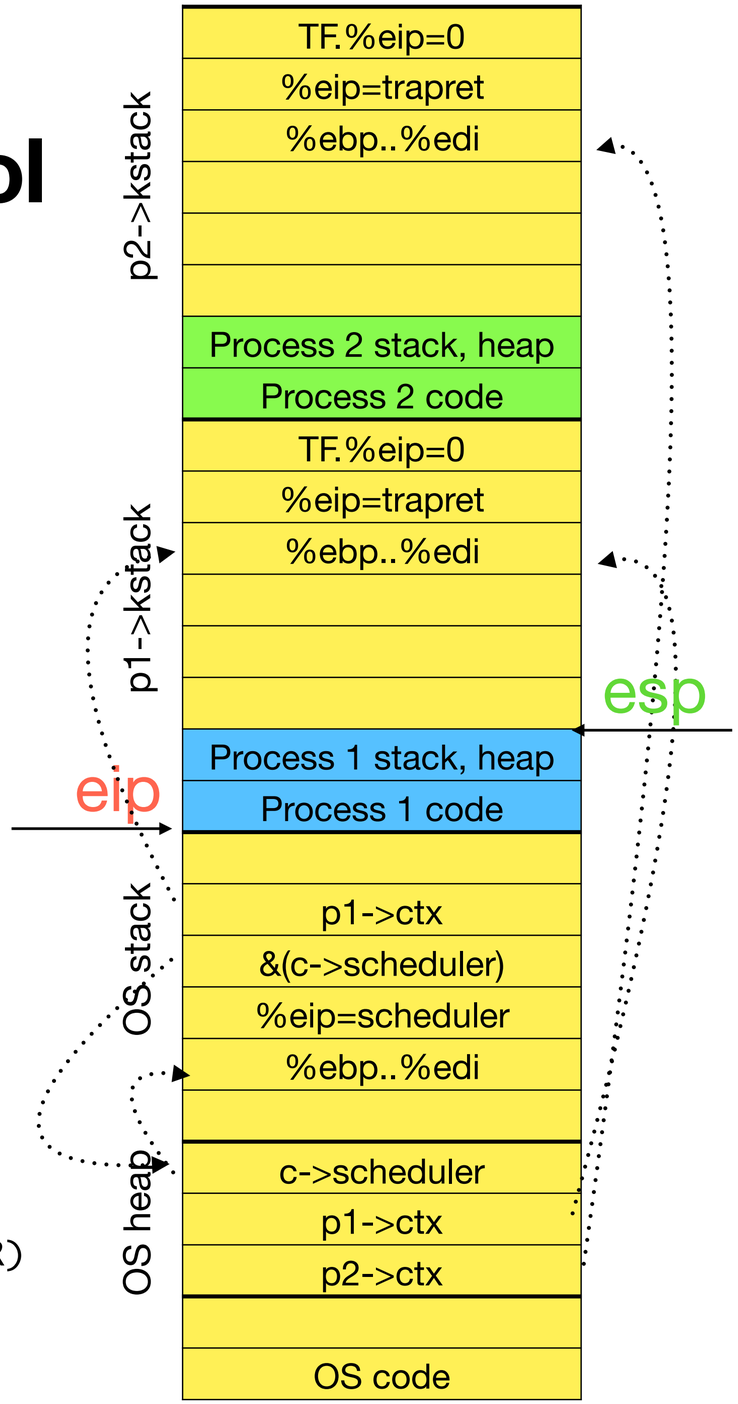

Context switching in action: taking control

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void trap(struct trapframe *tf) {
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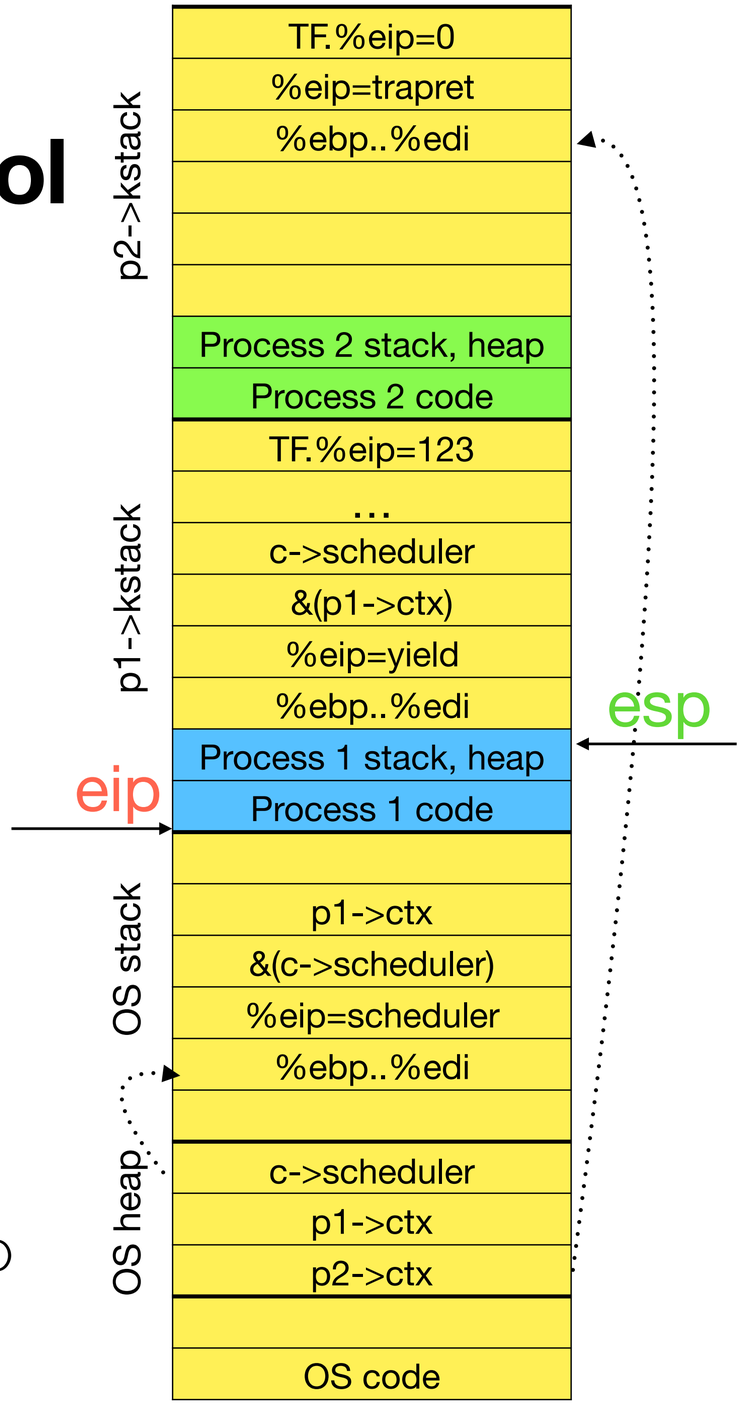

Context switching in action: taking control

p18-sched

```
.globl swtch
swtch:
  movl 4(%esp), %eax
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  pushl %ebp
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  movl %esp, (%eax)
  movl %edx, %esp
  popl %edi
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void scheduler(void) {
  struct proc *p;  struct cpu *c = mycpu();
  for(;;){
   for(p = ptable.proc; p < &ptable.proc[NPROC]; p++){
      if(p->state != RUNNABLE)
        continue;
      p->state = RUNNING;
      switchuvm(p);
      swtch(&(c->scheduler), p->context);
    }
  }
}
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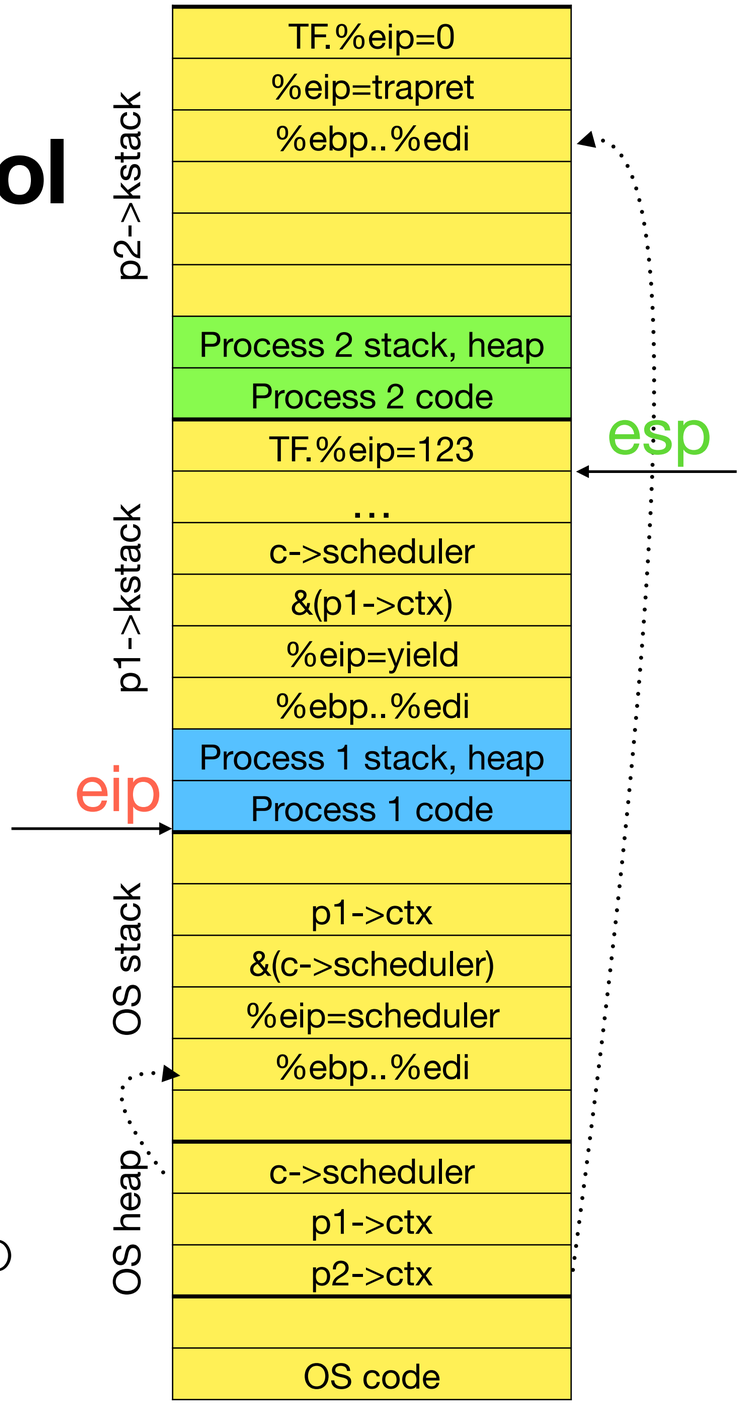

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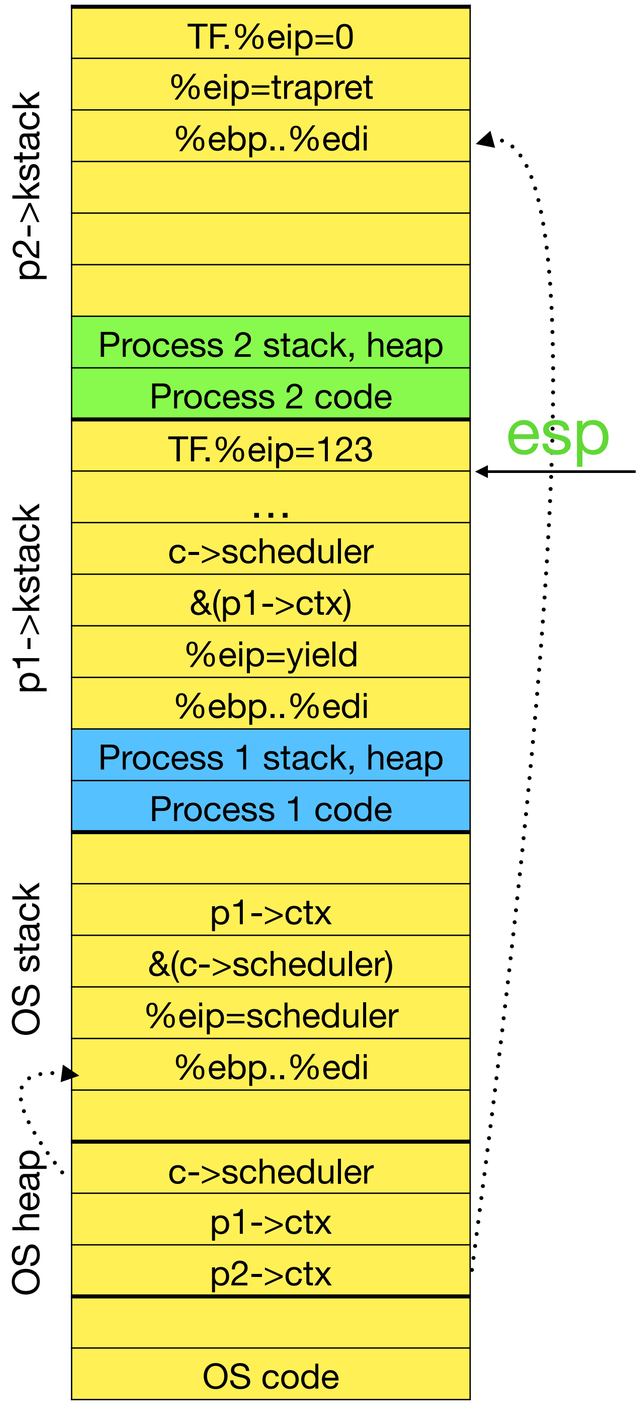

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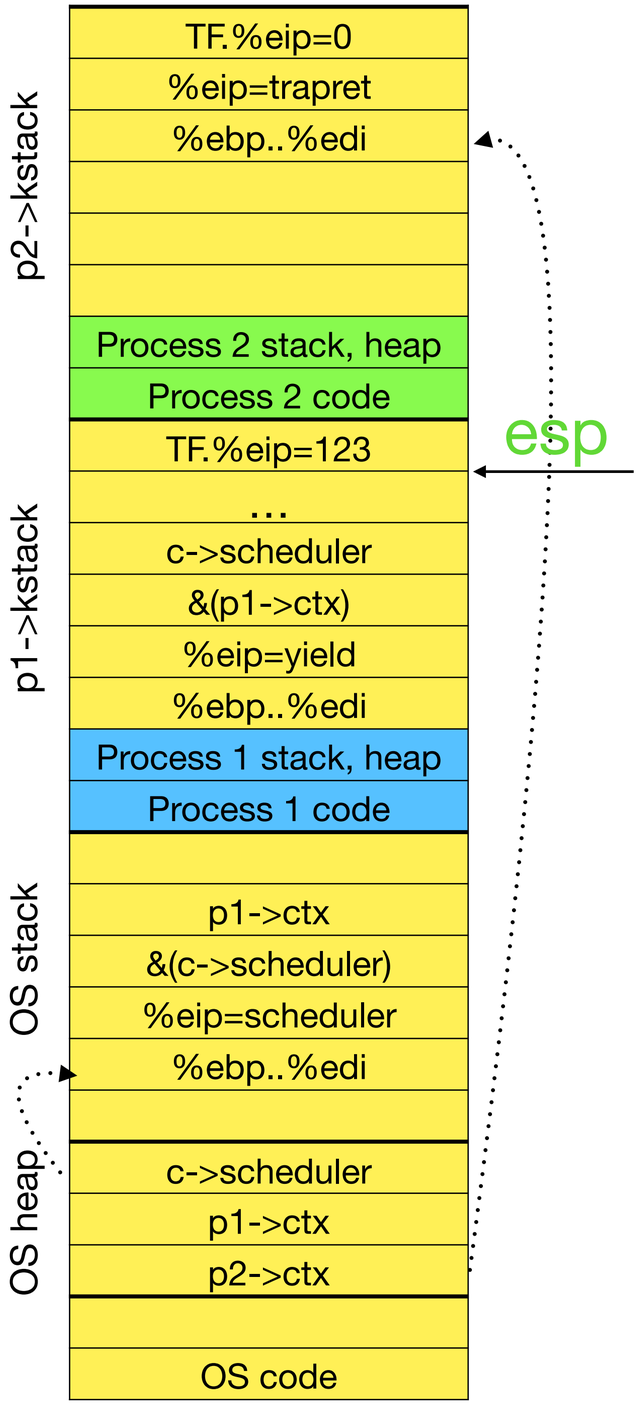

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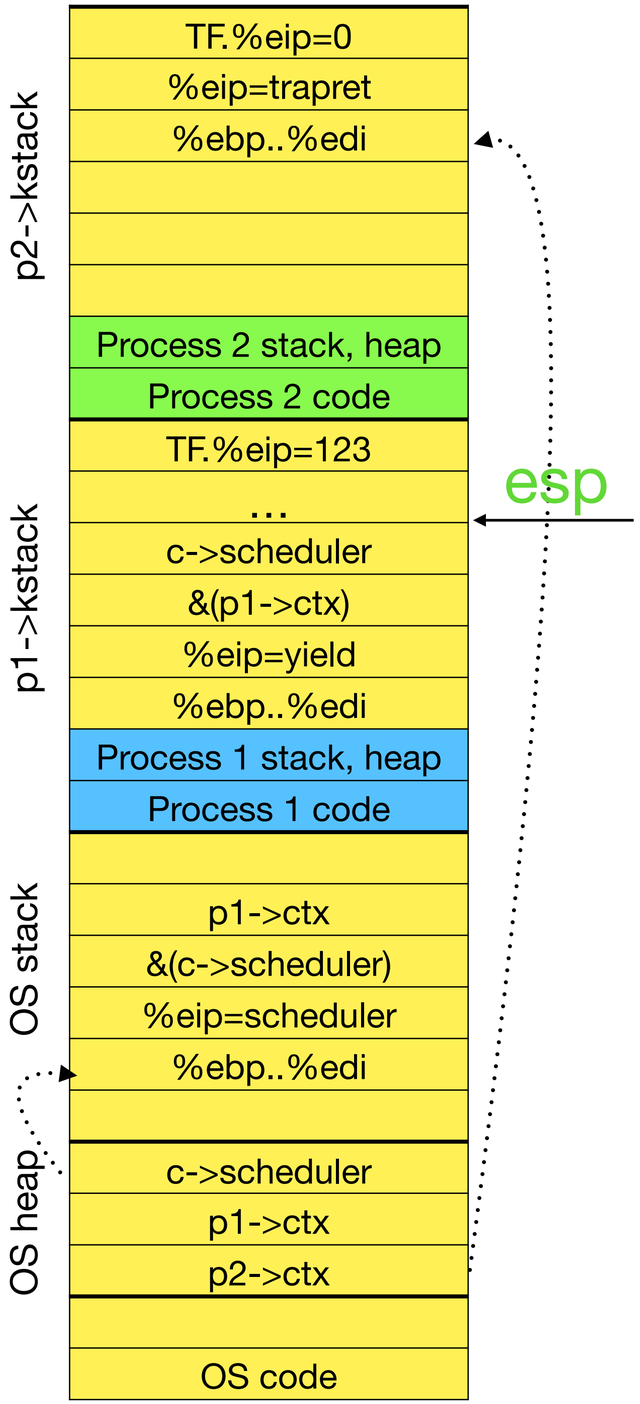

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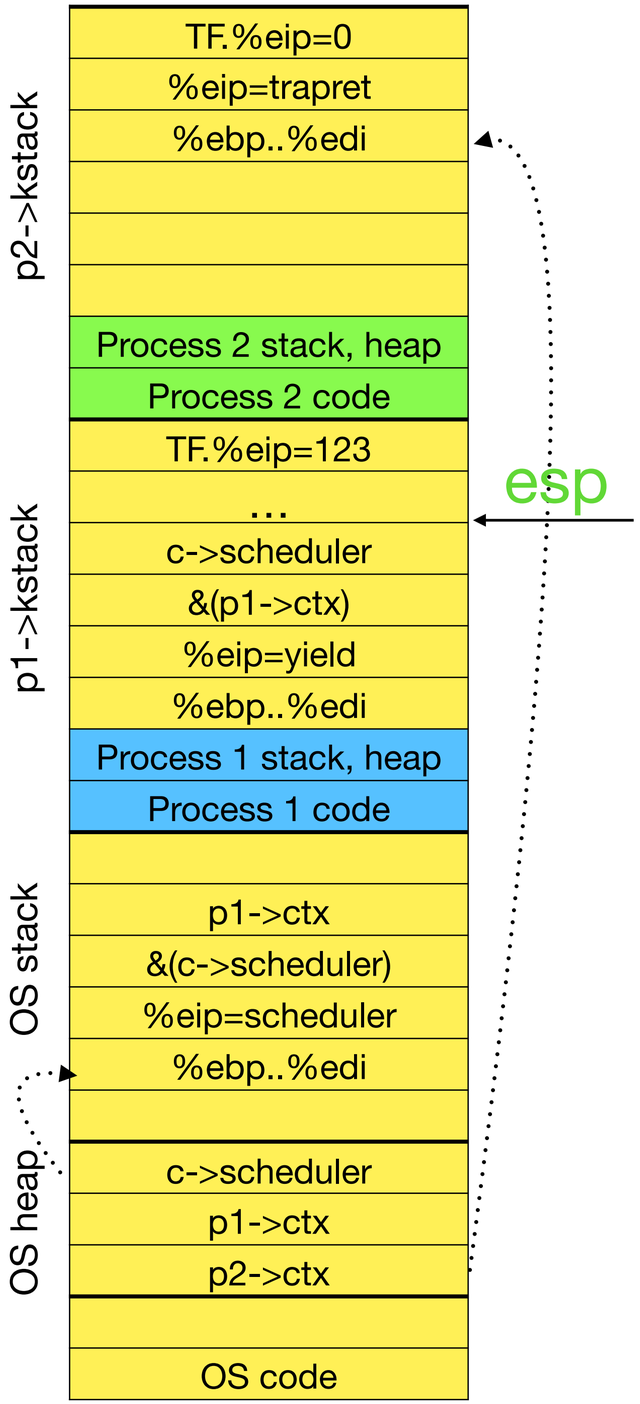

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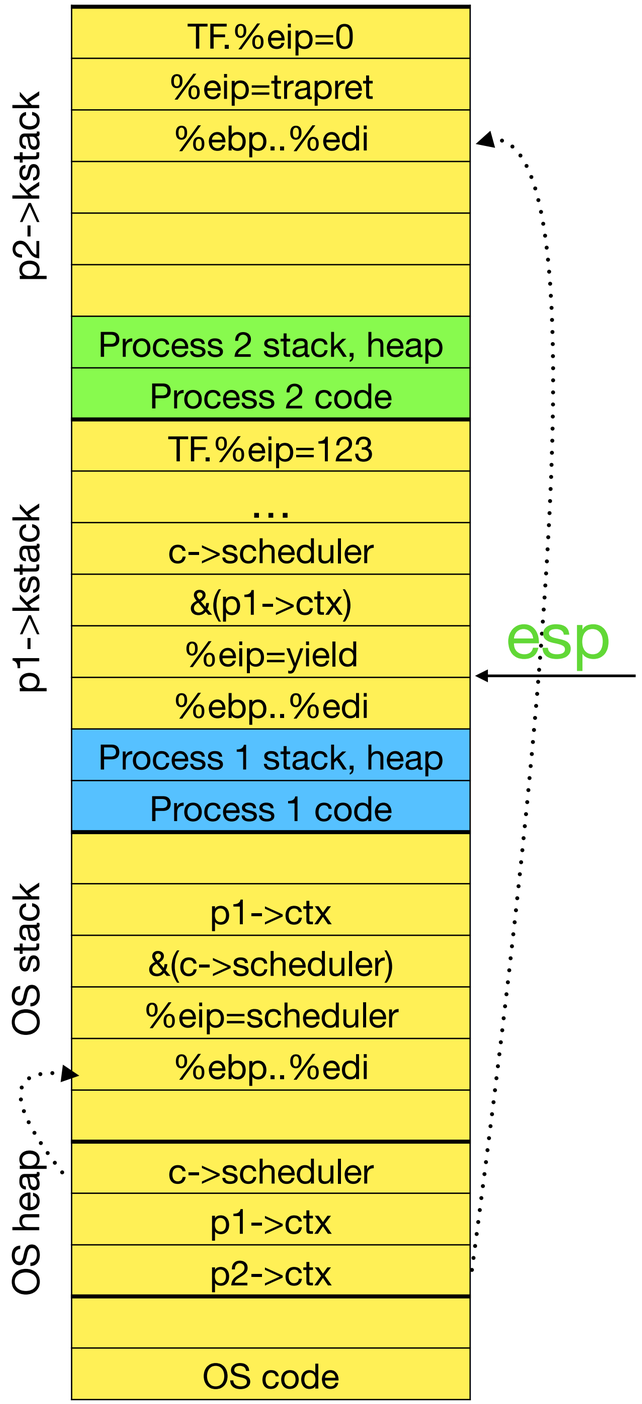

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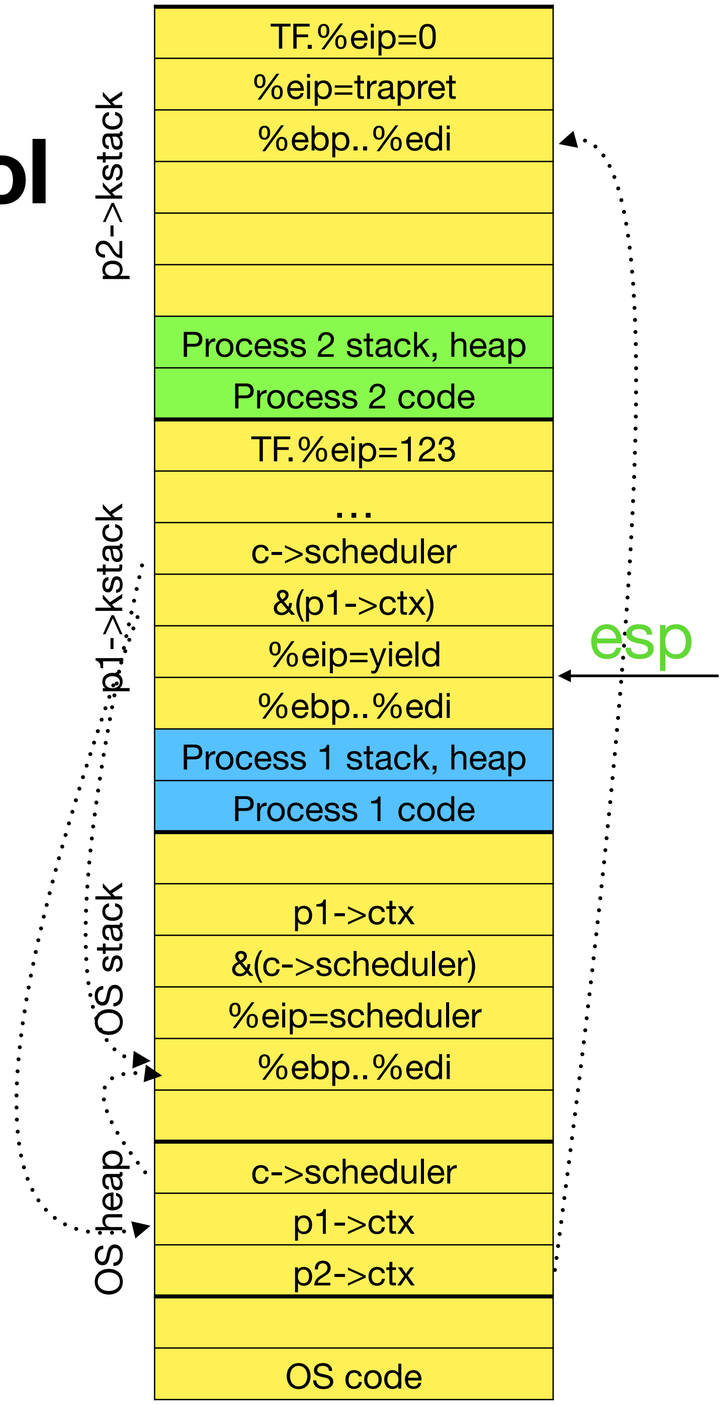

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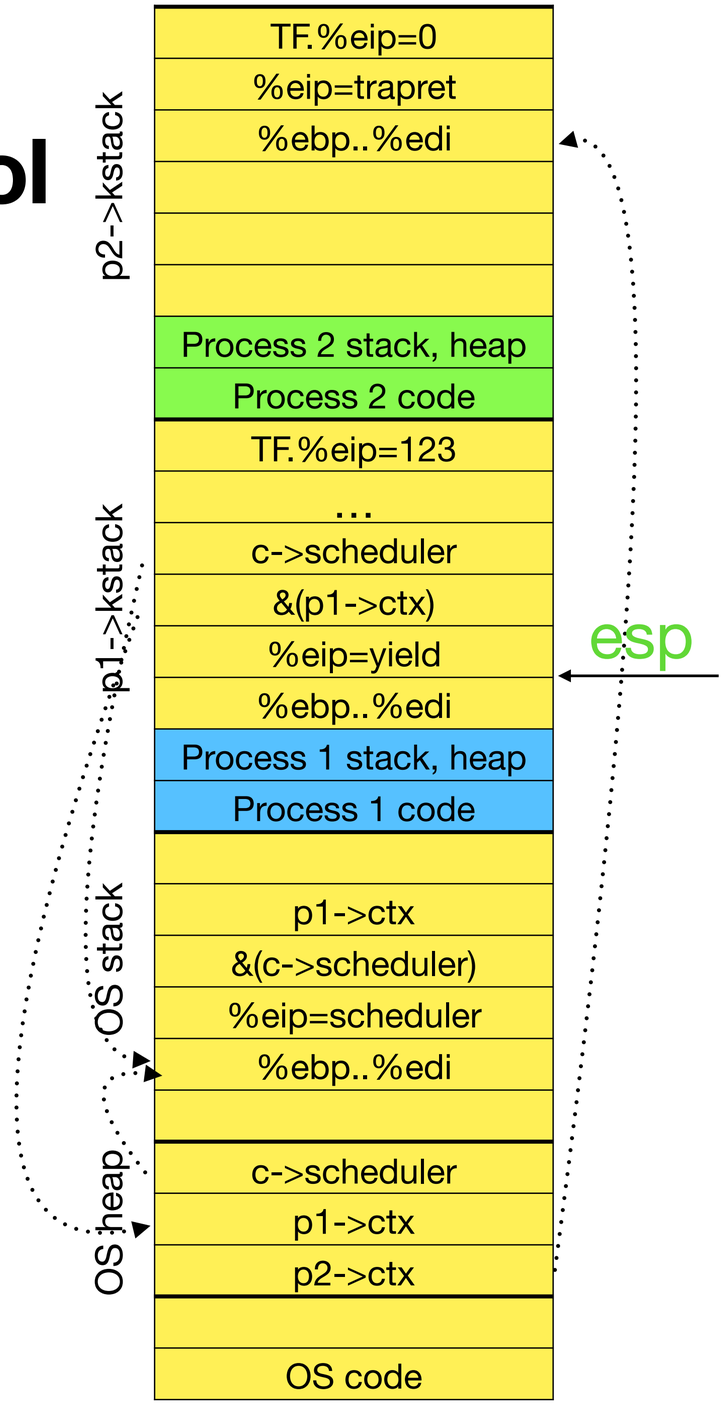

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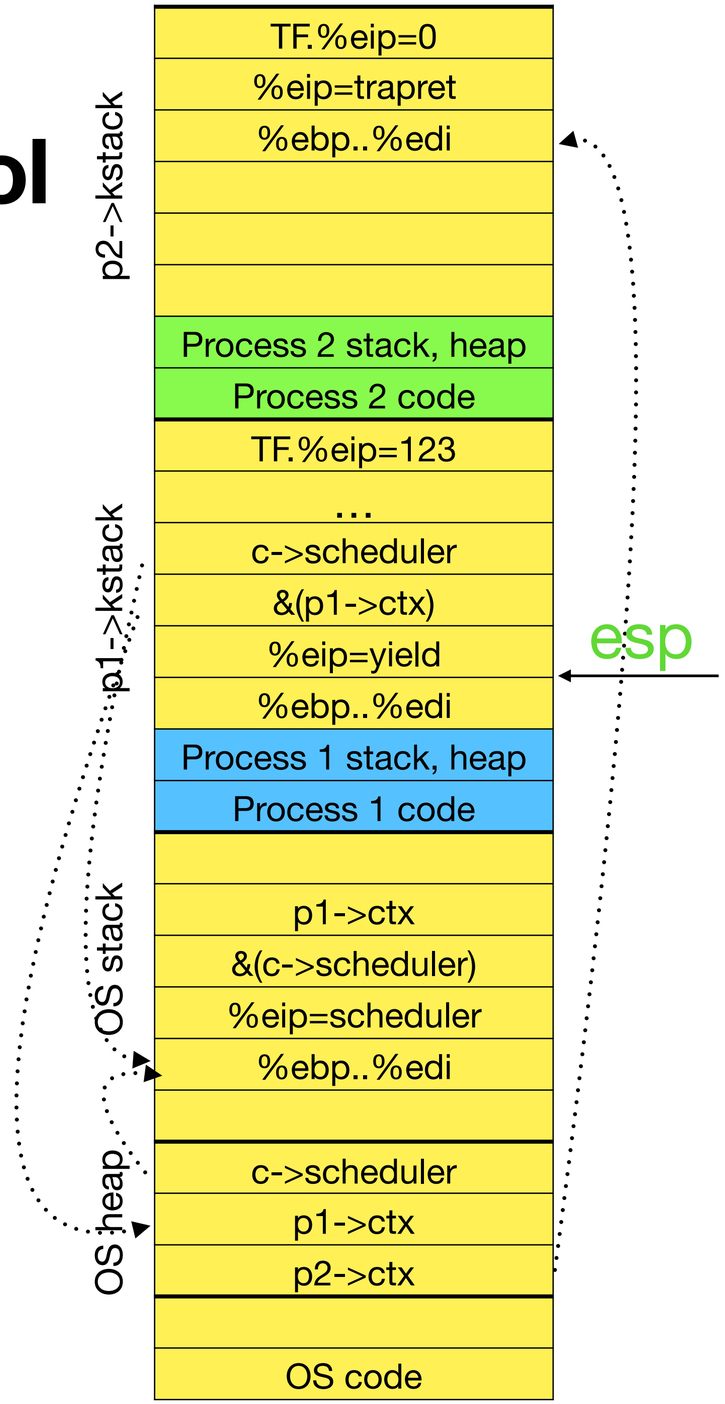

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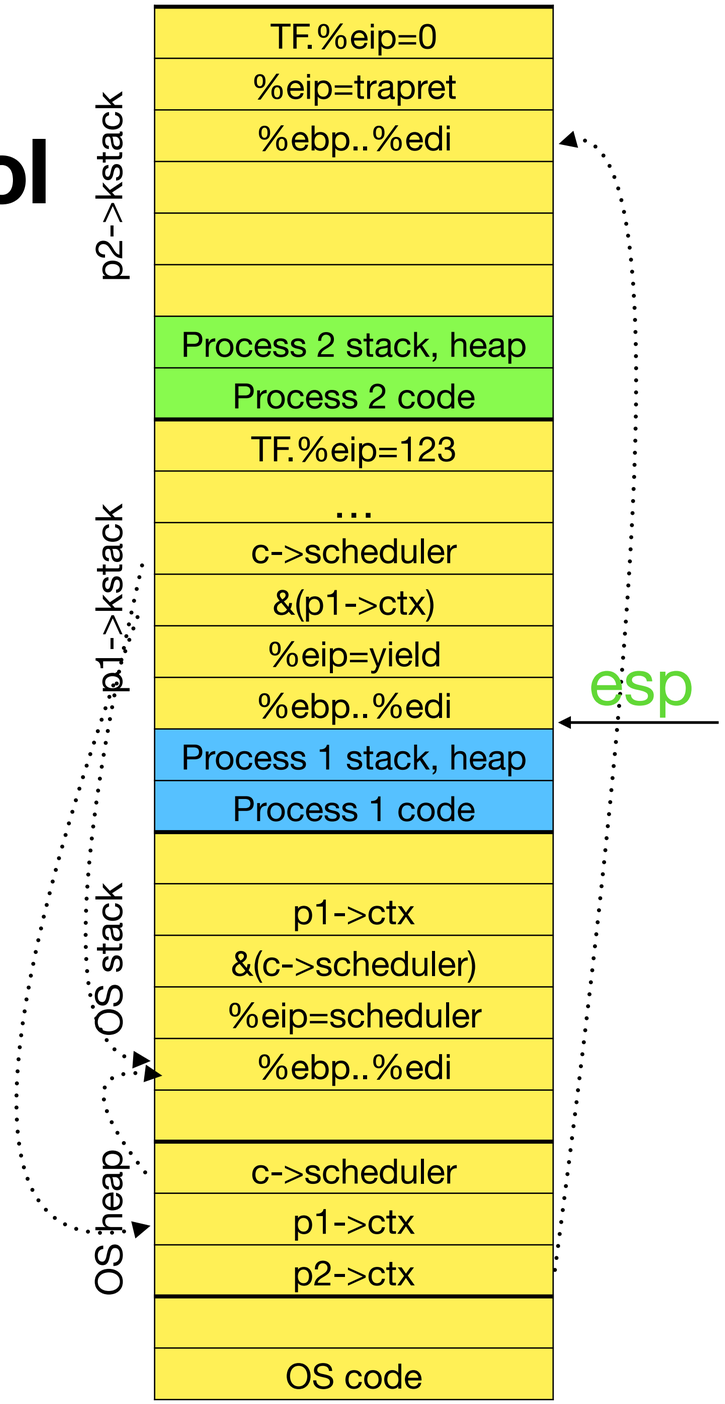

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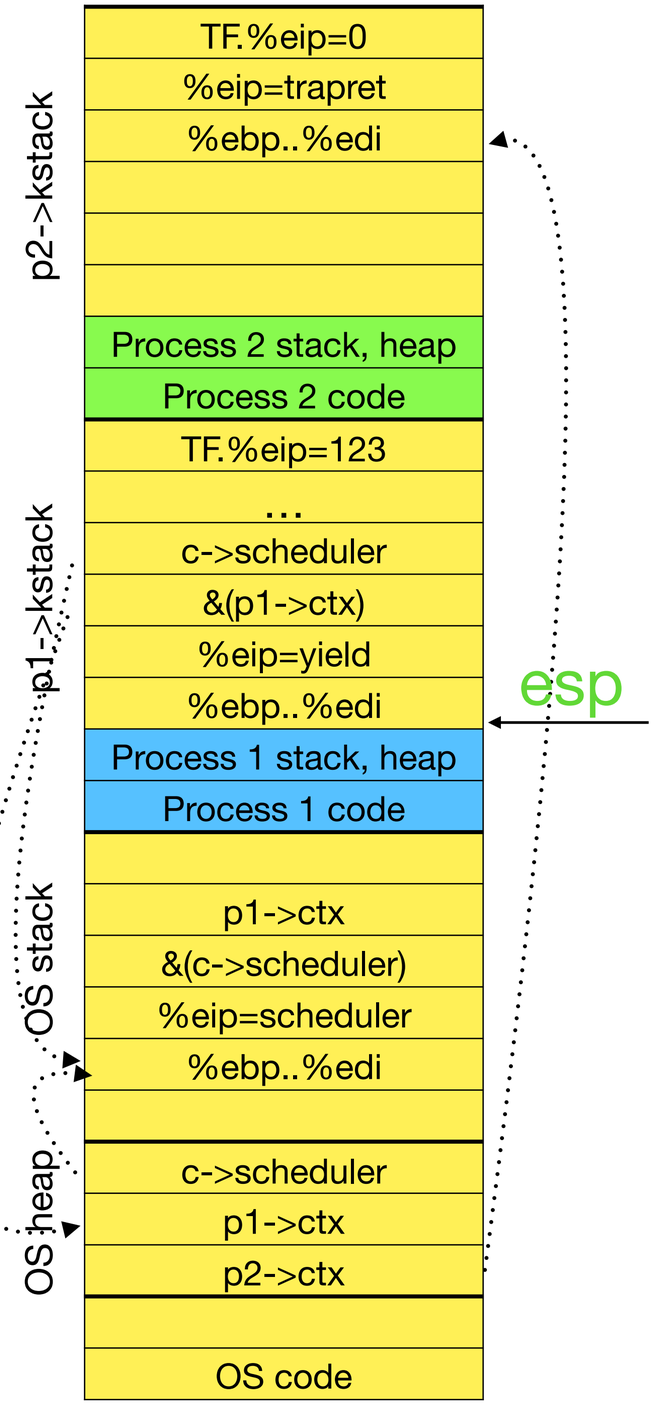

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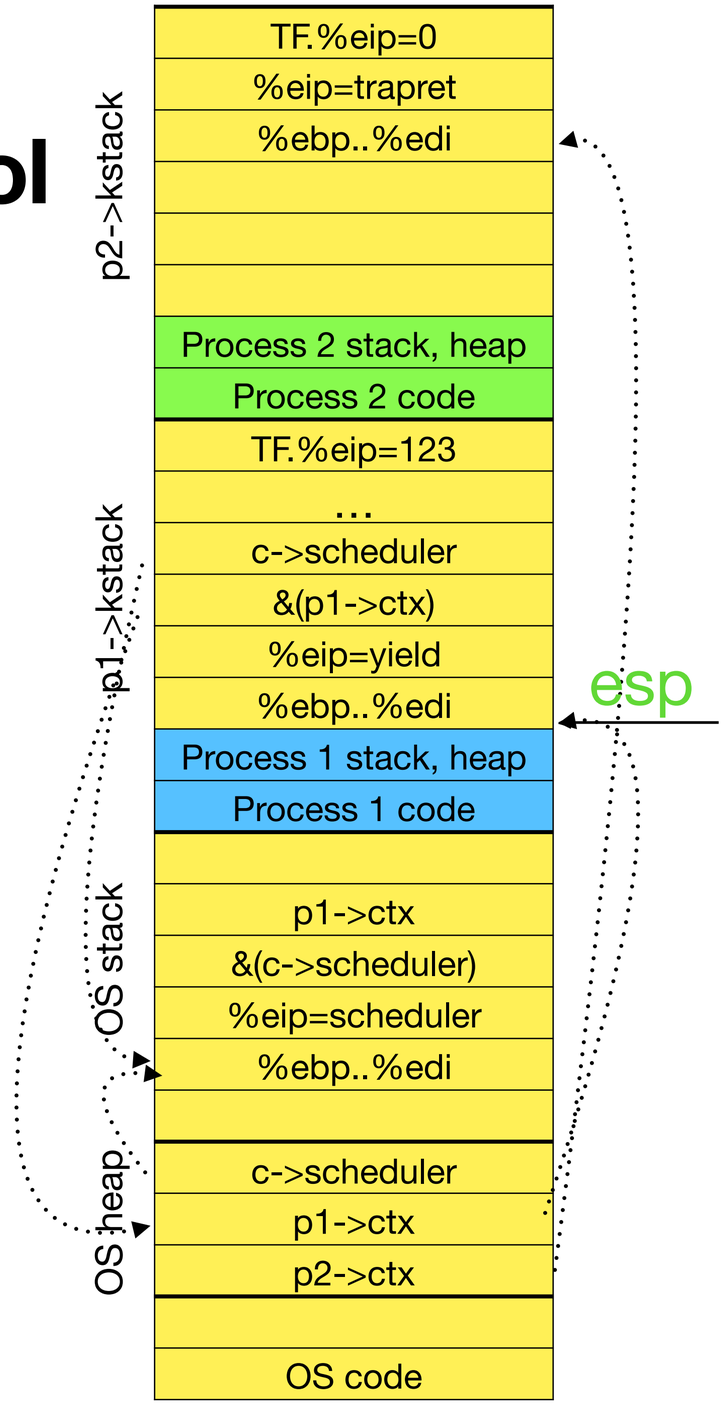

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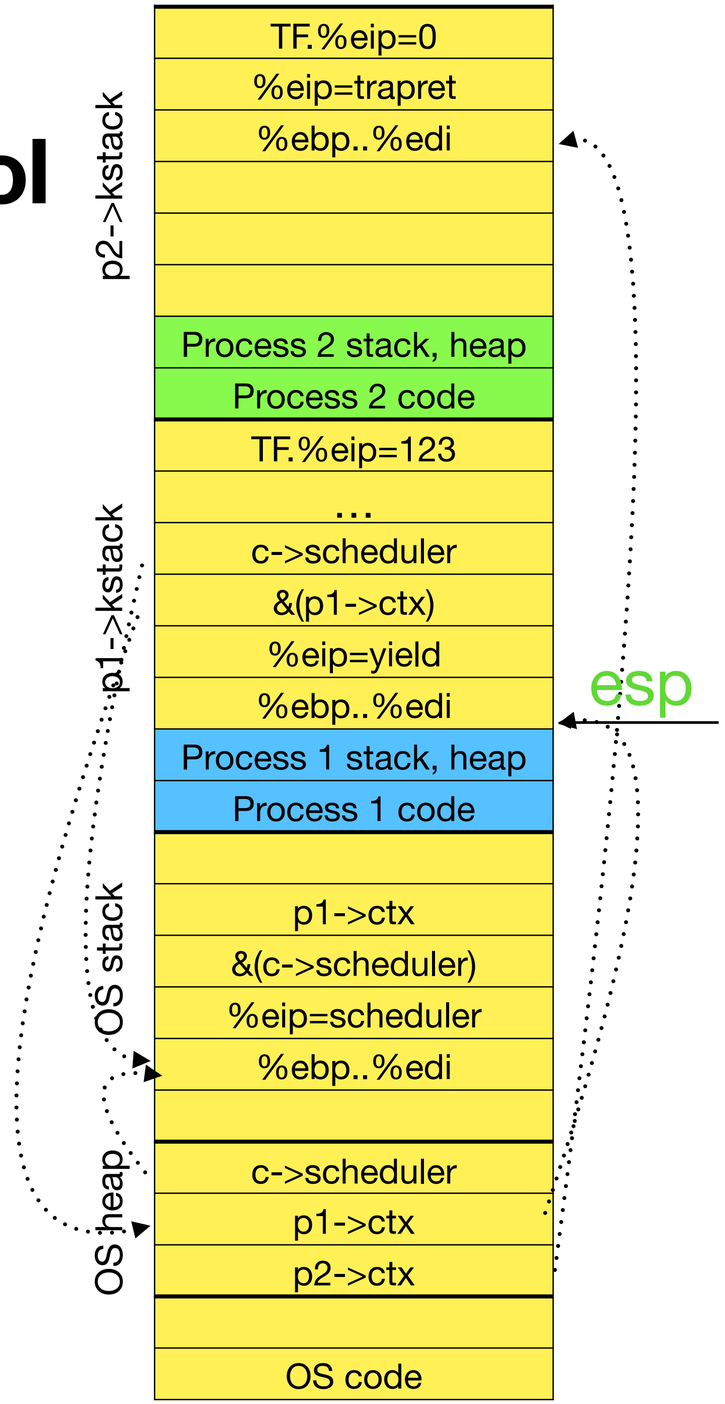

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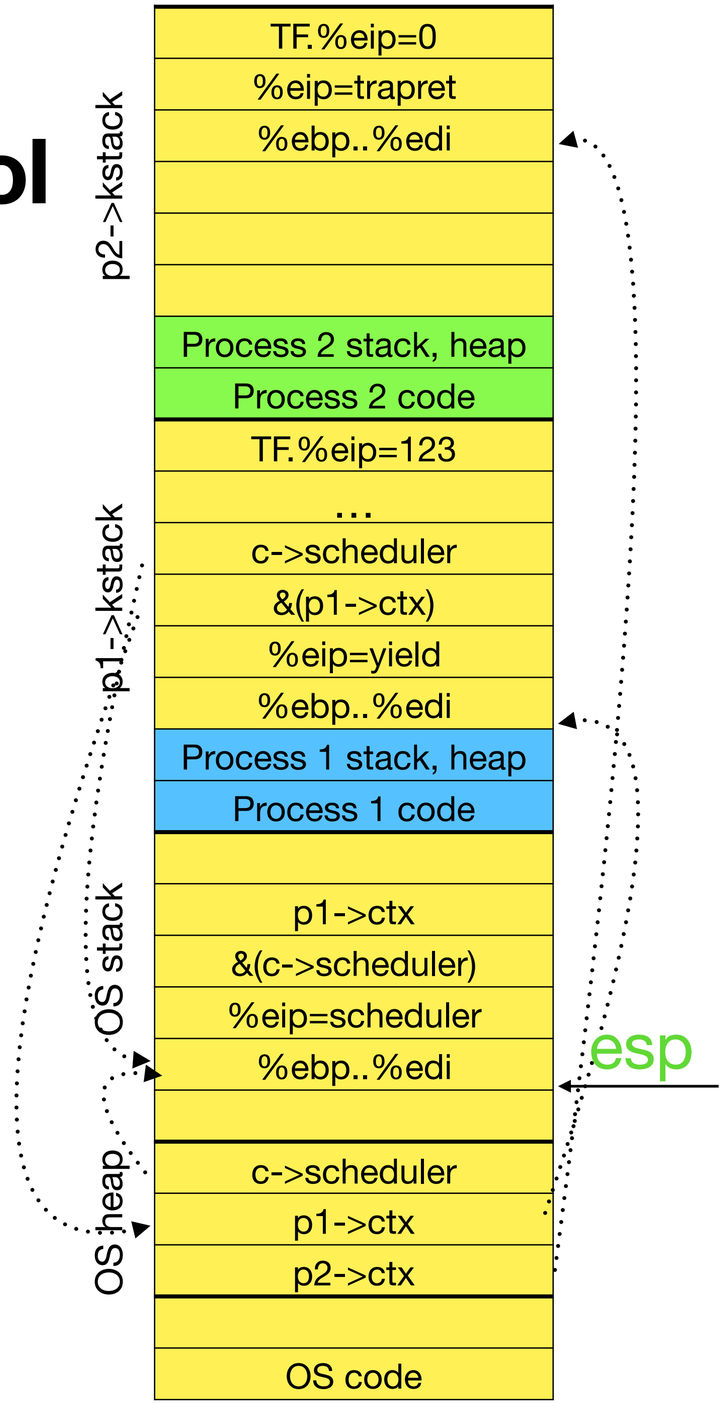

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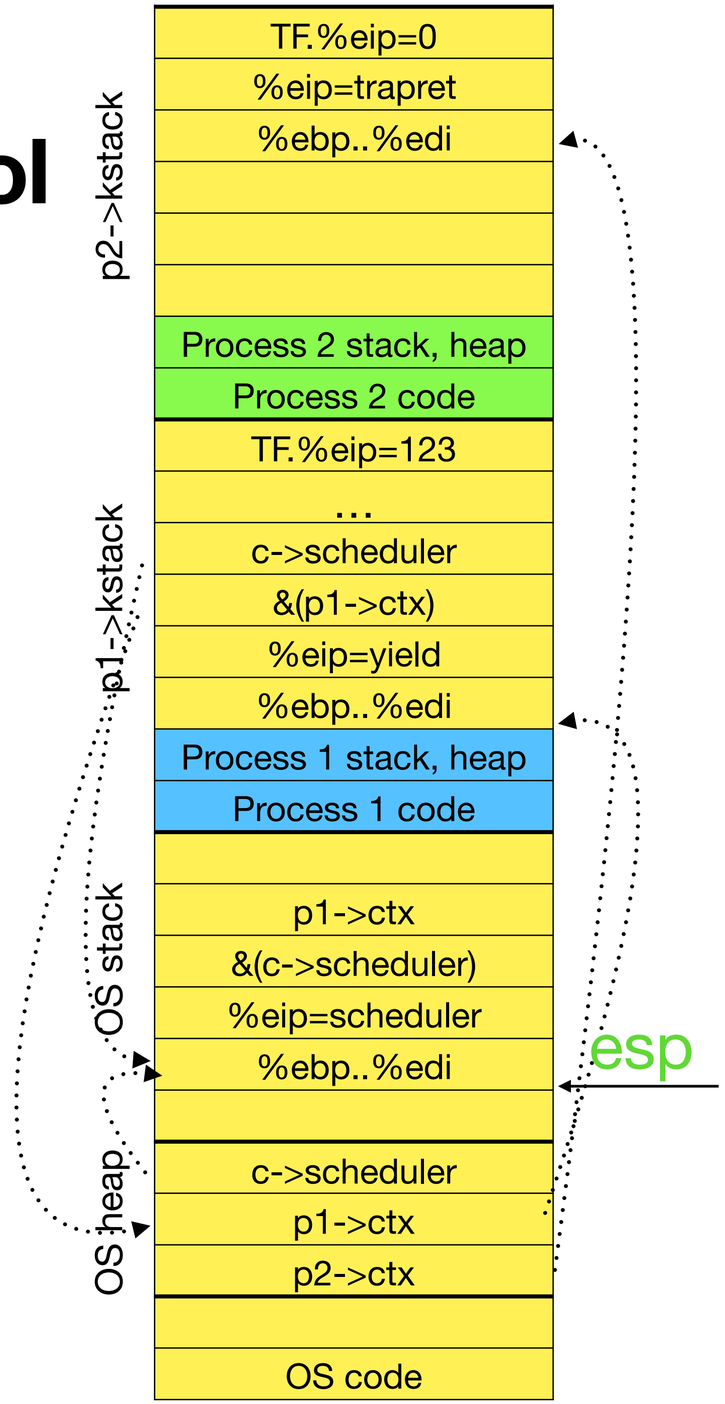

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  popl %edi
  popl %esi
  popl %ebx
  popl %ebp
  ret
```

eip

```
void scheduler(void) {
  struct proc *p;  struct cpu *c = mycpu();
  for(;;){
   for(p = ptable.proc; p < &ptable.proc[NPROC]; p++){
      if(p->state != RUNNABLE)
        continue;
      p->state = RUNNING;
      switchuvm(p);
      swtch(&(c->scheduler), p->context);
    }
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```

```
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```

```
void trap(struct trapframe *tf) {
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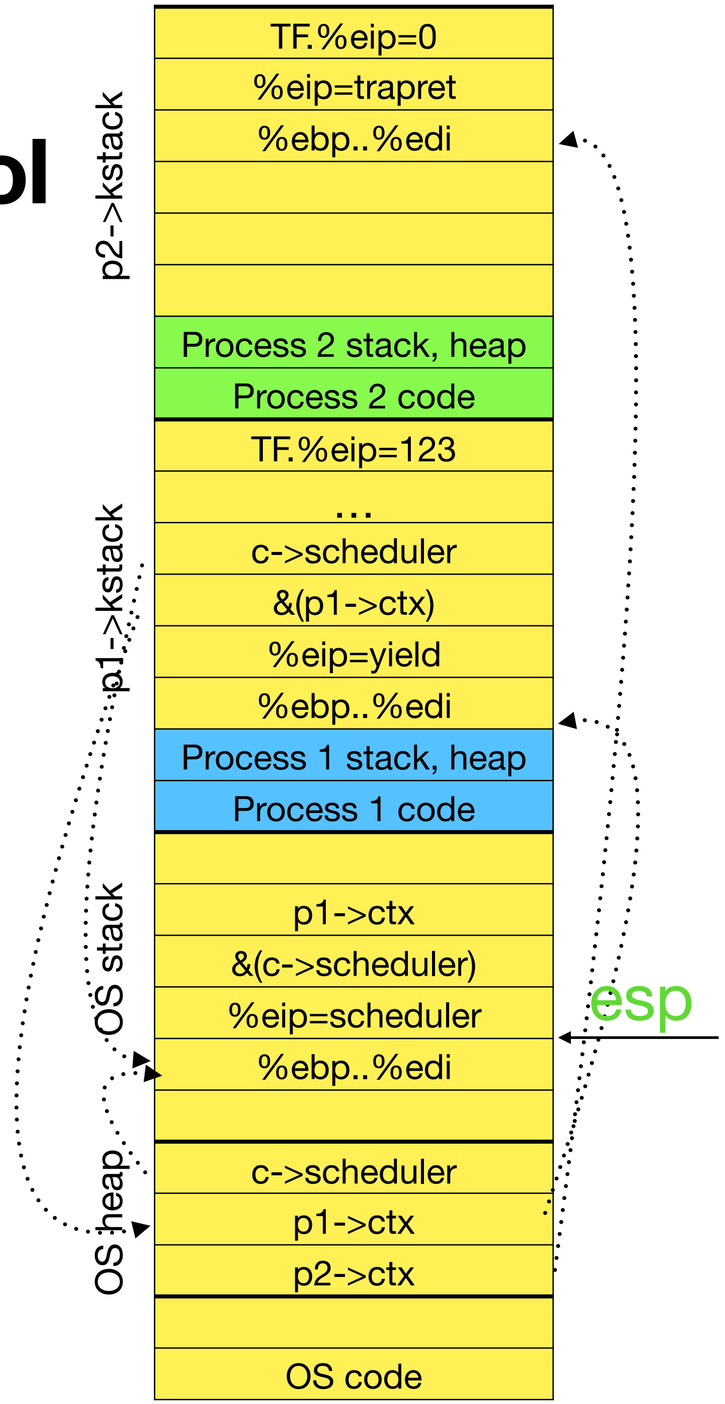
}
```



Context switching in action: taking control

p18-sched

```
.globl swtch
swtch:
  movl 4(%esp), %eax
  movl 8(%esp), %edx
  pushl %ebp
  pushl %ebx
  pushl %esi
  pushl %edi
  movl %esp, (%eax)
  movl %edx, %esp
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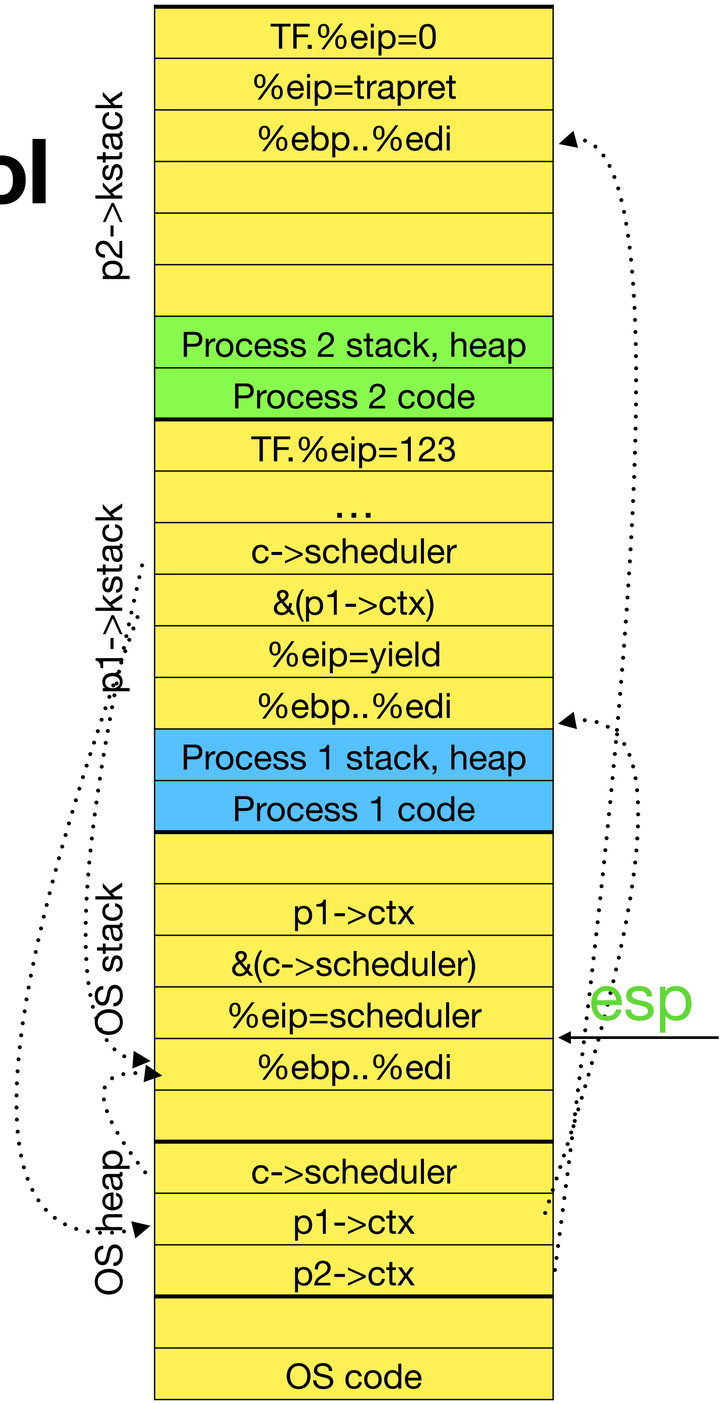

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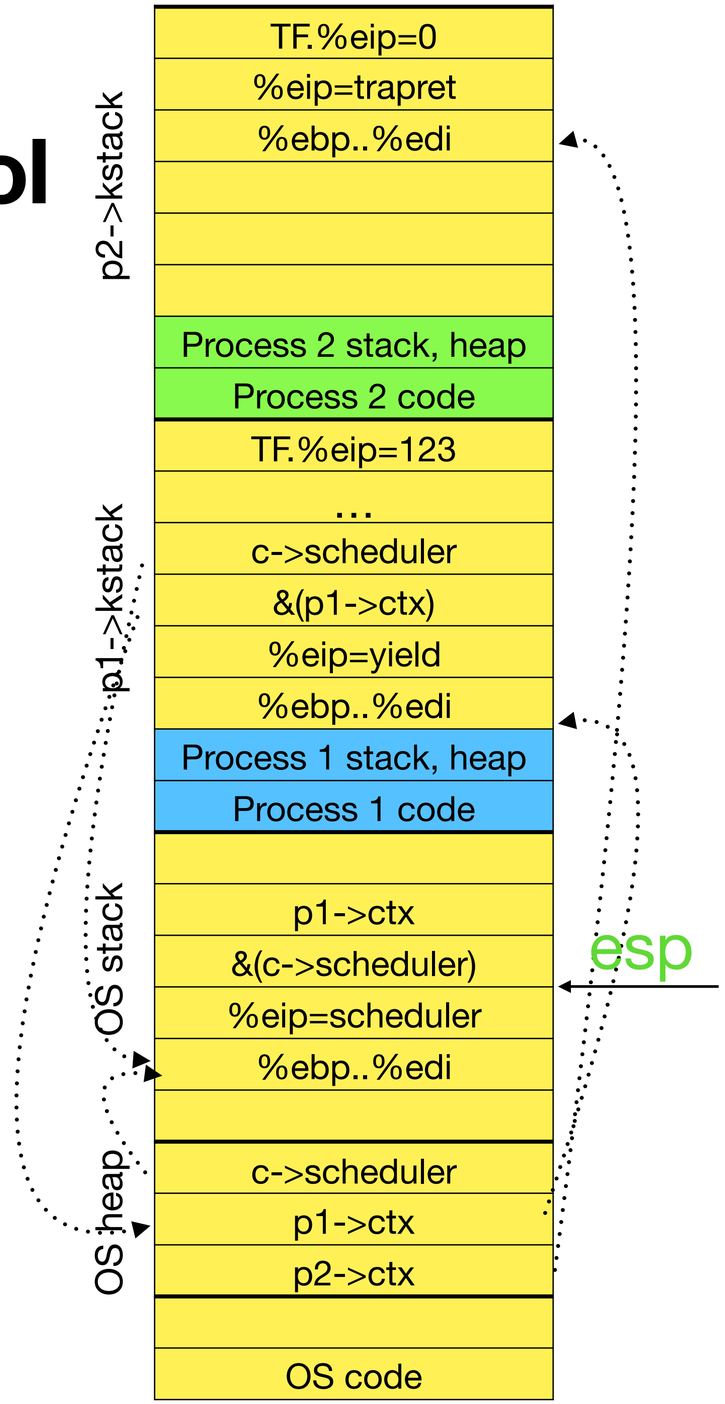

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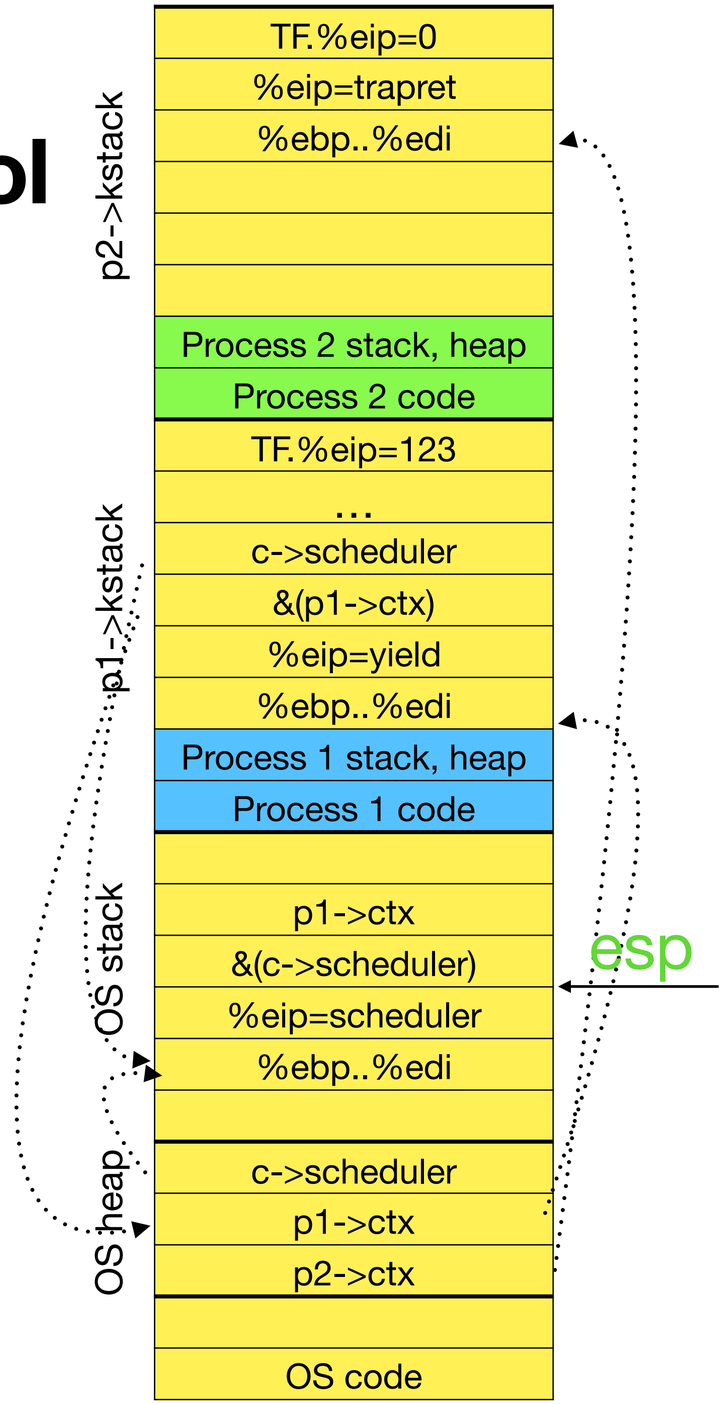
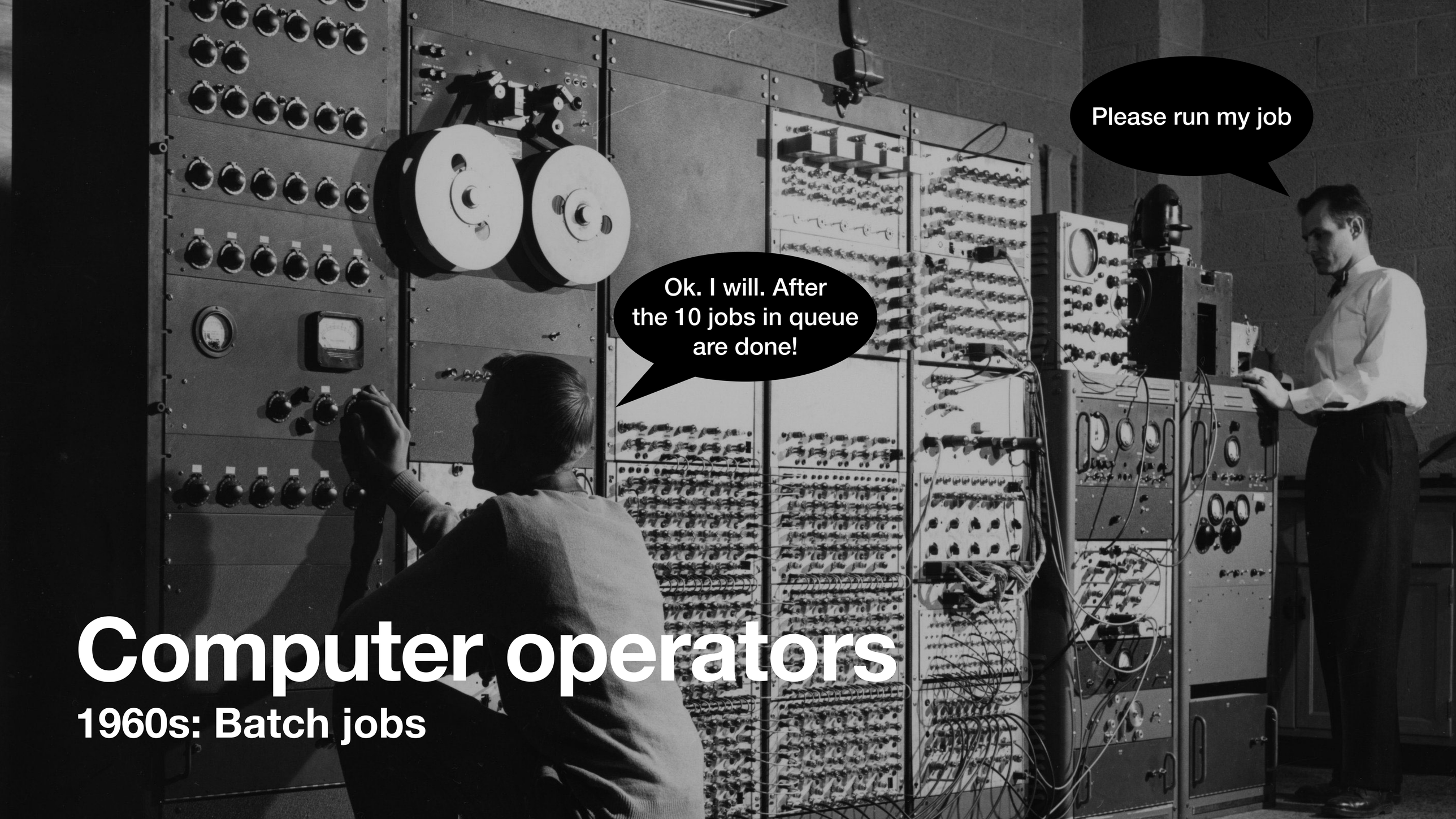


Scheduling policies

OSTEP Ch. 7-9

Scheduling problem

- A number of processes can be runnable.
  - Which process to run next?
  - How long to run each process for?
- What should scheduler try to optimise?
  - What do we know about the behaviour of each process?



Computer operators

1960s: Batch jobs

Batch job characteristics

- Once started, each job runs to completion
- Run-time of each job is known
- Main metric: turnaround time = (completion time - arrival time)

FIFO

- Avg turnaround time = (10+20+30)/3 = 20

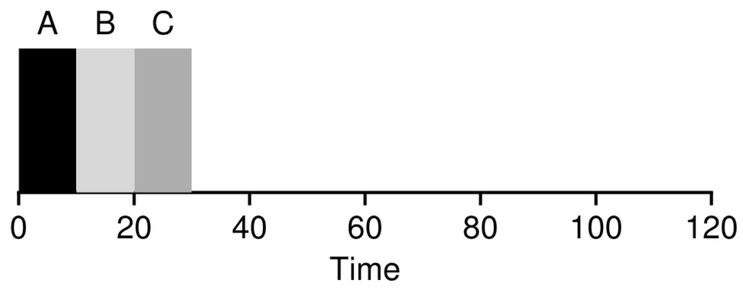
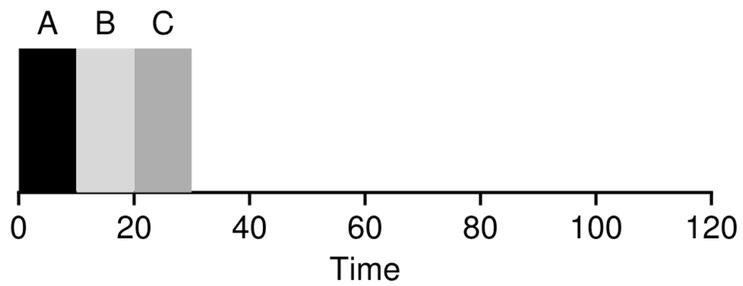


Figure 7.1: **FIFO Simple Example**

FIFO

- Avg turnaround time = (10+20+30)/3 = 20
- Avg turnaround time = (100+110+120)/3 = 110



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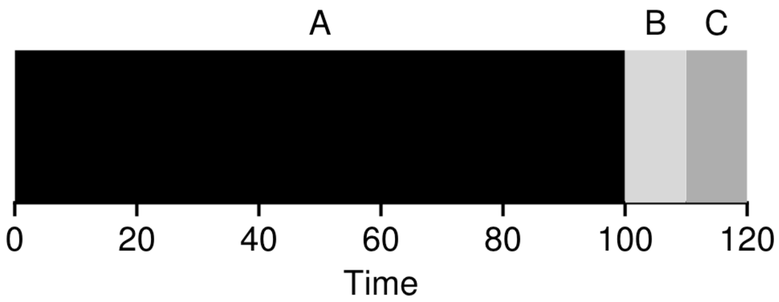
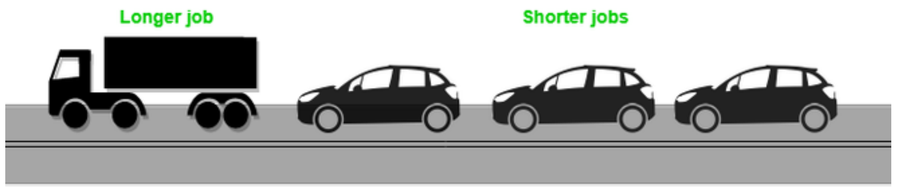
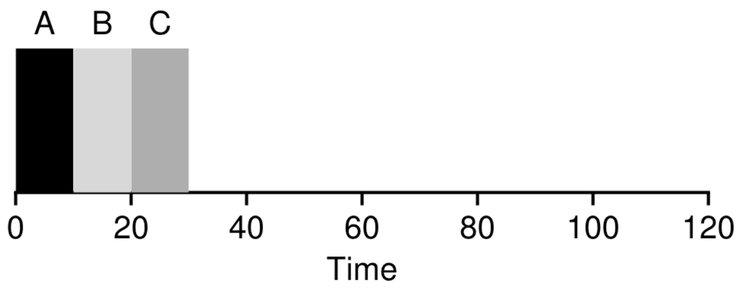


Figure 7.2: **Why FIFO Is Not That Great**

FIFO

- Avg turnaround time = (10+20+30)/3 = 20
- Avg turnaround time = (100+110+120)/3 = 110
- Convoy effect: fast jobs are stuck behind slow jobs





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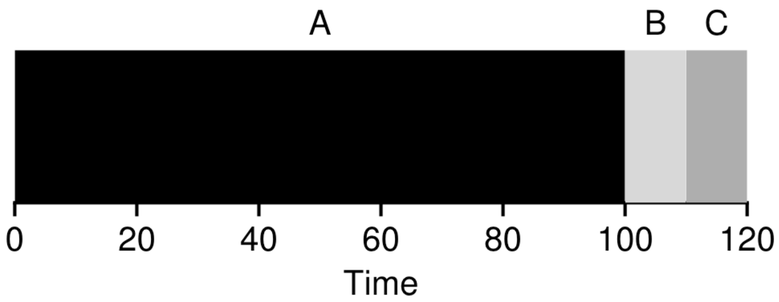


Figure 7.2: **Why FIFO Is Not That Great**

Shortest job first

- Avg turnaround time = (10+20+120)/3 = 50
- Optimal scheduling algorithm

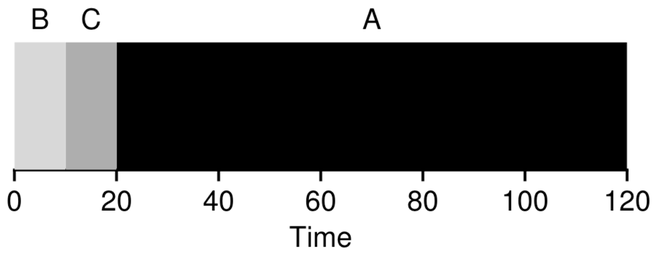
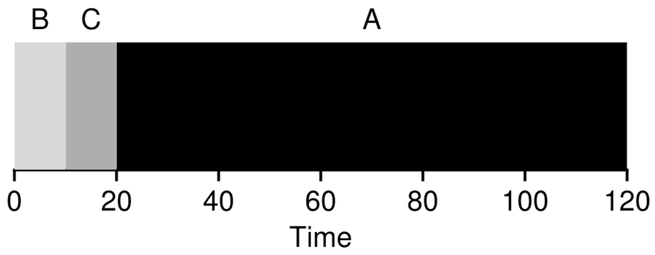


Figure 7.3: **SJF Simple Example**

Shortest job first

- Avg turnaround time = (10+20+120)/3 = 50
- Optimal scheduling algorithm
- Jobs may not arrive at the same time.



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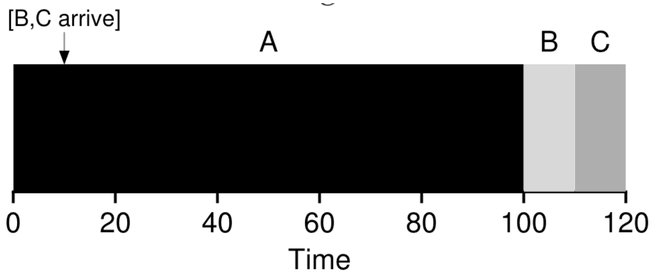
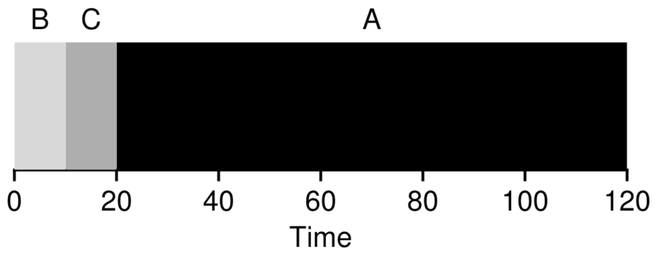


Figure 7.4: **SJF With Late Arrivals From B and C**

Shortest job first

- Avg turnaround time = (10+20+120)/3 = 50
- Optimal scheduling algorithm
- Jobs may not arrive at the same time.
- Avg turnaround time = (100+100+110)/3 = 103.33



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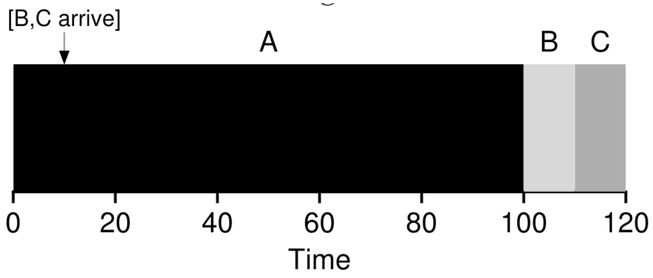
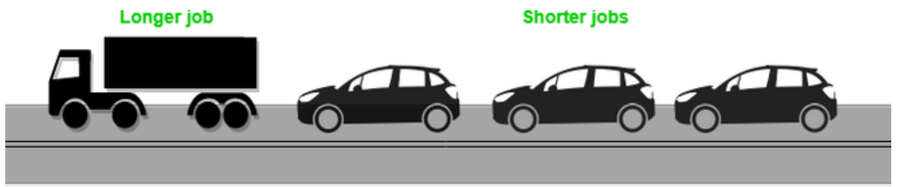
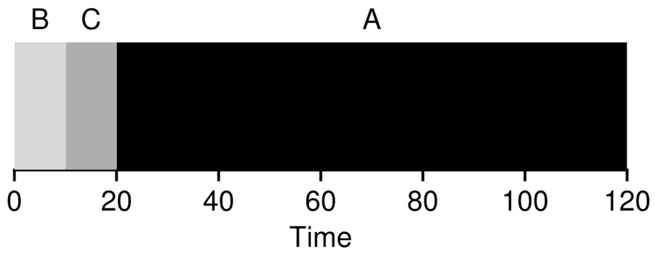


Figure 7.4: **SJF With Late Arrivals From B and C**

Shortest job first

- Avg turnaround time = (10+20+120)/3 = 50
- Optimal scheduling algorithm
- Jobs may not arrive at the same time.
- Avg turnaround time = (100+100+110)/3 = 103.33
- Again leads to convoy effect: fast jobs are stuck behind slow jobs





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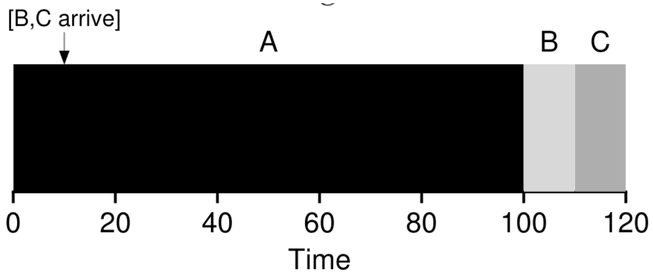


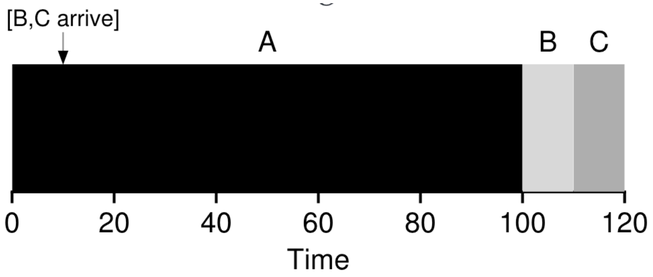
Figure 7.4: **SJF With Late Arrivals From B and C**

Batch job characteristics

- ~~Once started, each job runs to completion~~
- Preemptive schedulers switch to other processes before a job finishes
- Run-time of each job is known
- Main metric: turnaround time = (completion time - arrival time)

Shortest time to completion first

- Avg turnaround time = (10+20+120)/3 = 50
- Optimal scheduling algorithm



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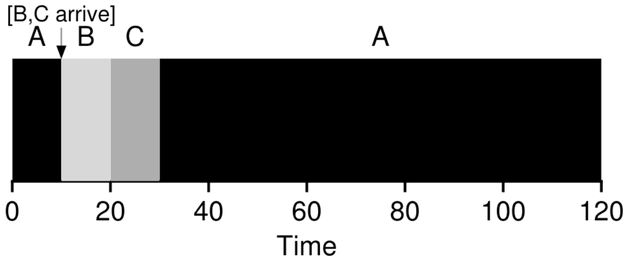


Figure 7.5: **STCF Simple Example**

Personal computers

1980s: Interactive jobs!

Interactive job characteristics

- Preemptive schedulers switch to other processes before a job finishes
- ~~Run-time of each job is known~~
- ~~Main metric: turnaround time = (completion time - arrival time)~~
- Main metric: response time = (first run - arrival time)

Interactive job characteristics

- Preemptive schedulers switch to other processes before a job finishes
- ~~Run-time of each job is known~~
- ~~Main metric: turnaround time = (completion time - arrival time)~~
- Main metric: response time = (first run - arrival time)
- Avg response time in SJF = (0+5+10)/3 = 15

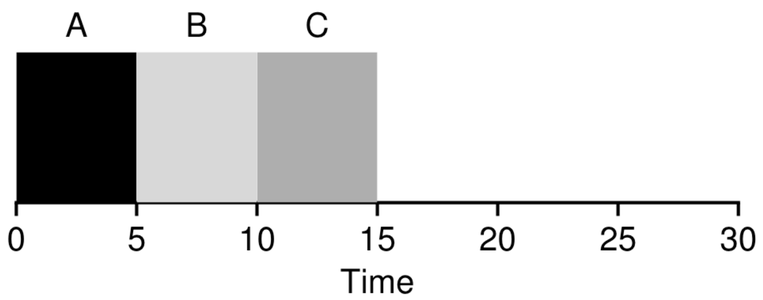


Figure 7.6: **SJF Again (Bad for Response Time)**

Round robin

- Run for a time slice T (scheduling quantum)

Round robin

- Run for a time slice T (scheduling quantum)
- Avg response time = (0+1+2)/3 = 1

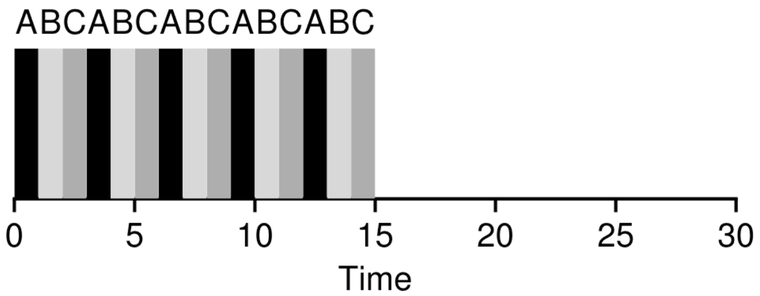
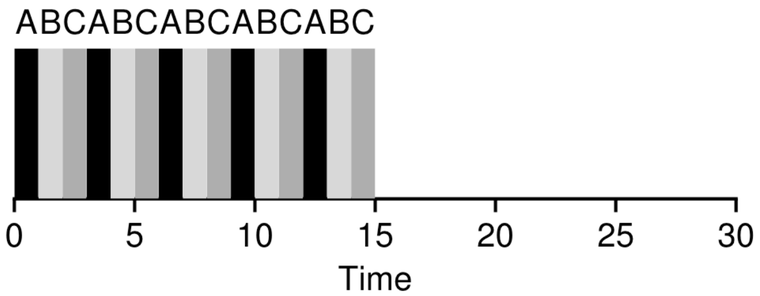


Figure 7.7: **Round Robin (Good For Response Time)**

Round robin

- Run for a time slice T (scheduling quantum)
- Avg response time = (0+1+2)/3 = 1
- How long should the time slice T be?



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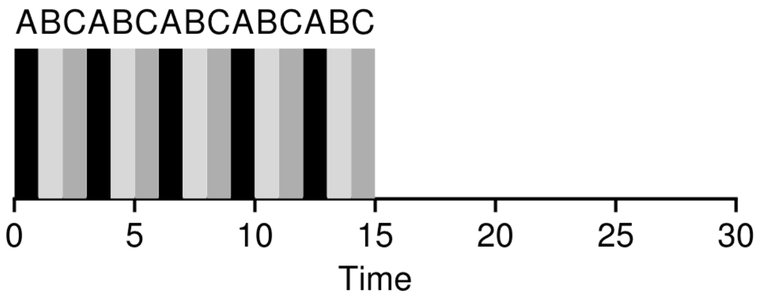
Round robin

- Run for a time slice T (scheduling quantum)
- Avg response time = (0+1+2)/3 = 1
- How long should the time slice T be?
  - T >> context switch time (~1 us)



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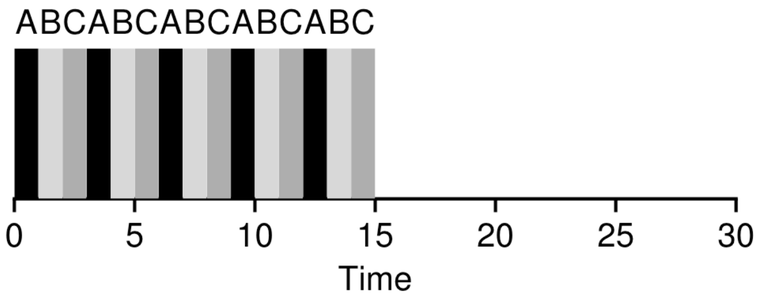
- Run for a time slice T (scheduling quantum)
- Avg response time = (0+1+2)/3 = 1
- How long should the time slice T be?
  - T >> context switch time (~1 us)
  - T ~ human response time (few ms)



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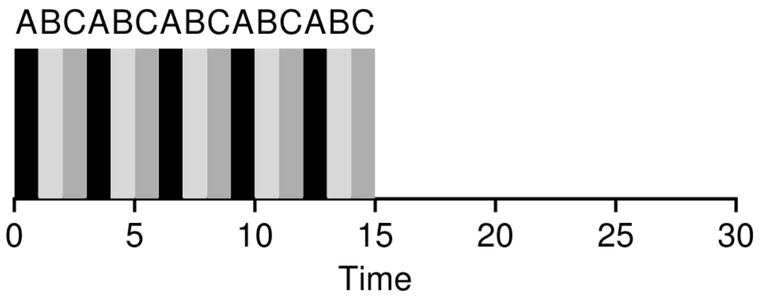

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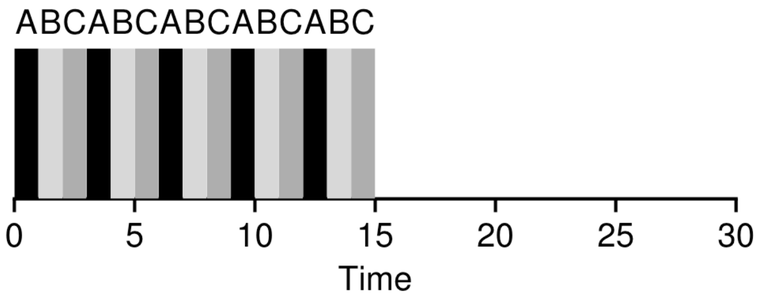
- Worst policy for turnaround time: elongates completion times of all jobs



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  - T ~ human response time (few ms)
  - T ~ Used to be ~10ms in 1970s. Still ~10ms. CPU speeds: 60MHz -> 3GHz.
- Worst policy for turnaround time: elongates completion times of all jobs
- Gives “fair share” to all jobs within small amount of time

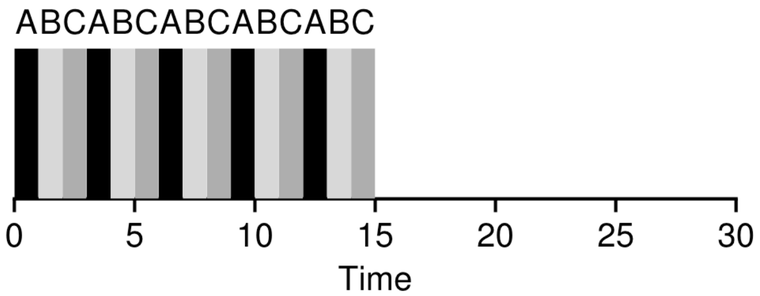

Figure 7.7: **Round Robin (Good For Response Time)**

Proportional share

- All jobs are not equally important

Proportional share

- All jobs are not equally important
  - Dropbox syncing should get lesser CPU time than music playback and gameplay

Proportional share

- All jobs are not equally important
  - Dropbox syncing should get lesser CPU time than music playback and gameplay
  - Give “proportional share” to jobs based on their importance

Stride scheduling

```
current = remove_min(queue);       // pick client with minimum pass
schedule(current);                 // use resource for quantum
current->pass += current->stride;  // compute next pass using stride
insert(queue, current);            // put back into the queue
```

- Higher priority processes have low strides

Stride scheduling

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- Higher priority processes have low strides
- Example: A:B:C = 2:1:5

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- Higher priority processes have low strides
- Example: A:B:C = 2:1:5

Pass(A) (stride=100)	Pass(B) (stride=200)	Pass(C) (stride=40)	Who Runs?
0	0	0	A
100	0	0	B
100	200	0	C
100	200	40	C
100	200	80	C
100	200	120	A
200	200	120	C
200	200	160	C
200	200	200	...

Figure 9.3: **Stride Scheduling: A Trace**

Stride scheduling

```
current = remove_min(queue);       // pick client with minimum pass
schedule(current);                 // use resource for quantum
current->pass += current->stride;  // compute next pass using stride
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```

- Higher priority processes have low strides
- Example: A:B:C = 2:1:5
- Deterministic scheduler

Pass(A) (stride=100)	Pass(B) (stride=200)	Pass(C) (stride=40)	Who Runs?
0	0	0	A
100	0	0	B
100	200	0	C
100	200	40	C
100	200	80	C
100	200	120	A
200	200	120	C
200	200	160	C
200	200	200	...

Figure 9.3: **Stride Scheduling: A Trace**

Lottery scheduling

- Probabilistic scheduler
  - A:B ~ 3:1
  - Generate a random number 0-99 in each time quantum
    - 0-74: run A, 75-99: run B

Lottery scheduling

- Probabilistic scheduler
  - A:B ~ 3:1
  - Generate a random number 0-99 in each time quantum
    - 0-74: run A, 75-99: run B

```
63 85 70 39 76 17 29 41 36 39 10 99 68 83 63 62 43  0 49 49

 A     A  A     A  A  A  A  A  A     A     A  A  A  A  A  A
    B         B                    B     B
```

Lottery scheduling implementation

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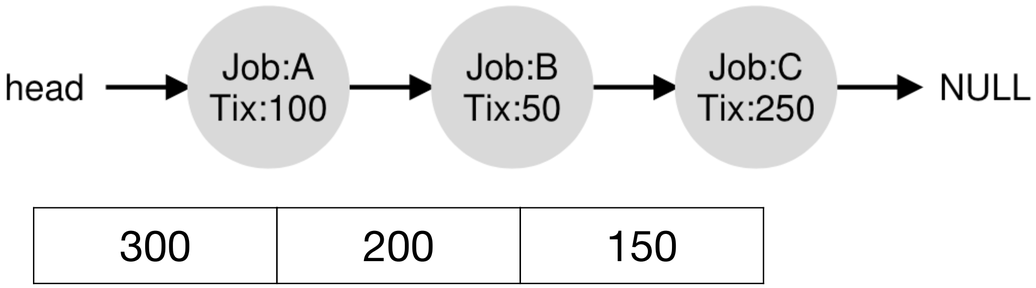

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300	200	150
125	25	

Setting priority

- When processes are trusted, they can raise or lower their priority
  - Example: music player lowers its priority when user pauses the song

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```
time taskset -c 1 ./nicedemo
time nice -n 19 taskset -c 1 ./nicedemo
```

Process states

- Processes can be blocked upon doing IO

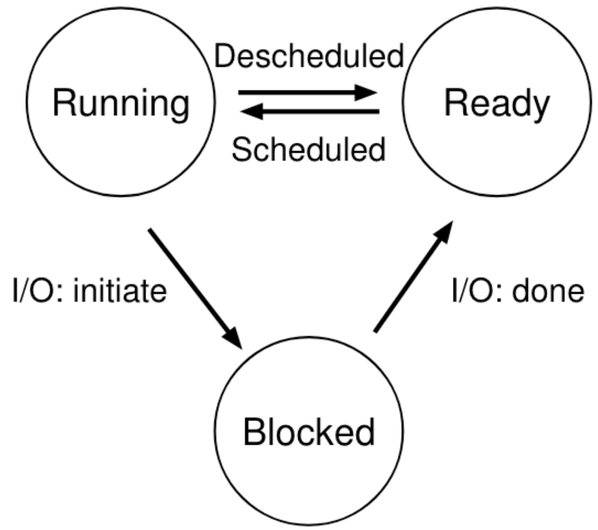

Figure 4.2: **Process: State Transitions**

Process states

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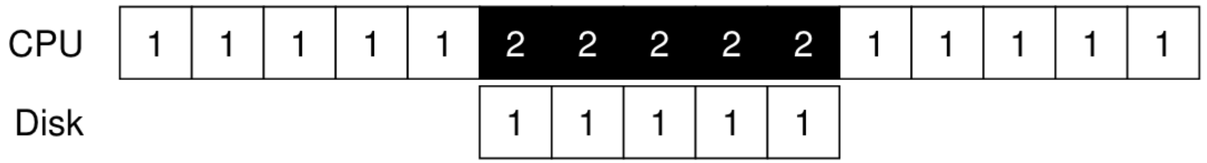


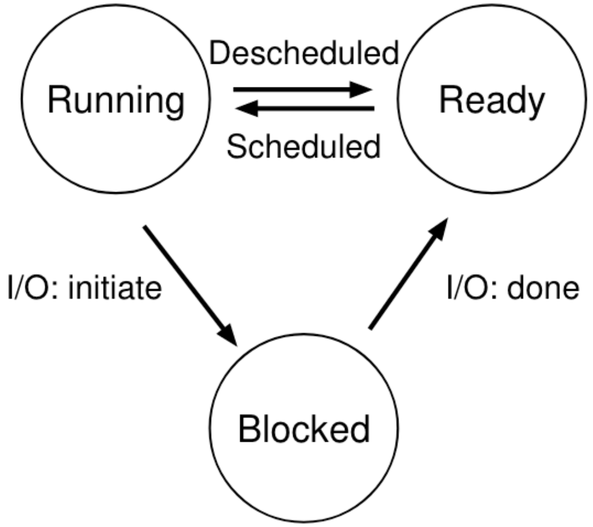
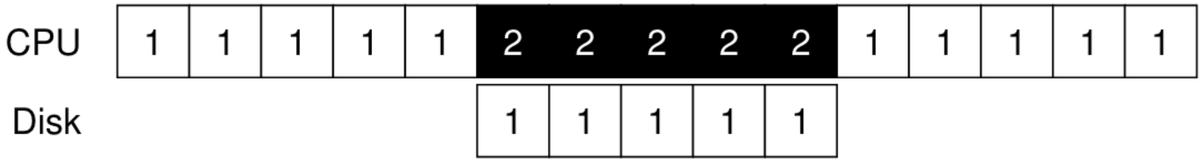


Figure 4.2: **Process: State Transitions**

Blocking in action

Case study: xv6 disk driver




```
void sleep(void *chan) {
  struct proc *p = myproc();
  // Go to sleep.
  p->chan = chan;
  p->state = SLEEPING;
  sched();
  // Tidy up.
  p->chan = 0;
}
void wakeup(void *chan) {
  struct proc *p;
  for(p = ptable.proc; p < &ptable.proc[NPROC]; p++)
    if(p->state == SLEEPING && p->chan == chan)
      p->state = RUNNABLE;
}
```

```
void ideintr(void) {
  struct buf *b = idequeue;
  if(!(b->flags & B_DIRTY) && idewait(1) >= 0)
    insl(0x1f0, b->data, BSIZE/4);
  b->flags |= B_VALID;
  b->flags &= ~B_DIRTY;
  wakeup(b);
}

void iderw(struct buf *b){
  if(idequeue == b)
    idestart(b);
  while((b->flags & (B_VALID|B_DIRTY)) != B_VALID){
    noop();
    sleep(b);
  }
}
```

IO aware scheduling

- Mixture of CPU intensive and IO intensive processes

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  - Turnaround time is important for CPU intensive processes, e.g, training an ML model

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- Challenge: OS does not know which process is CPU intensive / IO bound
- Round robin (fair share) and proportional share algorithms assume all processes are CPU intensive
- Example: xv6 scheduler gives poor response time for interactive processes

CPU	1	1	1	2	2	2	3	3	3	1	1	1	2	2	2	3	3	3	1
Disk																			

CPU	1	1	2	3	3	3	2	2	2	3	3	3	1	1	2	3	3	3	2
Disk			1	1	1	1	1								1	1	1	1	1

Multi-level feedback queue (MLFQ)

- Strict priority using multiple queues
  - (A > C) => A runs
  - (A = B) => Round robin

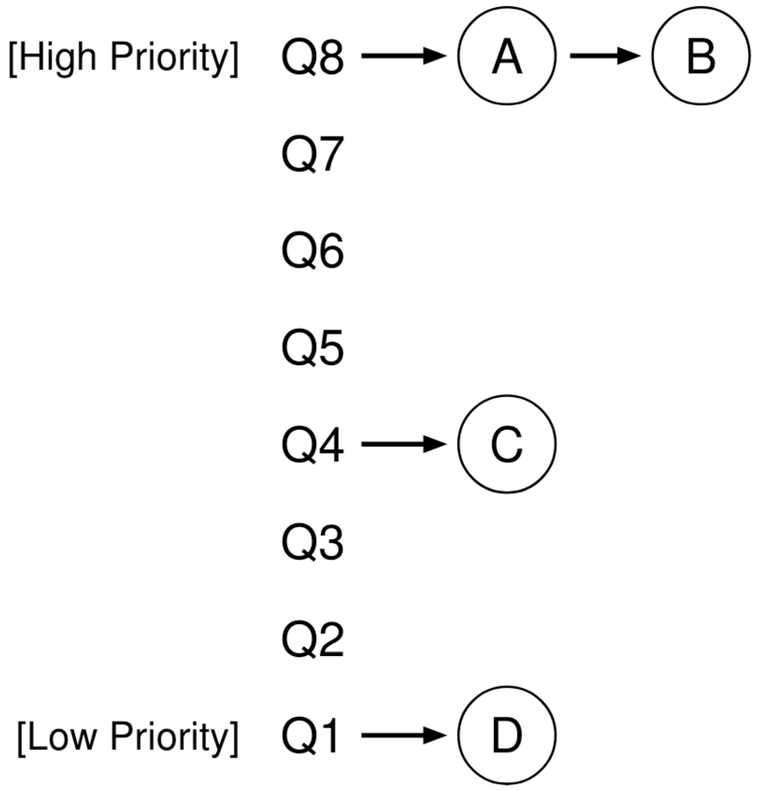

Figure 8.1: **MLFQ Example**

Multi-level feedback queue (MLFQ)

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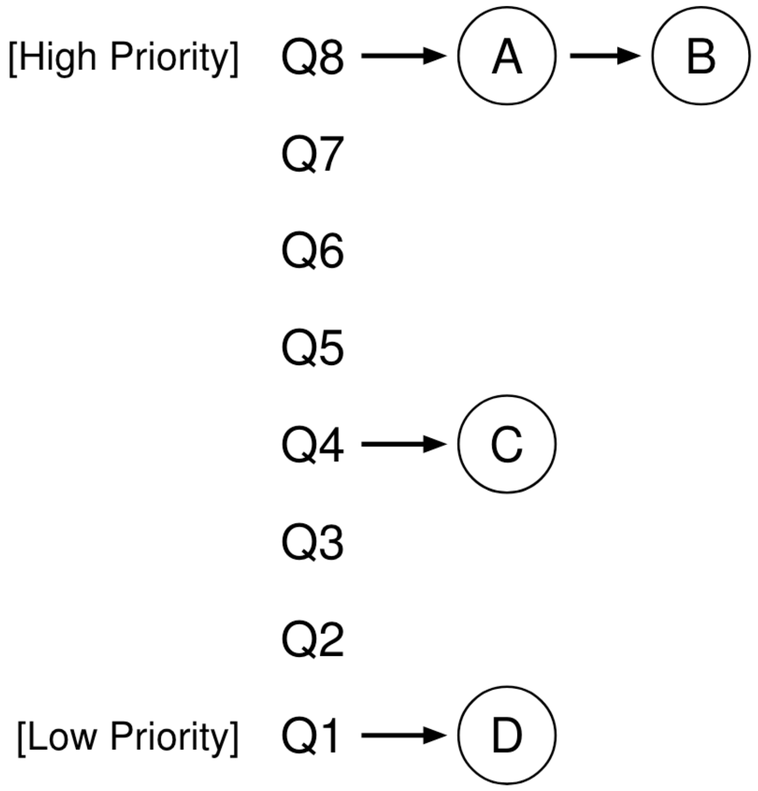
- Goal: IO bound (interactive) processes shall take higher priority over CPU intensive processes



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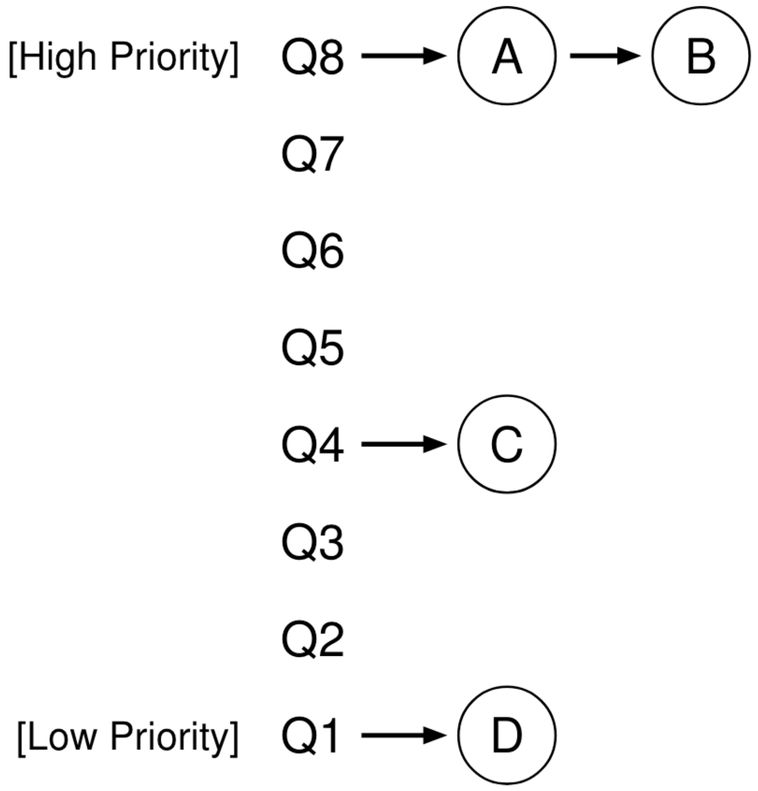

Figure 8.1: **MLFQ Example**

MLFQ level management

- Observation: A CPU intensive process completely uses up its time slice. e.g, process 2

CPU	1	1	2	3	3	3	2	2	2	3	3	3	1	1	2	3	3	3	2
Disk			1	1	1	1	1								1	1	1	1	1

MLFQ level management

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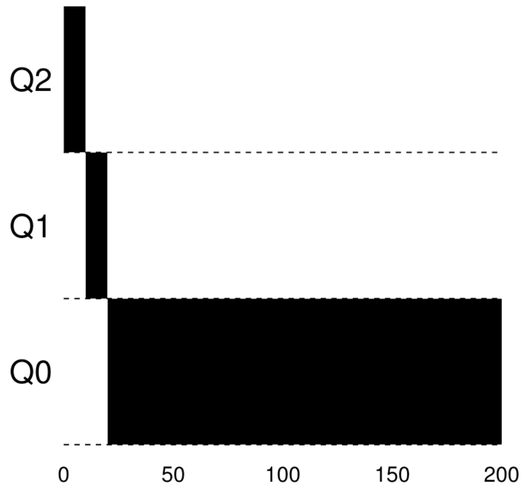


Figure 8.2: **Long-running Job Over Time**

MLFQ approximates STCF

- Short jobs get priority over long-running jobs

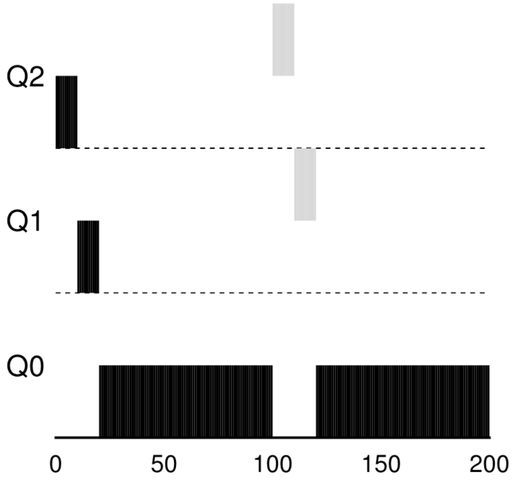


Figure 8.3: **Along Came An Interactive Job**

MLFQ approximates STCF

- Short jobs get priority over long-running jobs
- IO intensive jobs are prioritised over CPU intensive processes => better response time for interactive jobs

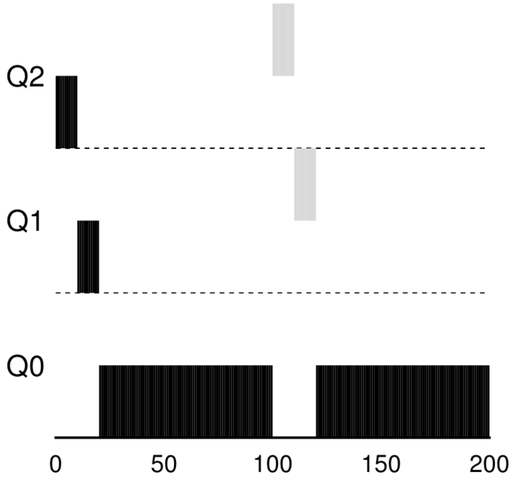


Figure 8.3: **Along Came An Interactive Job**

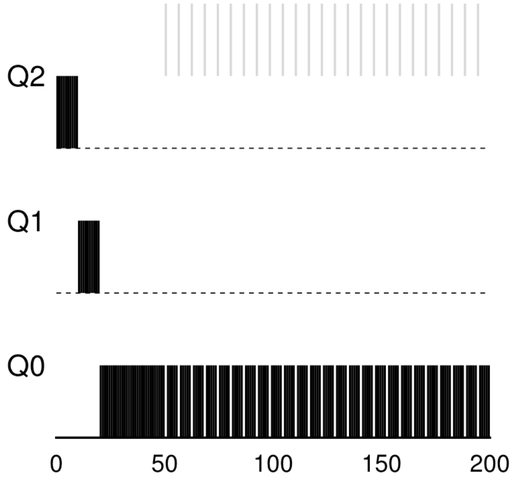
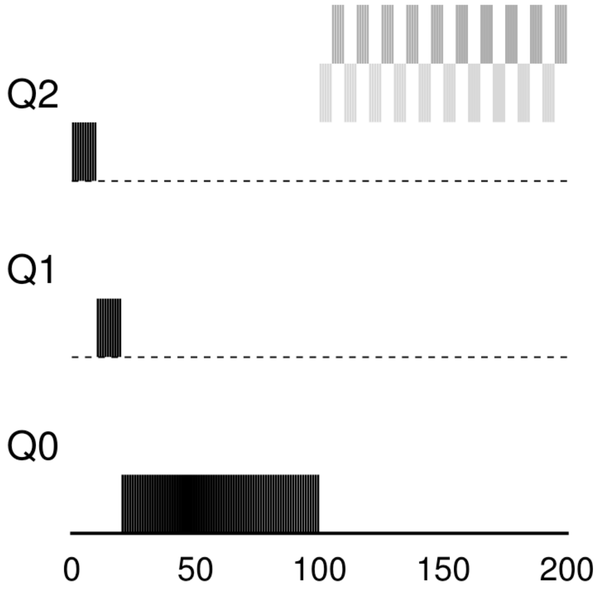


Figure 8.4: **A Mixed I/O-intensive and CPU-intensive Workload**

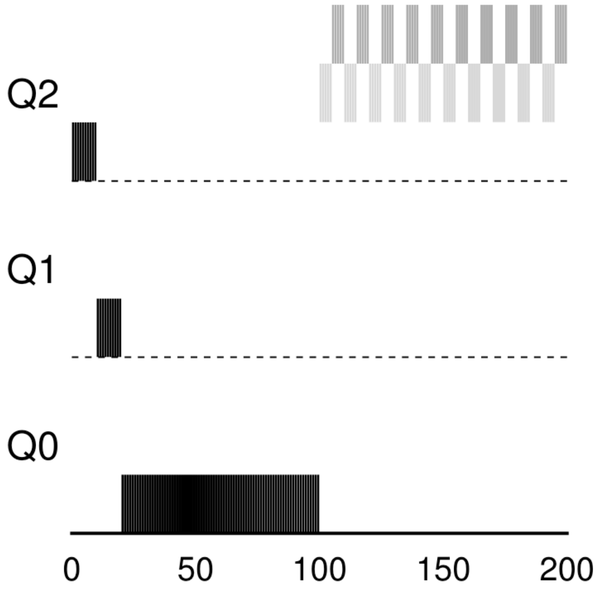
Starvation freedom

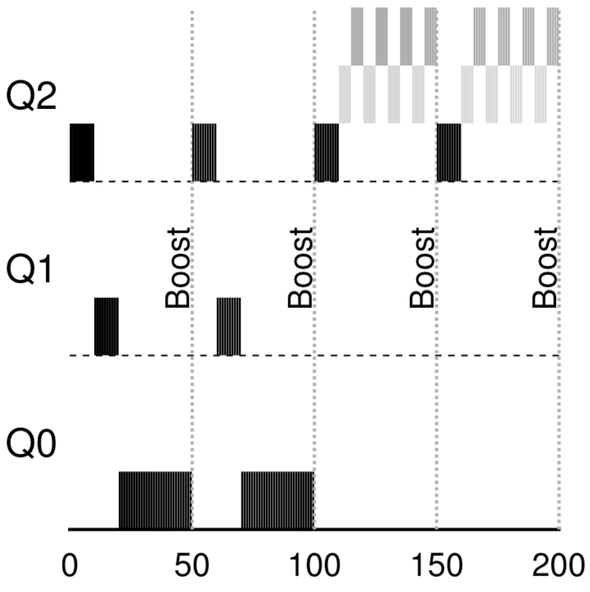
- Many IO bound jobs can starve CPU intensive jobs



Starvation freedom

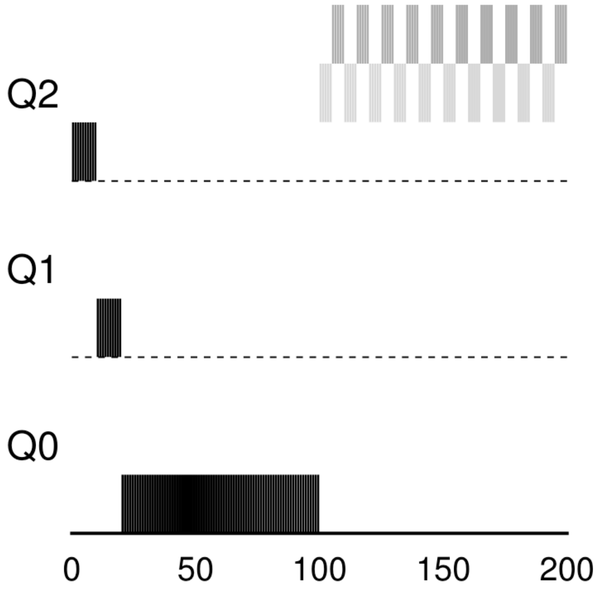
- Many IO bound jobs can starve CPU intensive jobs
- Boost all jobs to highest priority queue after some time quantum

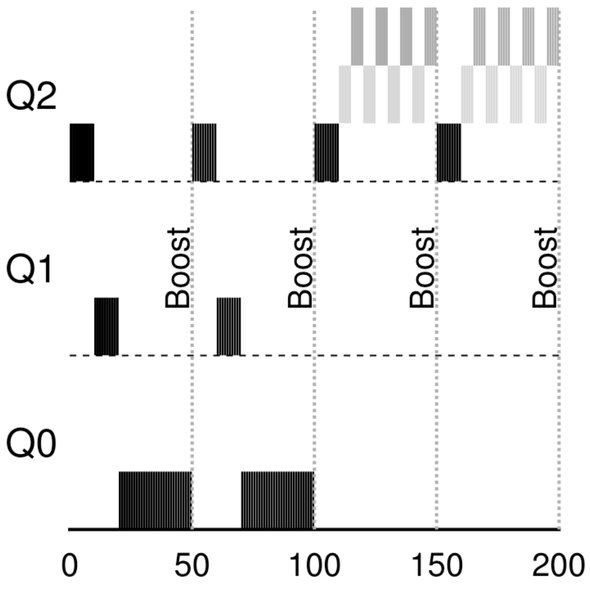




Starvation freedom

- Many IO bound jobs can starve CPU intensive jobs
- Boost all jobs to highest priority queue after some time quantum
- Also helps if CPU intensive job has become IO intensive job





Reduce scheduling overhead for CPU intensive jobs

- If there are no IO bound jobs, CPU intensive jobs run without preemption for a longer time slice

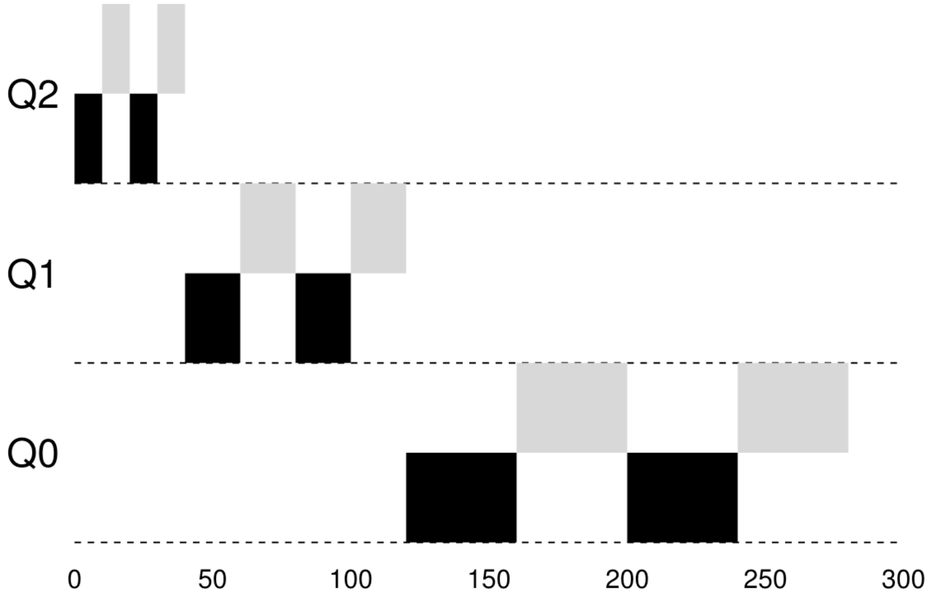
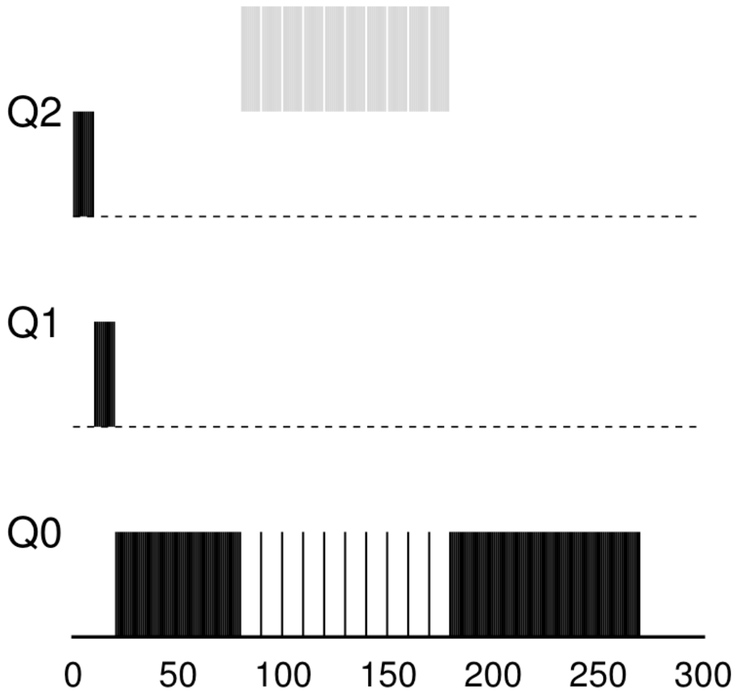


Figure 8.7: **Lower Priority, Longer Quanta**

Scheduler attacks

- Example: yield CPU right before time quanta expires to stay in highest priority
- Big concern in Linux 2.4 ~2006. Freeze up desktops



Linux Completely Fair Scheduler (CFS)

- Priority scheduler:
  - Low nice value => More CPU time

```
static const int prio_to_weight[40] = {
 /* -20 */     88761,     71755,     56483,     46273,     36291,
 /* -15 */     29154,     23254,     18705,     14949,     11916,
 /* -10 */      9548,      7620,      6100,      4904,      3906,
 /*  -5 */      3121,      2501,      1991,      1586,      1277,
 /*   0 */      1024,       820,       655,       526,       423,
 /*   5 */       335,       272,       215,       172,       137,
 /*  10 */       110,        87,        70,        56,        45,
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};
```

Linux Completely Fair Scheduler (CFS)

- Priority scheduler:
  - Low nice value => More CPU time
  - High priority processes get longer time slices

$$\texttt{time_slice}_k = \frac{\texttt{weight}_k}{\sum_{n=0}^{n-1} \texttt{weight}_i} \cdot \texttt{sched_latency}$$

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```

Completely Fair Scheduler (CFS)

- Each process has vruntime. Update vruntime after each time process is run.

$$\texttt{vruntime}_i = \texttt{vruntime}_i + \frac{\texttt{weight}_0}{\texttt{weight}_i} \cdot \texttt{runtime}_i$$

- Maintain runnable processes in a red-black tree (sorted by vruntime). Run the process with lowest vruntime.

- When a new process is run:

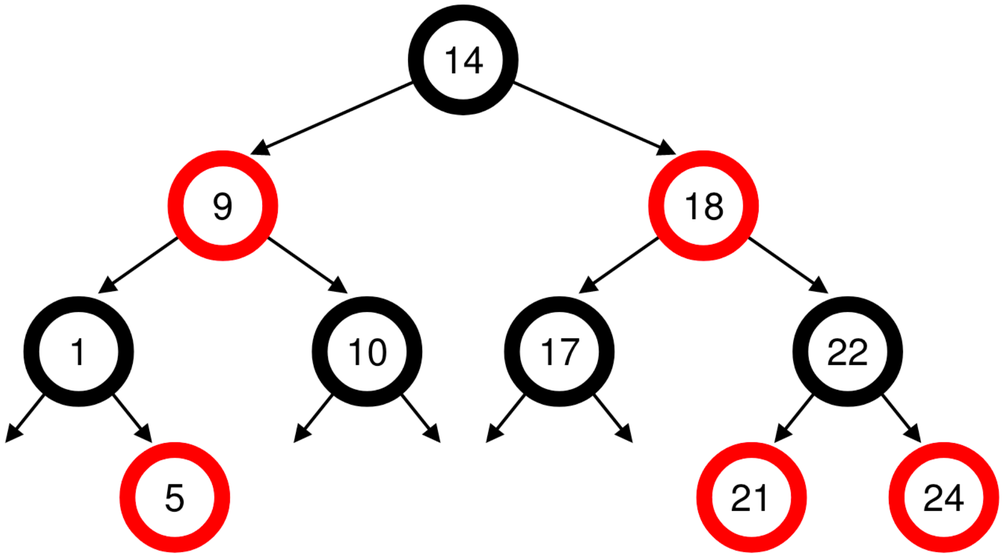

Figure 9.5: **CFS Red-Black Tree**

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- Maintain runnable processes in a red-black tree (sorted by vruntime). Run the process with lowest vruntime.

- When a new process is run:

  - Assign it lowest vruntime (instead of assigning it zero). Otherwise the new process monopolises the CPU

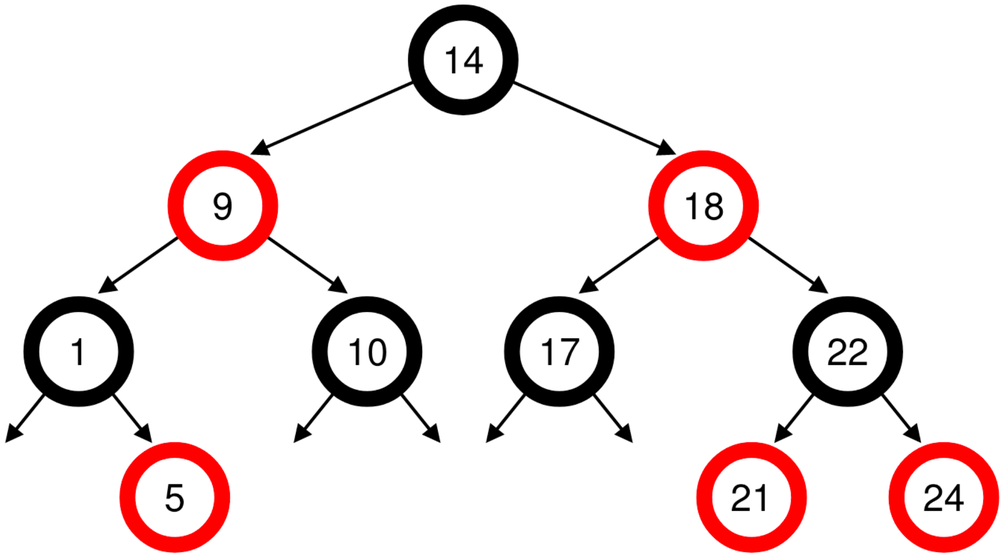


Figure 9.5: **CFS Red-Black Tree**

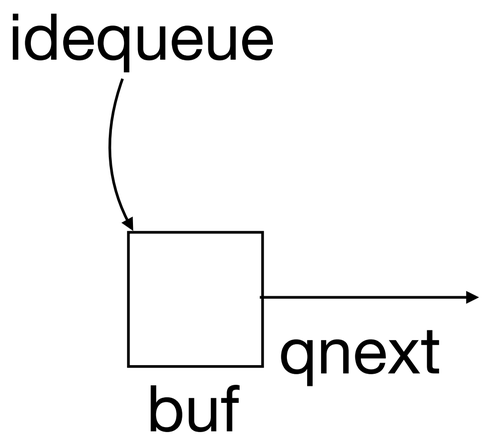
Concurrency (single processor)

Uniprocessor concurrency

- Software interrupts like system calls do not disable interrupts
  - While kernel is servicing system calls, timer interrupt can happen which can switch to other processes
  - If the kernel was updating its data structures, it needs to be careful to not run into races

Race conditions

Example: Processes reading a block in ide.c




```
struct buf {
  ..
  struct buf *qnext; // disk queue
  uchar data[BSIZE];
};

static struct buf *idequeue;

void iderw(struct buf *b) {
  struct buf **pp;
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  for(pp=&idequeue; *pp; pp=&(*pp)->qnext);
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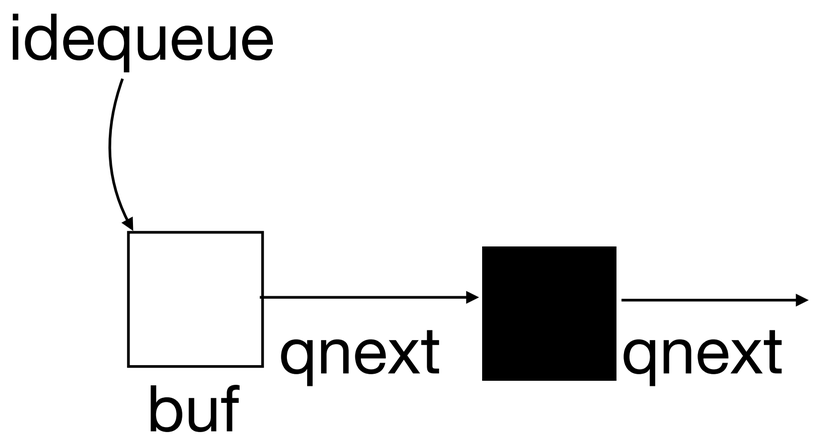


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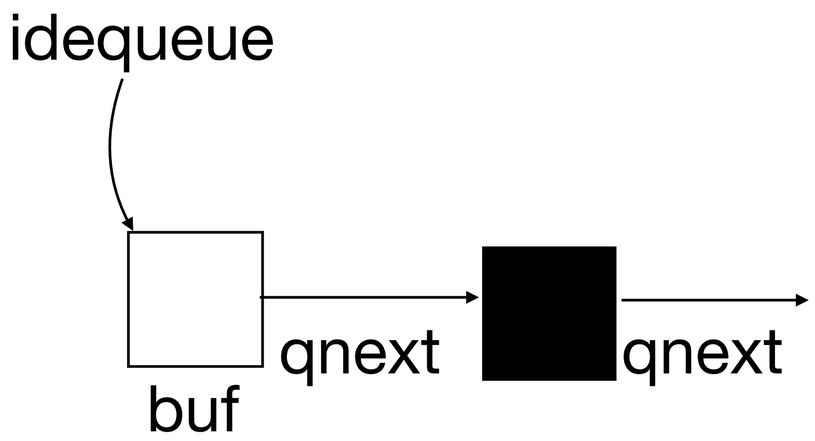


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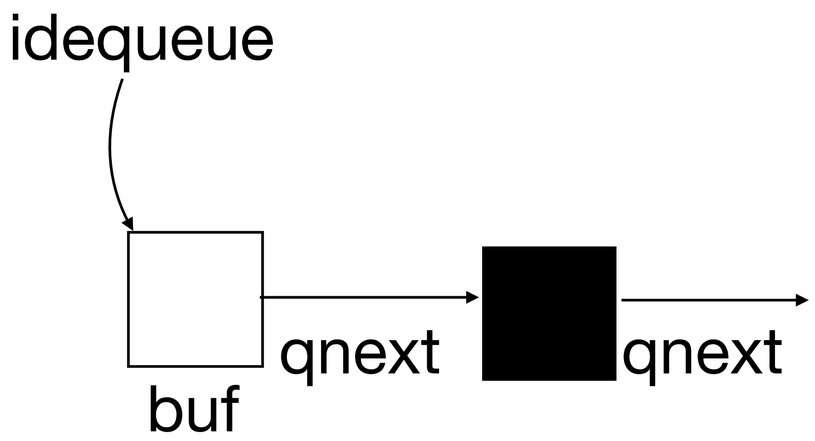


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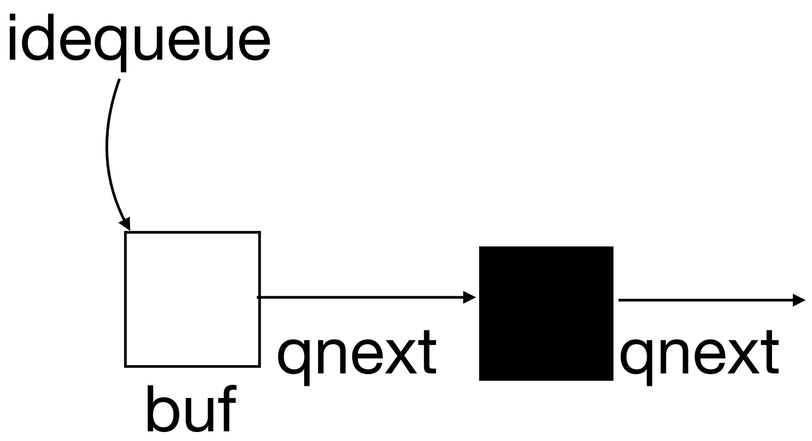


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Context switch

Race conditions

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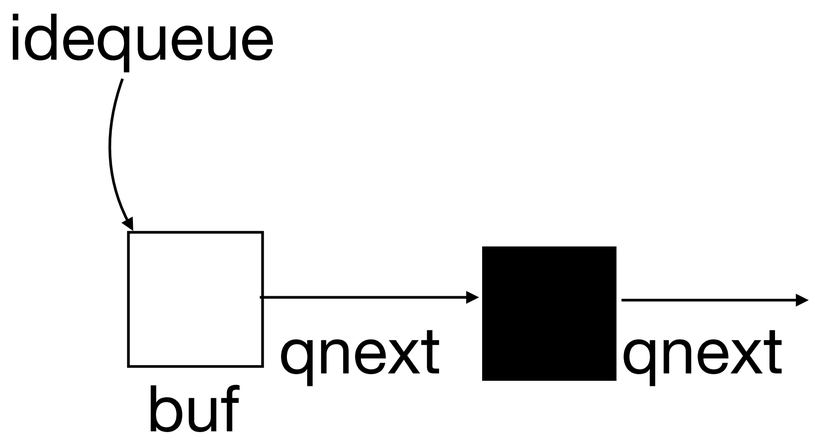


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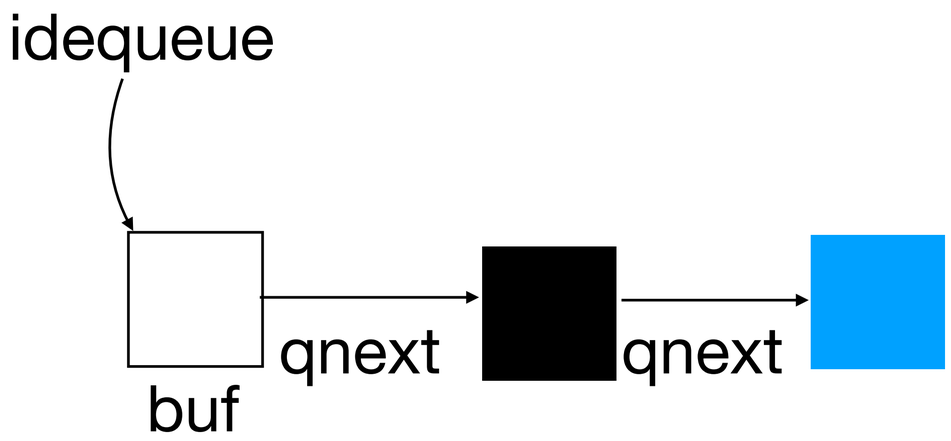


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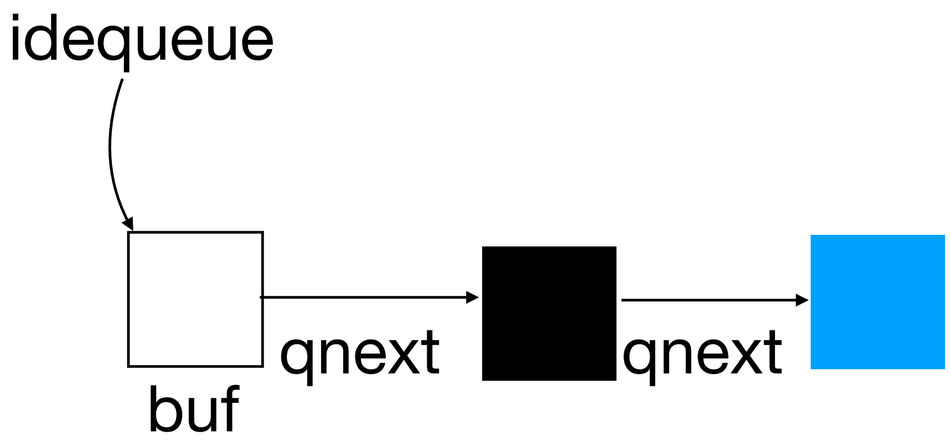
Race conditions

Example: Processes reading a block in ide.c




```
struct buf {
  ..
  struct buf *qnext; // disk queue
  uchar data[BSIZE];
};

static struct buf *idequeue;

void iderw(struct buf *b) {
  struct buf **pp;
  b->qnext = 0;
  for(pp=&idequeue; *pp; pp=&(*pp)->qnext);
  *pp = b;
  ..
}
```

Context switch

Race conditions

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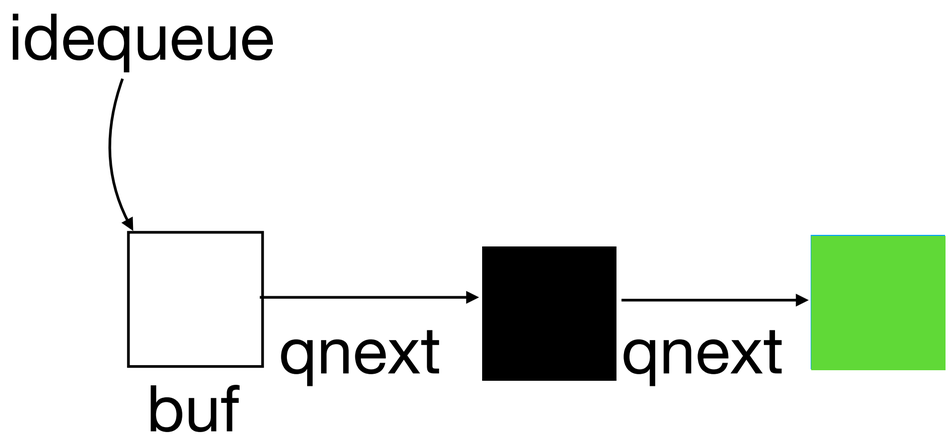


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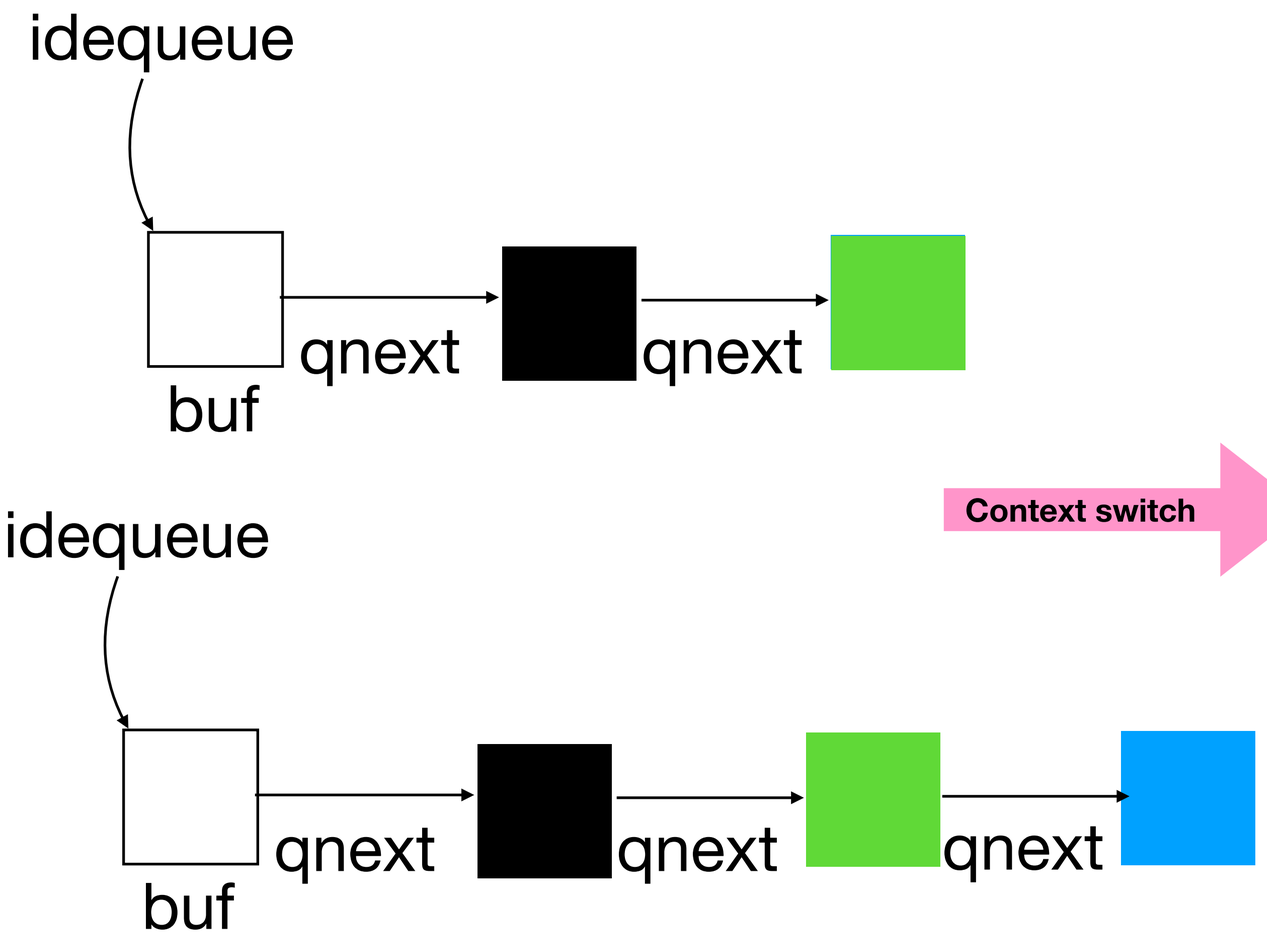


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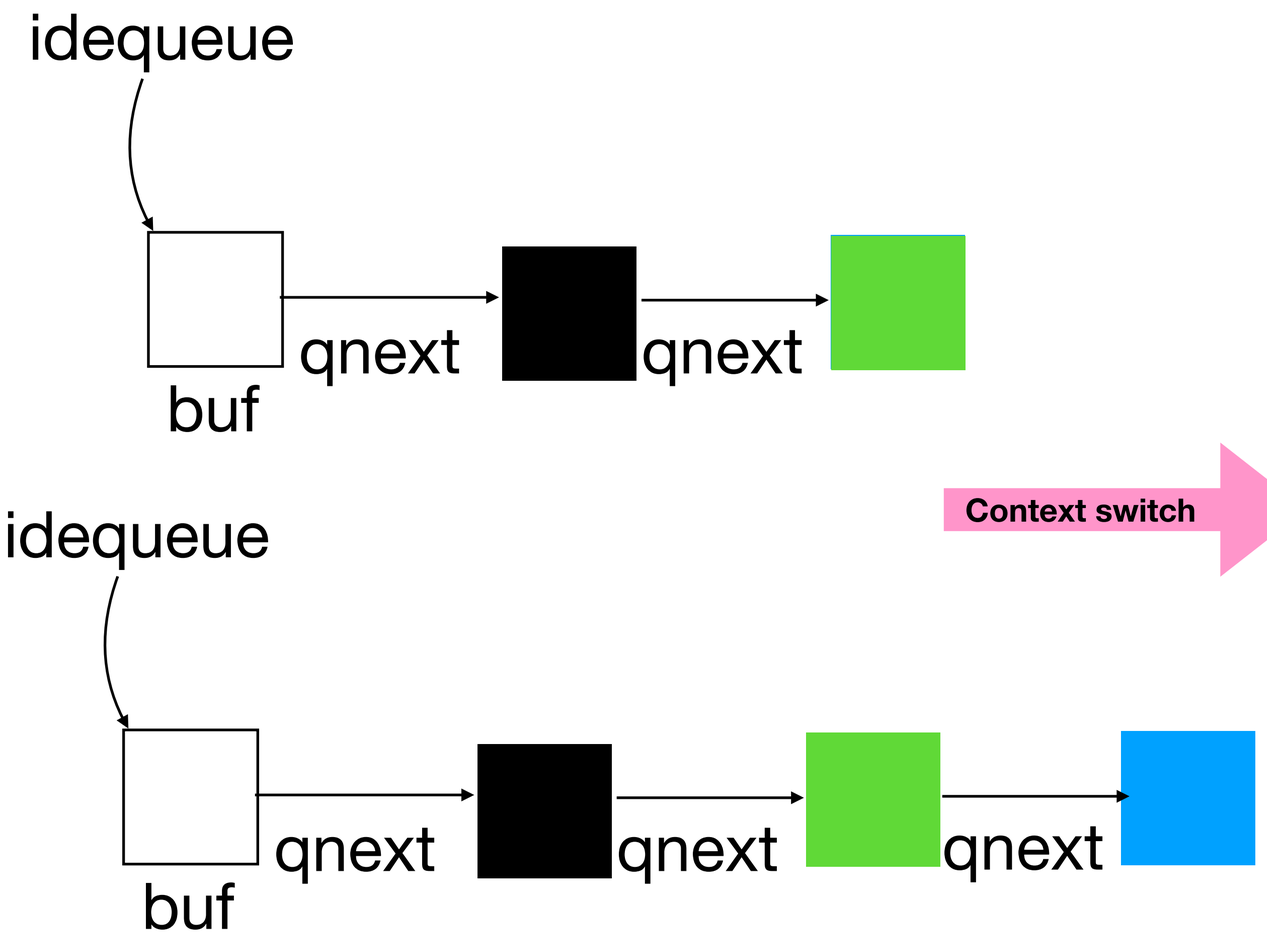


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}
```

Lock implementation

```
void iderw(struct buf *b) {
  struct buf **pp;
  acquire();
  for(pp=&idequeue; *pp; pp=&(*pp)->qnext);
  *pp = b;
  ..
  release();
}
```

Lock implementation

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```

```
void acquire() {
  pushcli();
}
void pushcli(void) {
  int eflags = readeflags();
  cli();
  if(cpu->ncli == 0)
    cpu->intena = eflags & FL_IF;
  cpu->ncli += 1;
}
```

Lock implementation

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```

```
void release() {
  popcli();
}
void popcli(void) {
  cpu->ncli--;
  if(cpu->ncli == 0 && cpu->intena)
    sti();
}
```

Lock implementation

```
void iderw(struct buf *b) {
  struct buf **pp;
  acquire();
  for(pp=&idequeue; *pp; pp=&(*pp)->qnext);
  *pp = b;
  ..
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}
```

- Timer interrupt and hence context switch cannot happen between acquire and release

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  popcli();
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Summary

- Memory management: How to manage and isolate memory? What are memory APIs? How are they implemented?
- Processes in action: Process control block, user stack<>kernel stack, sys call handling, system calls, protection
- Scheduling: response time, turnaround time, fairness
- Uniprocessor concurrency