

# Lecture 24: Virtual Memory III

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601.229 Computer Systems Fundamentals



# More refinements

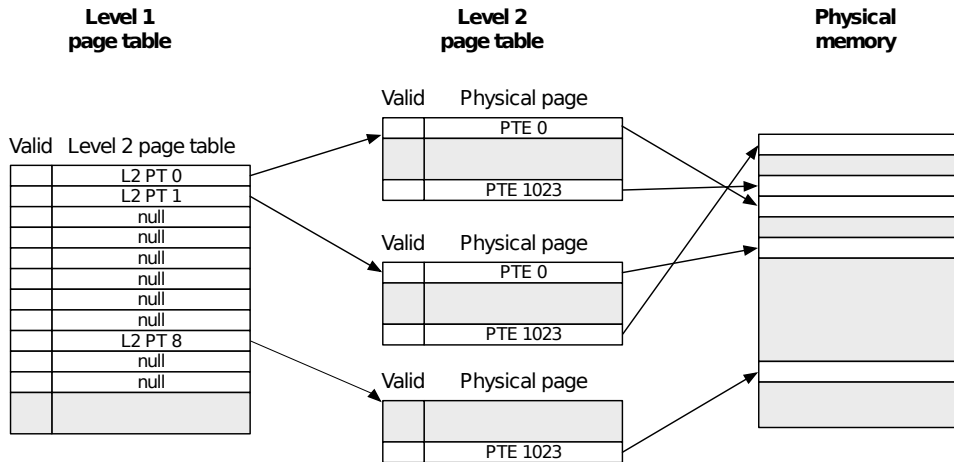
# Refinements

- ▶ On-CPU cache  
→ integrate cache and virtual memory
- ▶ Slow look-up time  
→ use translation lookahead buffer (TLB)
- ▶ **Huge address space**  
→ **multi-level page table**
- ▶ Putting it all together

# Page Table Size

- ▶ Example
  - ▶ 32 bit address space: 4GB
  - ▶ Page size: 4KB
  - ▶ Size of page table entry: 4 bytes
  - Number of pages: 1M
  - Size of page table: 4MB
- ▶ Recall: one page table per process
- ▶ Very wasteful: most of the address space is not used

# 2-Level Page Table



# Multi-Level Page Table

- ▶ Our example: 1M entries
- ▶ 2-level page table
  - each level 1K entry ( $1K^2=1M$ )
- ▶ 4-level page table
  - each level 32 entry ( $32^4=1M$ )

# Zoom poll!

On a 64-bit architecture, assume that pages are 4 KB (4096 bytes) in size. Assume that all page tables (Level 1, Level 2, etc.) are 4 KB. Note that  $4096 = 2^{12}$ .

How many levels (counting the physical pages as a level) would be needed to cover the entire  $2^{64}$  byte address space?

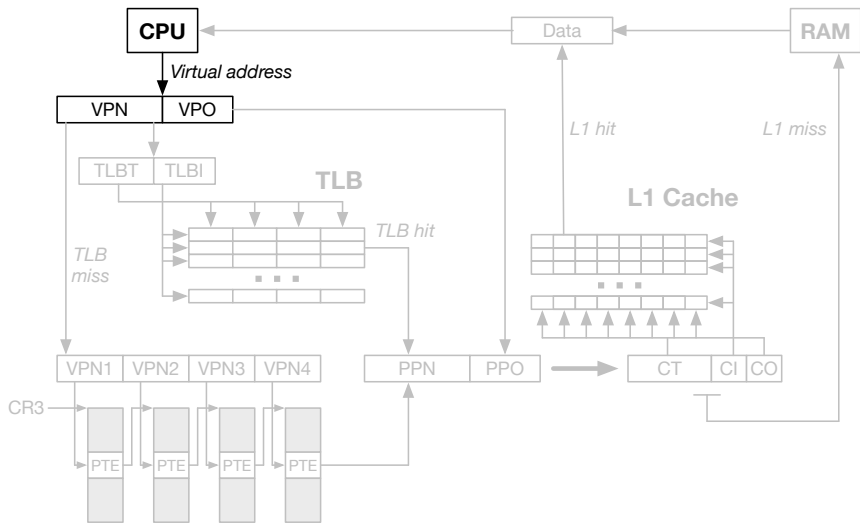
- A. 3
- B. 4
- C. 5
- D. 6
- E. More than 6

# Refinements

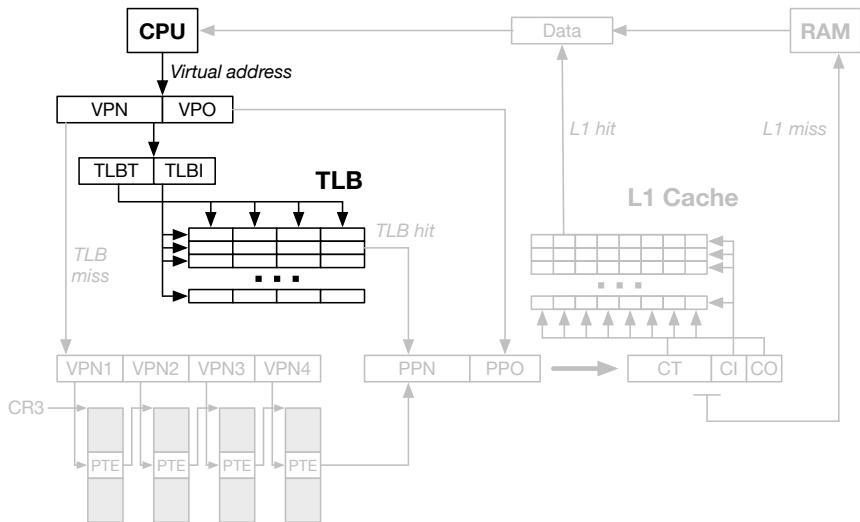
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→ integrate cache and virtual memory
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→ use translation lookahead buffer (TLB)
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→ multi-level page table
- ▶ **Putting it all together**



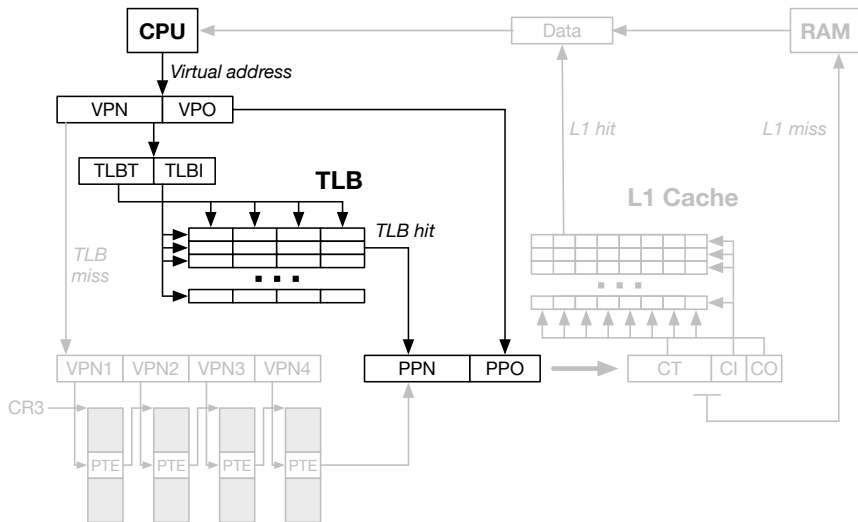
# Virtual Address



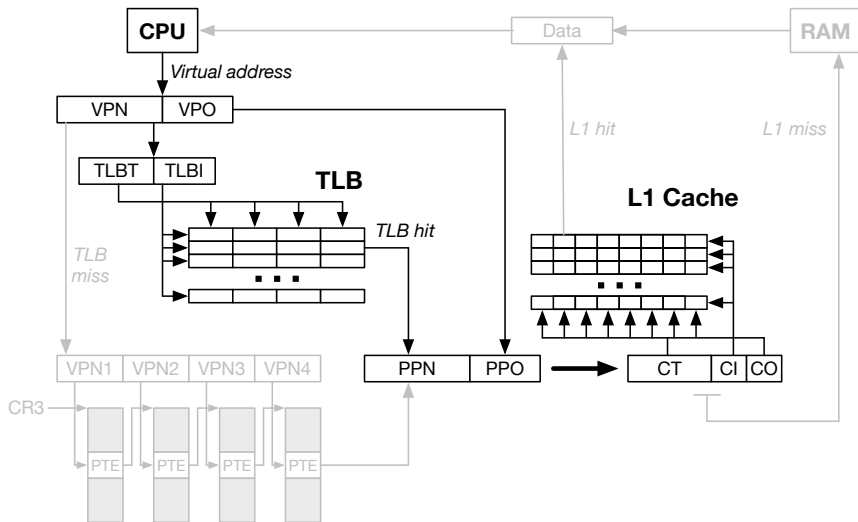
# Translation Lookup Buffer



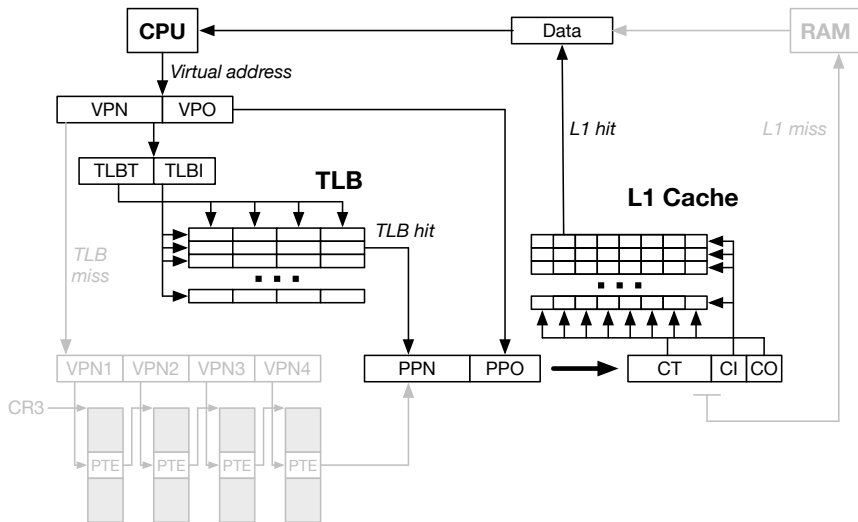
# Compose Address



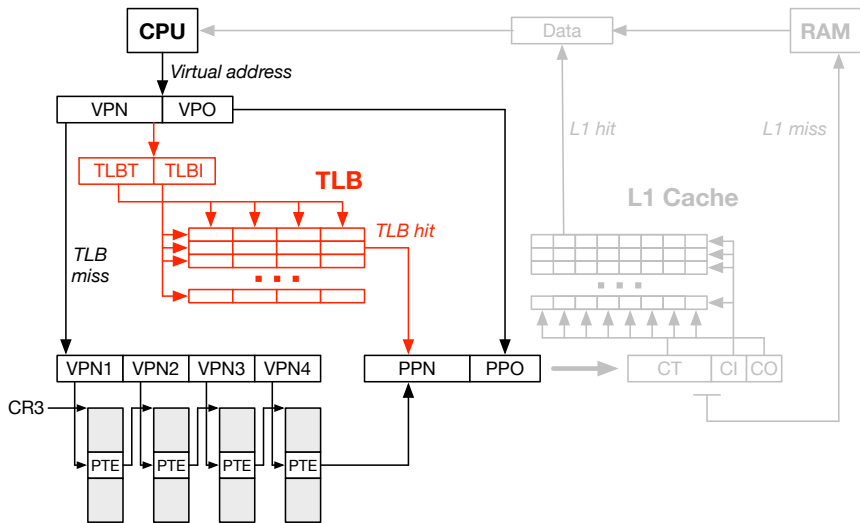
# L1 Cache Lookup



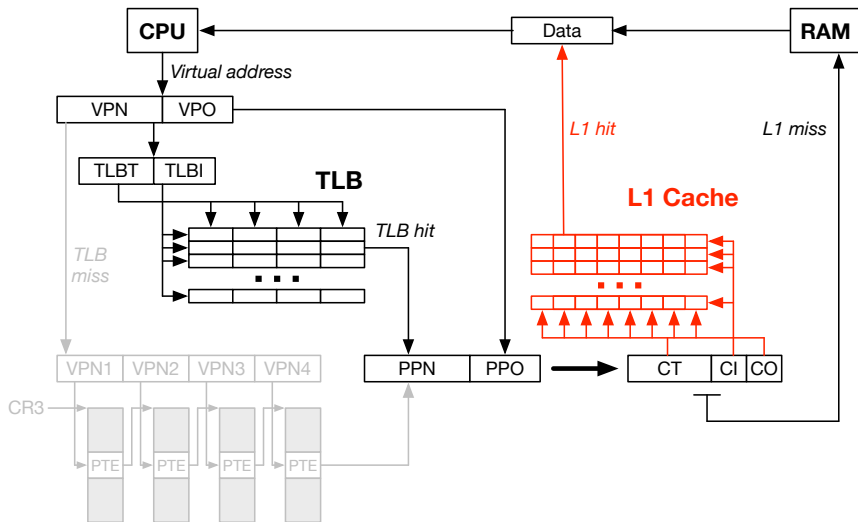
# Return Data From L1 Cache



# Translation Lookup Buffer Miss



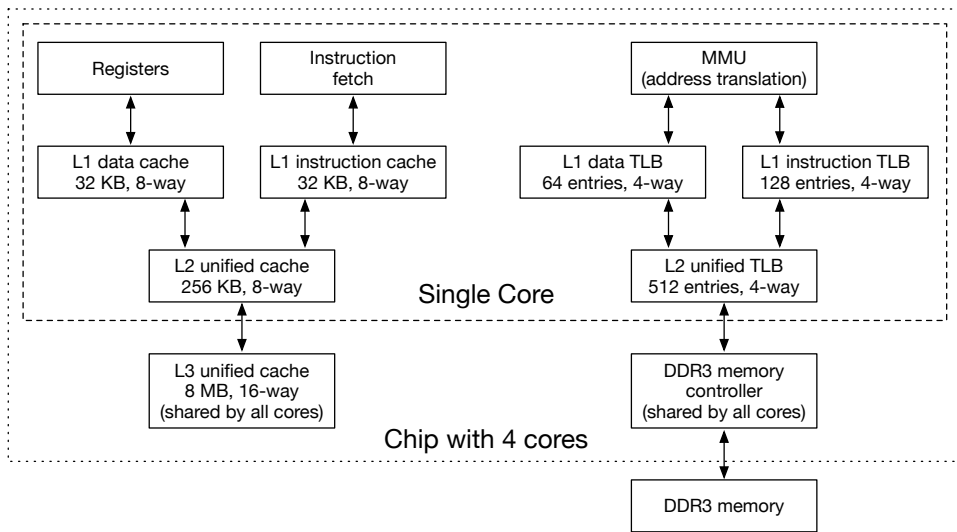
# L1 Cache Miss



Core i7



# Chip Layout



# Sizes

- ▶ Virtual memory: 48 bit ( $\rightarrow 2^{48} = 256\text{TB}$  address space)
- ▶ Physical memory: 52 bit ( $\rightarrow 2^{52} = 4\text{PB}$  address space)
- ▶ Page size: 12 bit ( $\rightarrow 2^{12} = 4\text{KB}$ )  
 $\Rightarrow 2^{36} = 64\text{G}$  entries, split in 4 levels (512 entries each)
- ▶ Translation lookup buffer (TLB): 4-way associative, 16 entries
- ▶ L1 cache: 8-way associative, 64 sets, 64 byte blocks (32 KB)
- ▶ L2 cache: 8-way associative, 512 sets, 64 byte blocks (256 KB)
- ▶ L3 cache: 16-way associative, 8K sets, 64 byte blocks (8 MB)

# Linux

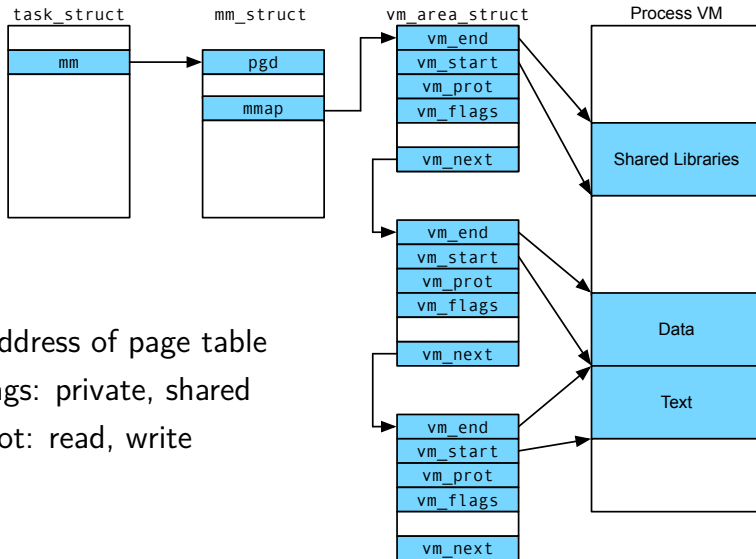
# Big Picture

- ▶ Close co-operation between hardware and software
- ▶ Each process has its own virtual address space, page table
- ▶ Translation look-up buffer  
when switching processes → flush
- ▶ Page table  
when switching processes → update pointer to top-level page table
- ▶ Page tables are always in physical memory  
→ pointers to page table do not require translation

# Handling Page Faults

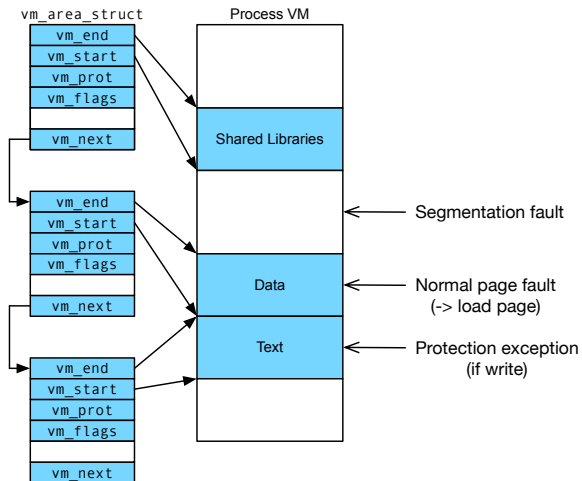
- ▶ Page faults trigger an exception (hardware)
- ▶ Exception is handled by software (Linux kernel)
- ▶ Kernel must determine what to do

# Linux Virtual Memory Areas



- ▶ pgd: address of page table
- ▶ vm\_flags: private, shared
- ▶ vm\_prot: read, write

# Handling Page Faults



Kernel walks through `vm_area_struct` list to resolve page fault

# Memory mapping



# Objects on Disk

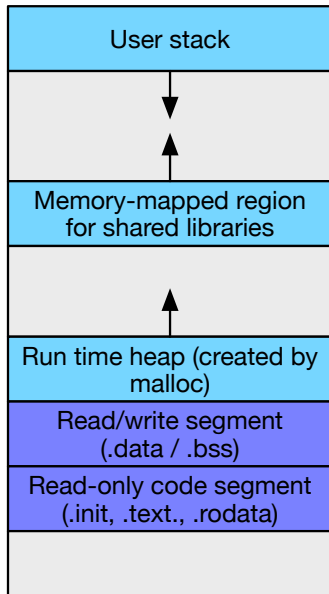
- ▶ Area of virtual memory = file on disk
- ▶ Regular file in file system
  - ▶ file divided up into pages
  - ▶ demand loading: just mapped to addresses, not actually loaded
  - ▶ could be code, shared library, data file
- ▶ Anonymous file
  - ▶ typically allocated memory
  - ▶ when used for the first time: set all values to zero
  - ▶ never really on disk, except when swapped out

# Shared Object

- ▶ A shared object is a file on disk
- ▶ Private object
  - ▶ only its process can read/write
  - ▶ changes not visible to other processes
- ▶ Shared object
  - ▶ multiple processes can read/write
  - ▶ changes visible to other processes

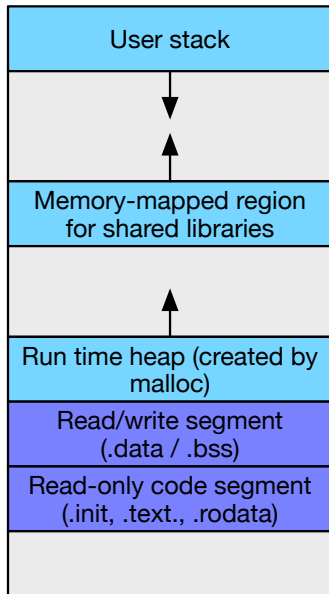
# fork()

- ▶ Creates a new child process
- ▶ Copies all
  - ▶ virtual memory area structures
  - ▶ memory mapping structures
  - ▶ page tables
- ▶ New process has identical access to existing memory



# execve()

- ▶ Creates a new process
- ▶ Deletes all user areas
- ▶ Map private areas (.data, .code, .bss)
- ▶ Map shared libraries
- ▶ Set program counter



# User-Level Memory Mapping

- ▶ Process can create virtual memory areas with mmap (may be loaded from file)
- ▶ Protection options (handled by kernel / hardware)
  - ▶ executable code
  - ▶ read
  - ▶ write
  - ▶ inaccessible
- ▶ Mapping options
  - ▶ anonymous: data object initially zeroed out
  - ▶ private
  - ▶ shared

# Dynamic memory allocation

# Memory Allocation in C

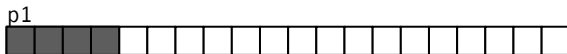
- ▶ `malloc()`
  - ▶ allocate specified amount of data
  - ▶ return pointer to (virtual) address
  - ▶ memory is allocated on heap
- ▶ `free()`
  - ▶ frees memory allocated at pointer location
  - ▶ may be between other allocated memory
- ▶ Need to track of list of allocated memory

# Assumptions

- ▶ Each square is a 4-byte word
- ▶ Heap consists of 20 words
- ▶ Allocations must be aligned on a multiple of 8
- ▶ Shading indicates use:
  - ▶ No shading: unallocated memory
  - ▶ Dark: allocated memory
  - ▶ Light: padding to ensure alignment

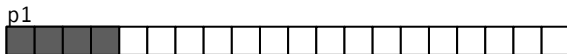


# Example



```
p1 = malloc(4*sizeof(int))
```

# Example

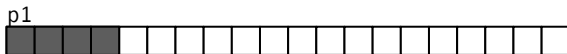


```
p1 = malloc(4*sizeof(int))
```



```
p2 = malloc(5*sizeof(int))
```

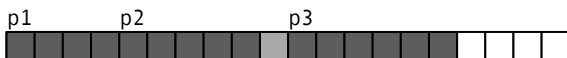
# Example



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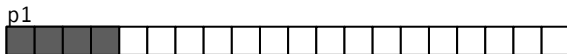


```
p2 = malloc(5*sizeof(int))
```



```
p3 = malloc(6*sizeof(int))
```

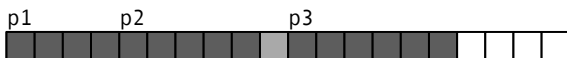
# Example



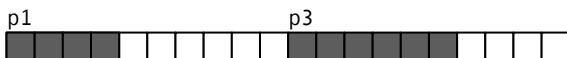
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p1 = malloc(4*sizeof(int))
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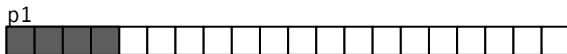


```
p3 = malloc(6*sizeof(int))
```



```
free(p2)
```

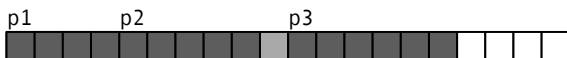
# Example



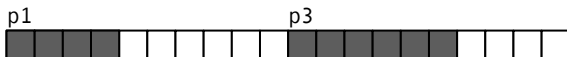
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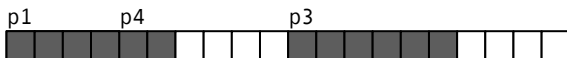
```
p2 = malloc(5*sizeof(int))
```



```
p3 = malloc(6*sizeof(int))
```



```
free(p2)
```



```
p4 = malloc(2*sizeof(int))
```

# Fragmentation

- ▶ Internal: unused space due to padding for
  - ▶ alignment
  - ▶ minimum block size
- ▶ External: as memory is allocated and freed:
  - ▶ allocated blocks are scattered over the heap area
  - ▶ there are gaps of various sizes between allocated blocks
  - ▶ it might not be possible to find a large enough gap to satisfy an allocation request, even though enough aggregate memory is available

# Free list

- ▶ Free list
  - ▶ need to maintain a list of free memory areas
  - ▶ implicit: space between allocated memory
  - ▶ explicit: maintain a separate list