Lecture 24: Virtual Memory III

Philipp Koehn

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601.229 Computer Systems Fundamentals

More refinements

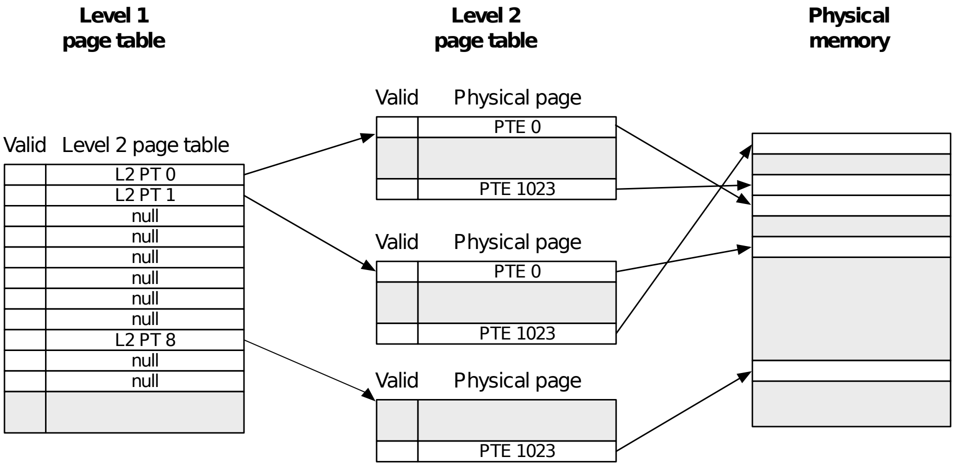
Refinements

- 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
  - $\rightarrow$ Number of pages: 1M
  - $\rightarrow$ 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
  $\rightarrow$ each level 1K entry ($1K^2$=1M)
- 4-level page table
  $\rightarrow$ 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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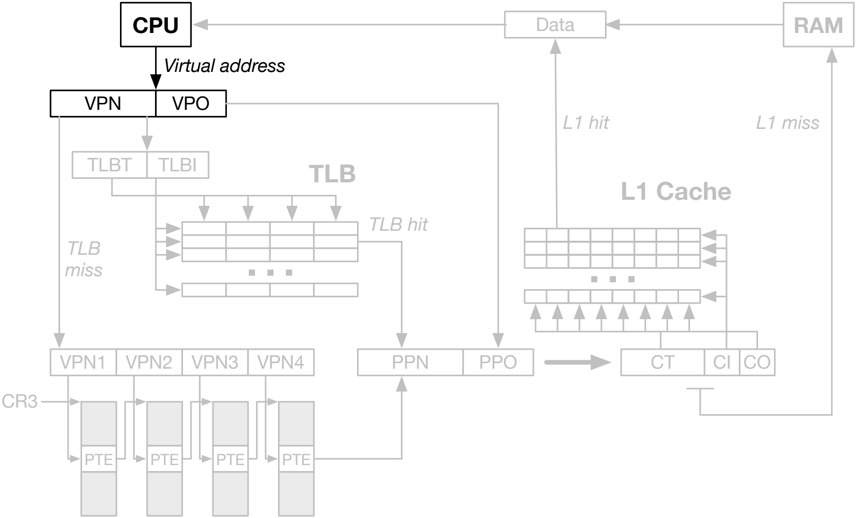
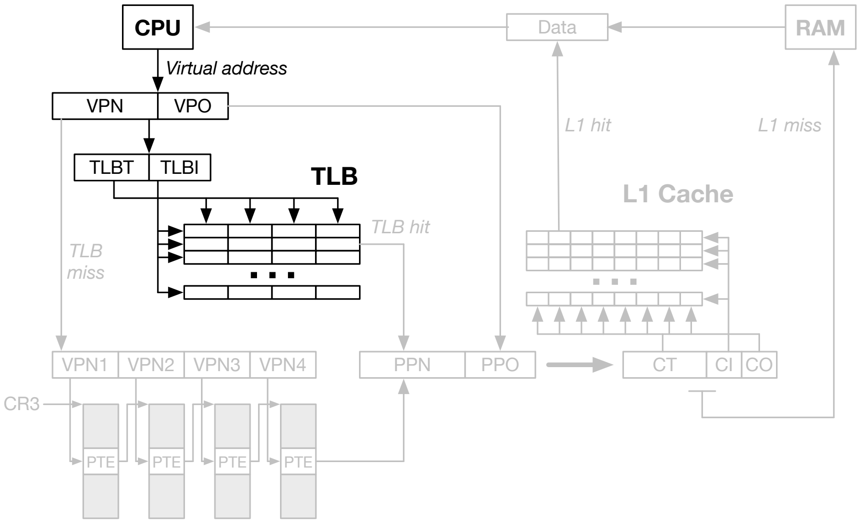
  $\rightarrow$ integrate cache and virtual memory
- Slow look-up time
  $\rightarrow$ use translation lookahead buffer (TLB)
- Huge address space
  $\rightarrow$ multi-level page table
- **Putting it all together**

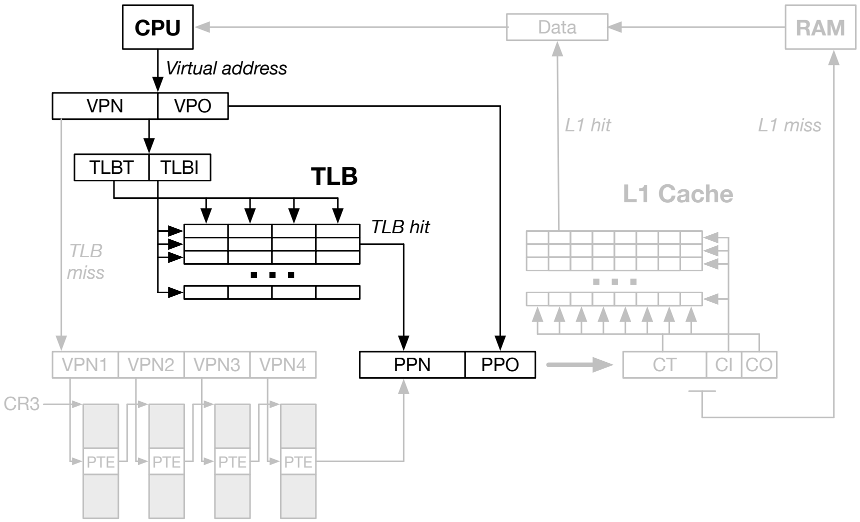
Virtual Address



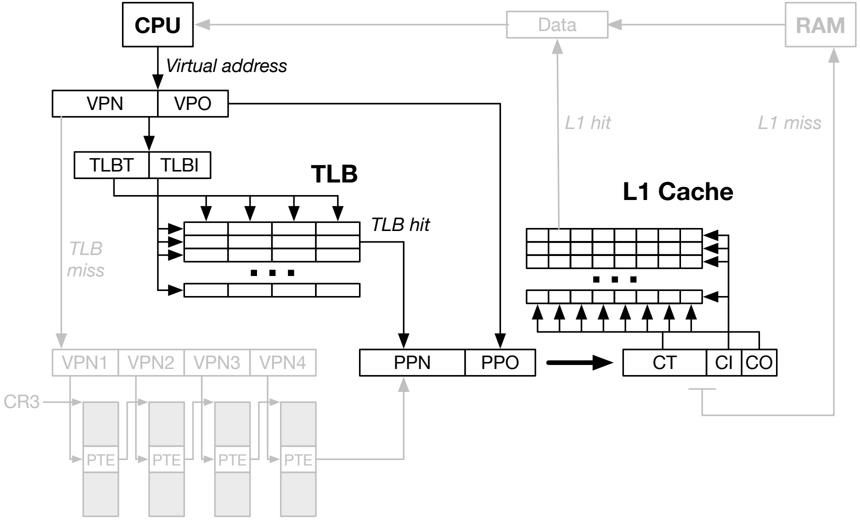
Translation Lookup Buffer



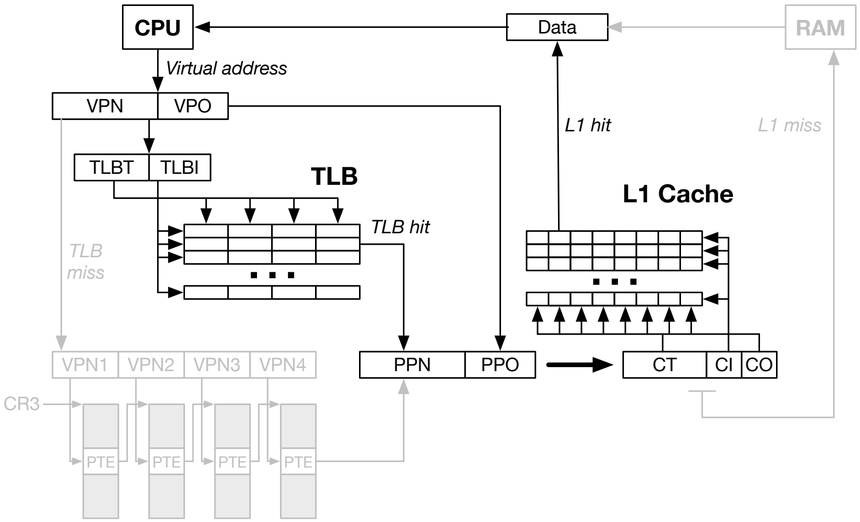
Compose Address



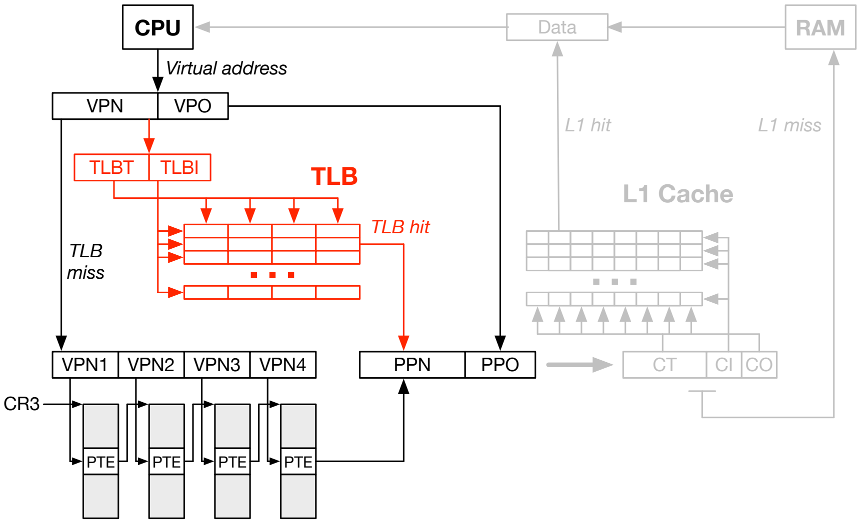
L1 Cache Lookup



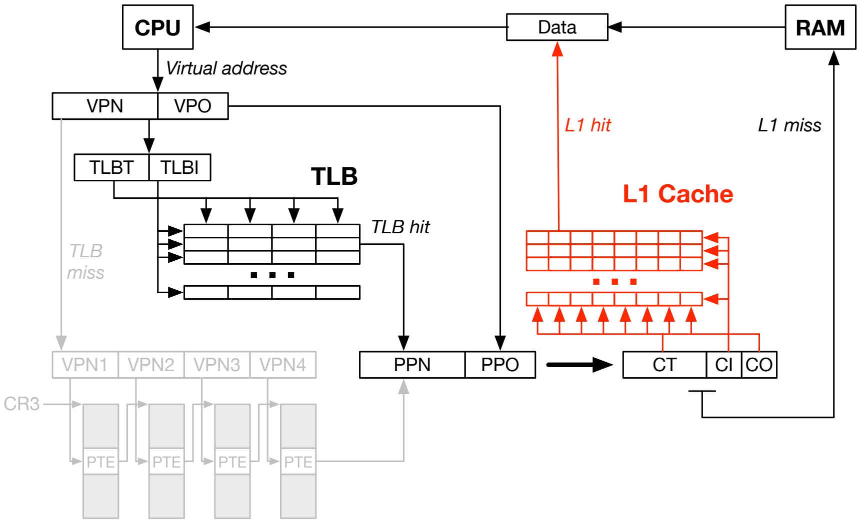
Return Data From L1 Cache



Translation Lookup Buffer Miss

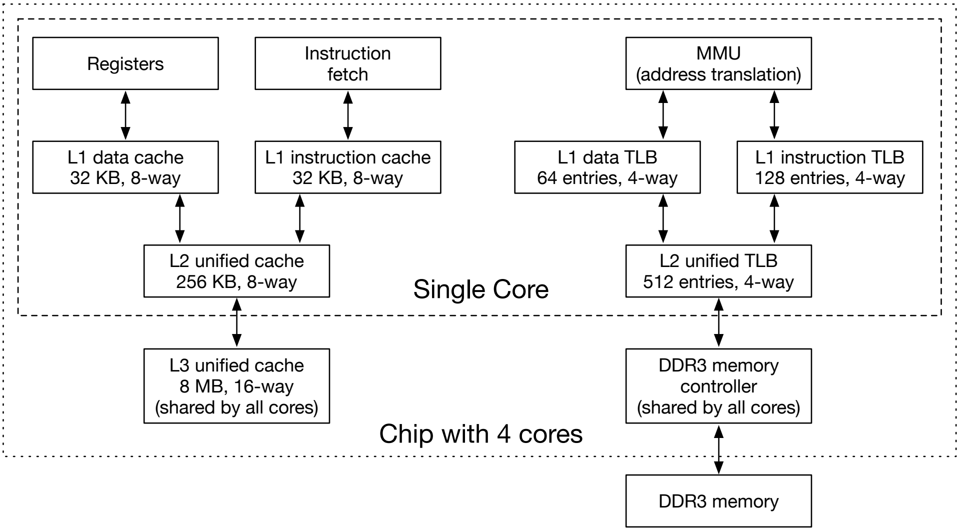


L1 Cache Miss



Core i7

Chip Layout



Registers
Instruction fetch
MMU (address translation)
L1 data cache 32 KB, 8-way
L1 instruction cache 32 KB, 8-way
L1 data TLB 64 entries, 4-way
L1 instruction TLB 128 entries, 4-way
L2 unified cache 256 KB, 8-way
Single Core
L2 unified TLB 512 entries, 4-way
L3 unified cache 8 MB, 16-way (shared by all cores)
DDR3 memory controller (shared by all cores)
Chip with 4 cores
DDR3 memory

Sizes

- Virtual memory: 48 bit ($\rightarrow 2^{48} = 256$TB address space)
- Physical memory: 52 bit ($\rightarrow 2^{52} = 4$PB address space)
- Page size: 12 bit ($\rightarrow 2^{12} = 4$KB)
  $\Rightarrow 2^{36} = 64$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

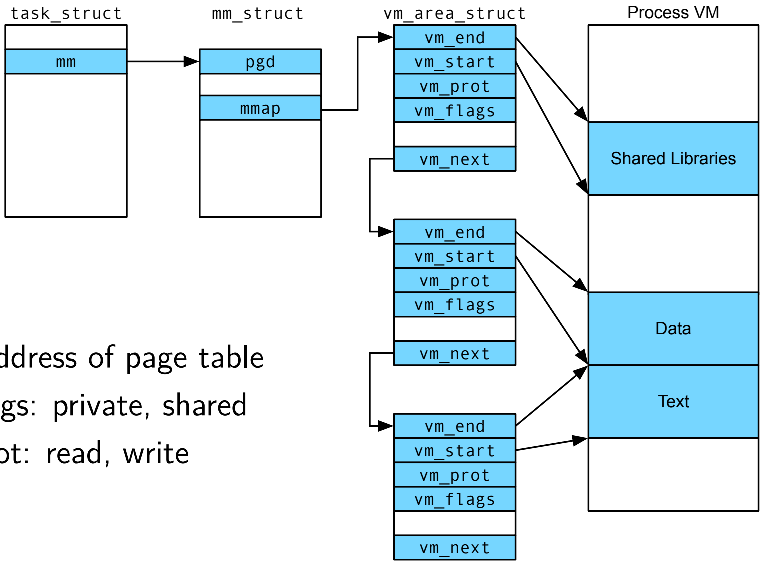
Big Picture

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

Handling Page Faults

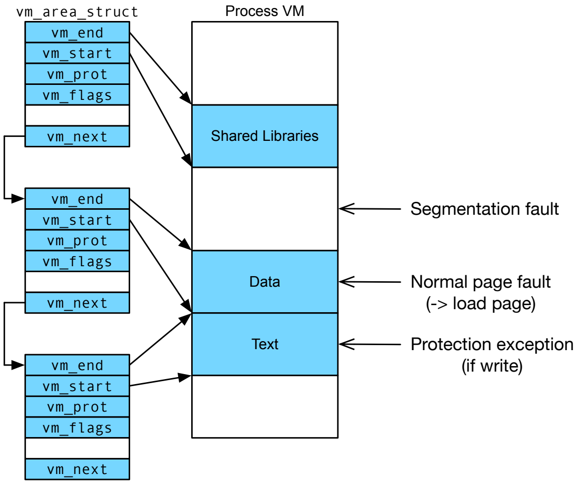
- Page faults trigger an exception (hardware)
- Exception is handled by software (Linux kernel)
- Kernel must determine what to do

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

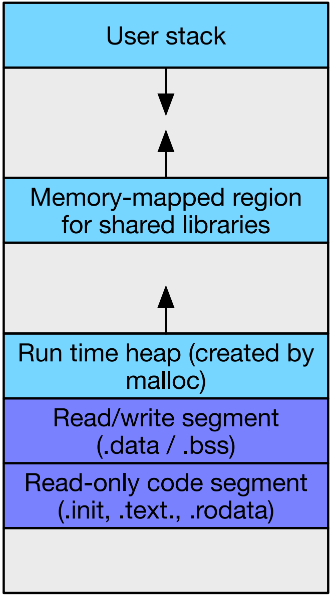
- Area of virtual memory = file on disk
- Regular file in file system
  - file divided up into pages
  - demand loading: just mapped to addresses, not actually loaded
  - could be code, shared library, data file
- Anonymous file
  - typically allocated memory
  - when used for the first time: set all 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

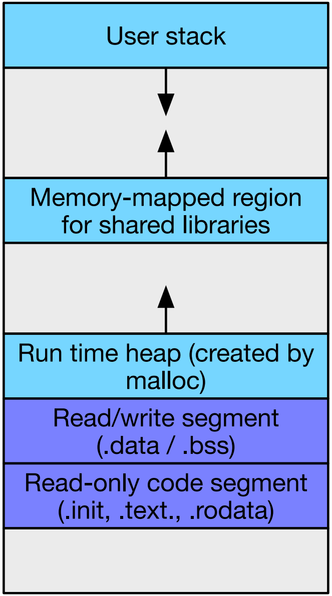
fork()

- 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

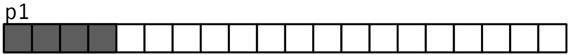
Memory Allocation in C

- 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

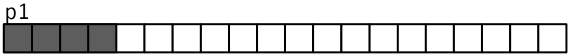
- Each square is a 4-byte word
- Heap consists of 20 words
- Allocations must be aligned on a multiple of 8
- Shading indicates use:
  - No shading: unallocated memory
  - Dark: allocated memory
  - Light: padding to ensure alignment

Example




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

Example

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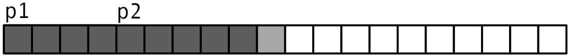


```
p2 = malloc(5*sizeof(int))
```

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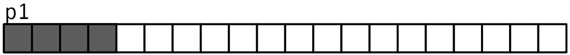


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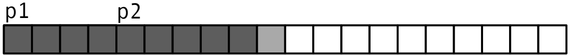


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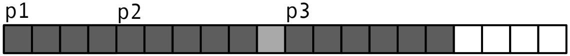


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p3 = malloc(6*sizeof(int))
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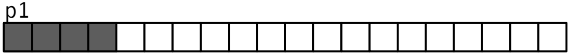
Example

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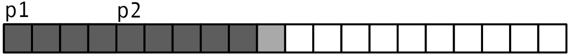


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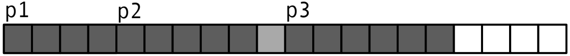


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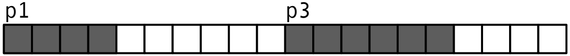
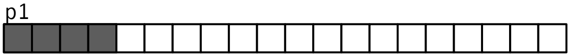



```
free(p2)
```

Example



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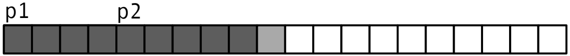

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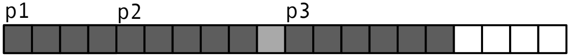

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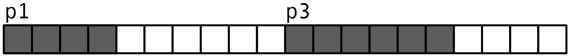

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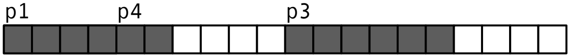

`p4 = malloc(2*sizeof(int))`

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