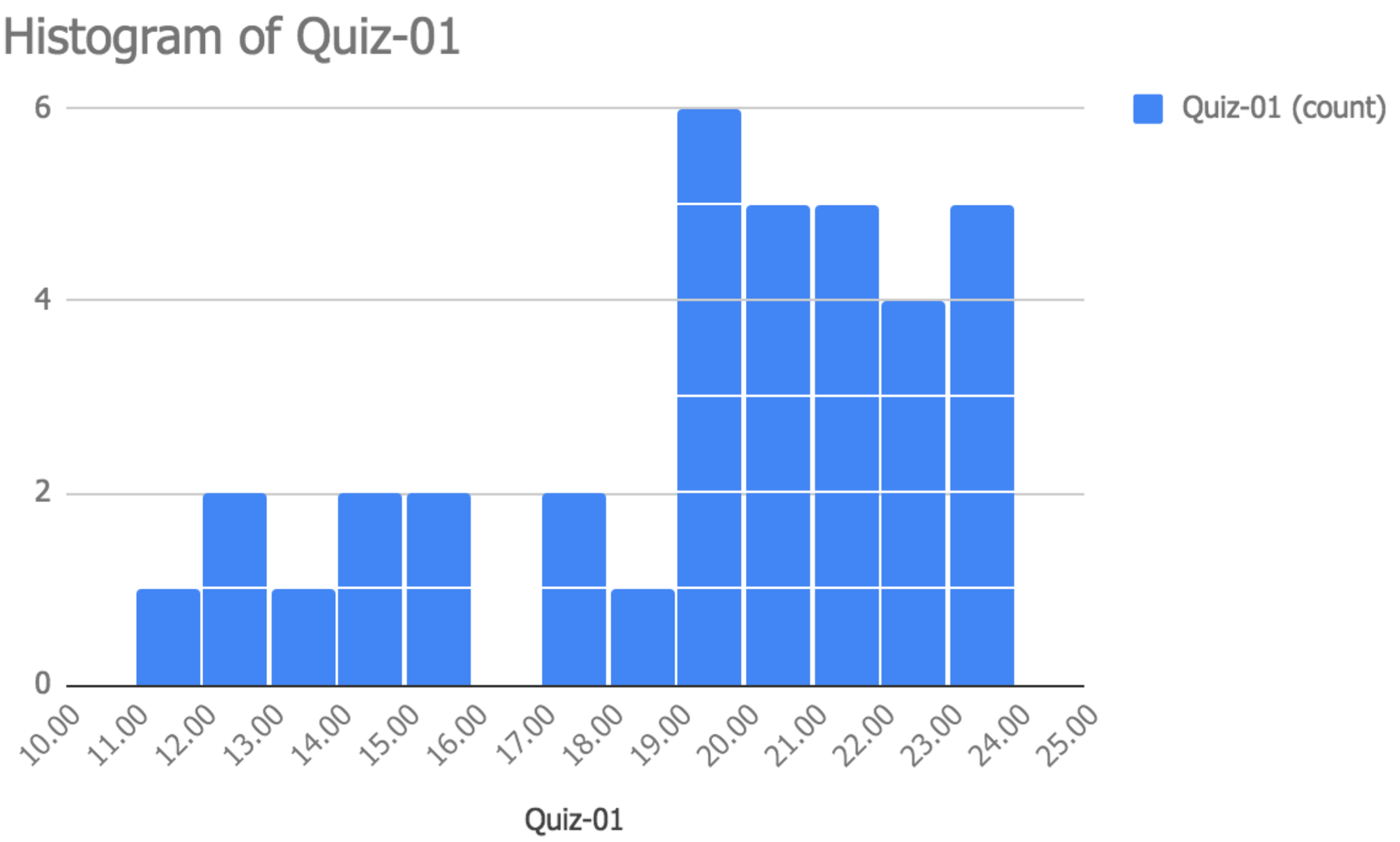
Operating Systems
Lecture 14: Advanced Paging + Swapping

Nipun Batra
Sep 4, 2018

Administrative



Administrative

Administrative

- Completing Virtualisation by this week

Administrative

- Almost 1/2 course done

Administrative

- Homework on Memory Virtualisation coming soon

Administrative

- Followed by Quiz on **13th Sept, Thursday**

Revision - Picture Thus Far

Revision - Picture Thus Far

Revision - Picture Thus Far

- Base & Bounds

Revision - Picture Thus Far

- Base & Bounds
  - Pros: Very quick, 2 registers

Revision - Picture Thus Far

- Base & Bounds
  - Pros: Very quick, 2 registers
  - Cons: Contiguous block of memory -> fragmentation

Revision - Picture Thus Far

- Base & Bounds
  - Pros: Very quick, 2 registers
  - Cons: Contiguous block of memory -> fragmentation
- Segmentation

Revision - Picture Thus Far

- Base & Bounds
  - Pros: Very quick, 2 registers
  - Cons: Contiguous block of memory -> fragmentation
- Segmentation
  - Pros: Still relatively simple, 3 registers, lesser fragmentation

Revision - Picture Thus Far

- Base & Bounds
  - Pros: Very quick, 2 registers
  - Cons: Contiguous block of memory -> fragmentation
- Segmentation
  - Pros: Still relatively simple, 3 registers, lesser fragmentation
  - Cons: Still contiguous block of memory for segment

Revision - Picture Thus Far

- Base & Bounds
  - Pros: Very quick, 2 registers
  - Cons: Contiguous block of memory -> fragmentation
- Segmentation
  - Pros: Still relatively simple, 3 registers, lesser fragmentation
  - Cons: Still contiguous block of memory for segment
- Paging

Revision - Picture Thus Far

- Base & Bounds
  - Pros: Very quick, 2 registers
  - Cons: Contiguous block of memory -> fragmentation
- Segmentation
  - Pros: Still relatively simple, 3 registers, lesser fragmentation
  - Cons: Still contiguous block of memory for segment
- Paging
  - Pros: Very low chances of segmentation

Revision - Picture Thus Far

- Base & Bounds
  - Pros: Very quick, 2 registers
  - Cons: Contiguous block of memory -> fragmentation
- Segmentation
  - Pros: Still relatively simple, 3 registers, lesser fragmentation
  - Cons: Still contiguous block of memory for segment
- Paging
  - Pros: Very low chances of segmentation
  - Cons: Slow, lots of memory accesses; memory overhead/ process is huge!

Revision - Picture Thus Far

- Base & Bounds
  - Pros: Very quick, 2 registers
  - Cons: Contiguous block of memory -> fragmentation
- Segmentation
  - Pros: Still relatively simple, 3 registers, lesser fragmentation
  - Cons: Still contiguous block of memory for segment
- Paging
  - Pros: Very low chances of segmentation
  - Cons: Slow, lots of memory accesses; memory overhead/ process is huge!
- Paging + TLB

Revision - Picture Thus Far

- Base & Bounds
  - Pros: Very quick, 2 registers
  - Cons: Contiguous block of memory -> fragmentation
- Segmentation
  - Pros: Still relatively simple, 3 registers, lesser fragmentation
  - Cons: Still contiguous block of memory for segment
- Paging
  - Pros: Very low chances of segmentation
  - Cons: Slow, lots of memory accesses; memory overhead/ process is huge!
- Paging + TLB
  - Pros: Improves the address translation speed (spatial & temporal locality)

Revision - Picture Thus Far

- Base & Bounds
  - Pros: Very quick, 2 registers
  - Cons: Contiguous block of memory -> fragmentation
- Segmentation
  - Pros: Still relatively simple, 3 registers, lesser fragmentation
  - Cons: Still contiguous block of memory for segment
- Paging
  - Pros: Very low chances of segmentation
  - Cons: Slow, lots of memory accesses; memory overhead/process is huge!
- Paging + TLB
  - Pros: Improves the address translation speed (spatial & temporal locality)
  - Cons: Limited in size, memory overhead/process still huge

Revision - Reducing Memory Overheads of Paging

Revision - Reducing Memory Overheads of Paging

- 32 bit address space with 4 KB pages

Revision - Reducing Memory Overheads of Paging

- 4 KB pages ->12 bits?

Revision - Reducing Memory Overheads of Paging

-
-
- Remaining bits = 32 - 12 = 20

Revision - Reducing Memory Overheads of Paging

- 20 bit VPN

Revision - Reducing Memory Overheads of Paging

-
-
-
- # pages = 2^20

Revision - Reducing Memory Overheads of Paging

-
-
-
-
-
- 4 bytes per translation -> 4 * 2^20 MB = **4 MB/process**

Revision - Reducing Memory Overheads of Paging

Revision - Reducing Memory Overheads of Paging

Solution 0: Decrease the size of VA space

Revision - Reducing Memory Overheads of Paging

Solution 0: Decrease the size of VA space

- 12 bit offset for 4 K pages

Revision - Reducing Memory Overheads of Paging

Solution 0: Decrease the size of VA space

-
- 30 bit address space

Revision - Reducing Memory Overheads of Paging

Solution 0: Decrease the size of VA space

-
-
- 18 bit VPNs

Revision - Reducing Memory Overheads of Paging

Solution 0: Decrease the size of VA space

-
-
- 4 bytes per translation -> 4 * 2^18 MB = **1 MB/process**

Revision - Reducing Memory Overheads of Paging

Solution 0: Decrease the size of VA space

-
-
- 4 bytes per translation -> 4 * 2^18 MB = **1 MB/process**
- 32 bit address space —> 4 GB

Revision - Reducing Memory Overheads of Paging

Solution 0: Decrease the size of VA space

-
-
- 4 bytes per translation -> 4 * 2^18 MB = **1 MB/process**
-
- 30 bit address space —> 1 GB

Revision - Reducing Memory Overheads of Paging

Revision - Reducing Memory Overheads of Paging

Solution 1: Increase the page size

Revision - Reducing Memory Overheads of Paging

Solution 1: Increase the page size

- 32 bit address space with 16 KB pages

Revision - Reducing Memory Overheads of Paging

Solution 1: Increase the page size

- 16 KB pages ->14 bits?

Revision - Reducing Memory Overheads of Paging

Solution 1: Increase the page size

-
-

- Remaining bits = 32 - 14 = 18

Revision - Reducing Memory Overheads of Paging

Solution 1: Increase the page size

-
-
-
- 18 bit VPN

Revision - Reducing Memory Overheads of Paging

Solution 1: Increase the page size

-
-
-
- # pages = 2^18

Revision - Reducing Memory Overheads of Paging

Solution 1: Increase the page size

-
-
-
-
-
-
- 4 bytes per translation -> 4 * 2^18 MB = **1 MB/process**

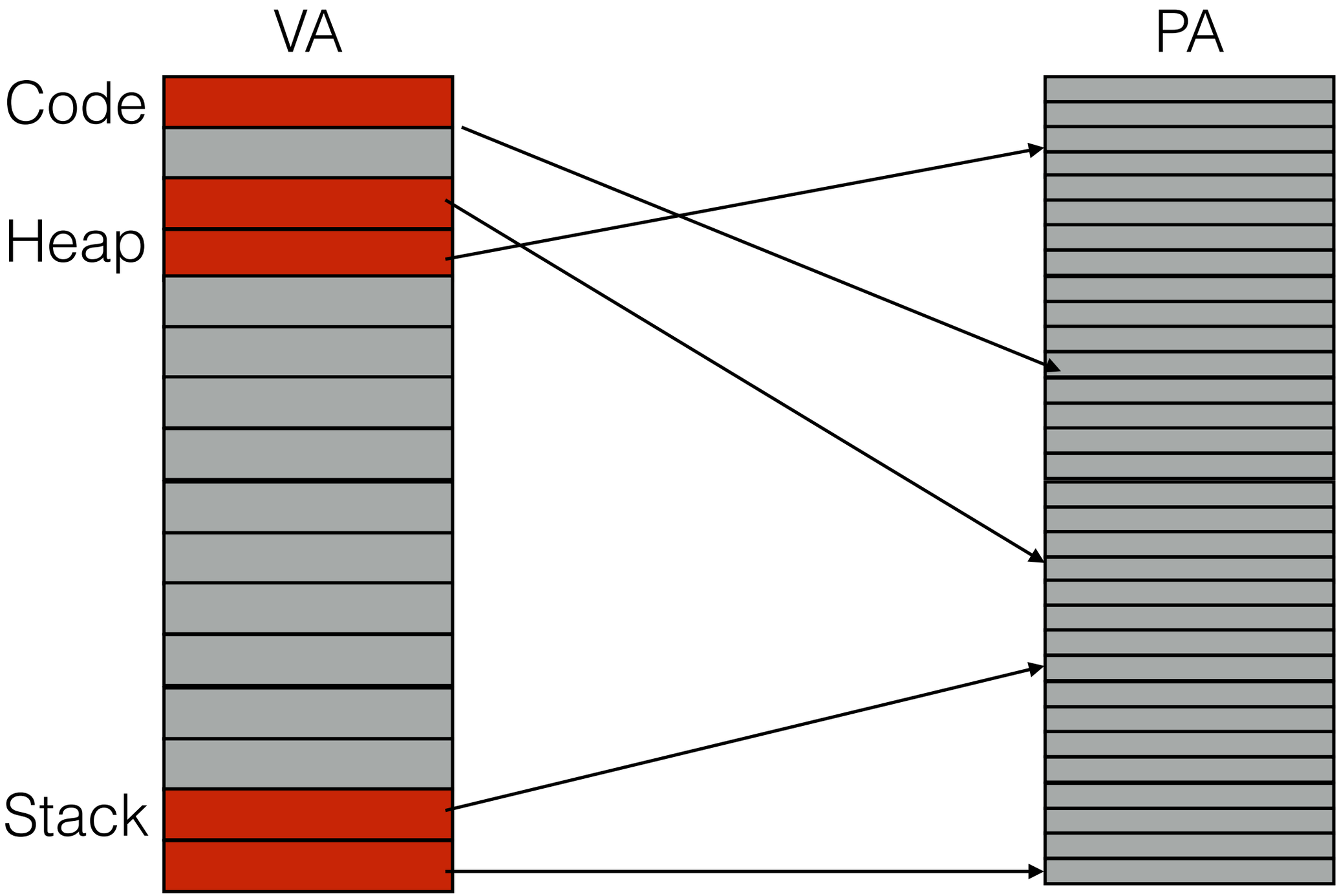
Revision - Reducing Memory Overheads of Paging

Solution 1: Increase the page size

-
-
-
-
-
-
- 4 bytes per translation -> 4 * 2^18 MB = **1 MB/process**

Larger page size —> Fragmentation

Reducing Memory Overheads of Paging



Reducing Memory Overheads of Paging

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Reducing Memory Overheads of Paging

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Reducing Memory Overheads of Paging

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Wasted

Reducing Memory Overheads of Paging

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Wasted

Reducing Memory Overheads of Paging

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Wasted

Linear Page Table

Reducing Memory Overheads of Paging

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Wasted

Linear Page Table

Reducing Memory Overheads of Paging

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Wasted

Linear Page Table

Lookup = O(1)

Reducing Memory Overheads of Paging

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Wasted

Linear Page Table

Lookup = O(1)
Space = 16*Size

Reducing Memory Overheads of Paging

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Wasted

Reducing Memory Overheads of Paging

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Wasted

Convert

Reducing Memory Overheads of Paging

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Wasted

Convert

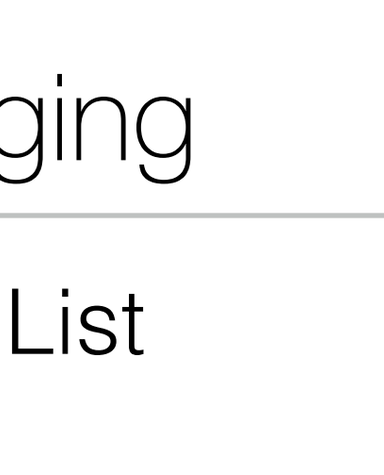
Reducing Memory Overheads of Paging

PFN	Valid	...
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Wasted

Linked List

Convert



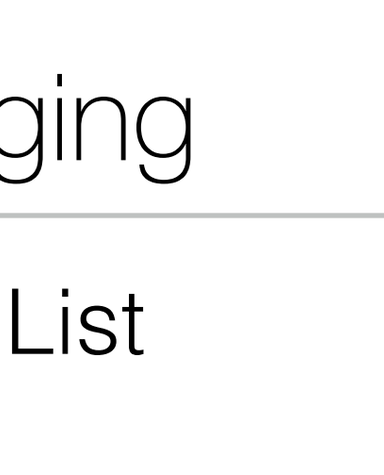
Reducing Memory Overheads of Paging

PFN	Valid	...
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Wasted

Linked List

Convert



Reducing Memory Overheads of Paging

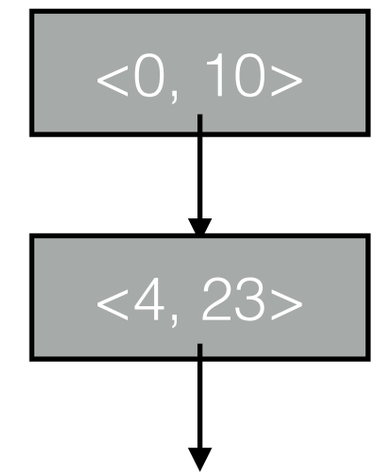
PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Wasted

Linked List

Lookup = O(n) for n

Convert



Reducing Memory Overheads of Paging

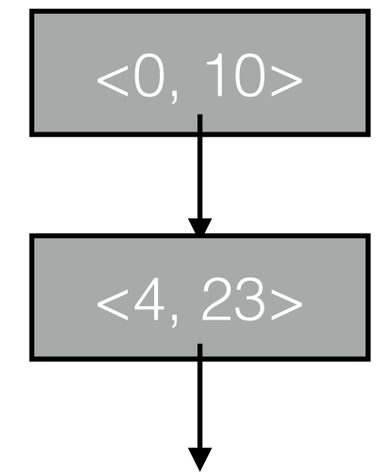
PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Wasted

Linked List

Lookup = O(n) for n valid pages (n<<16)

Convert



Reducing Memory Overheads of Paging

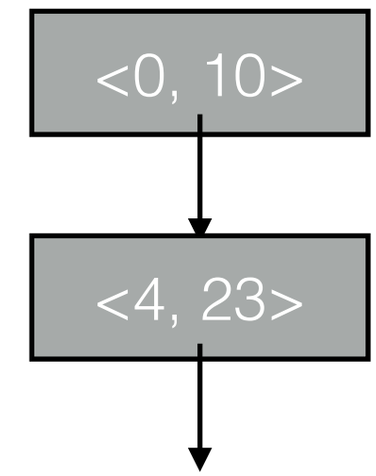
PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Wasted

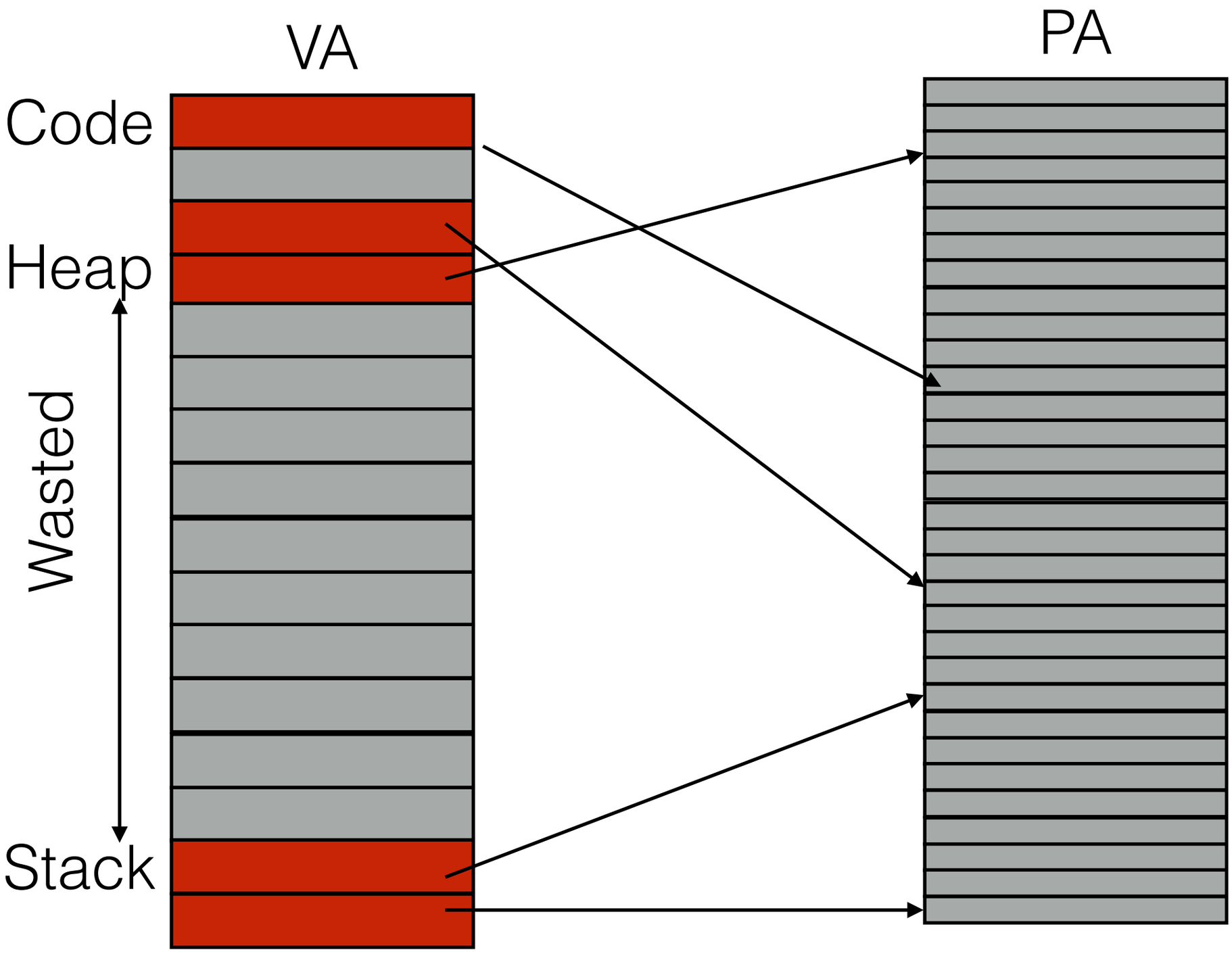
Linked List

Lookup = O(n) for n valid pages (n<<16)
Space = n*Size

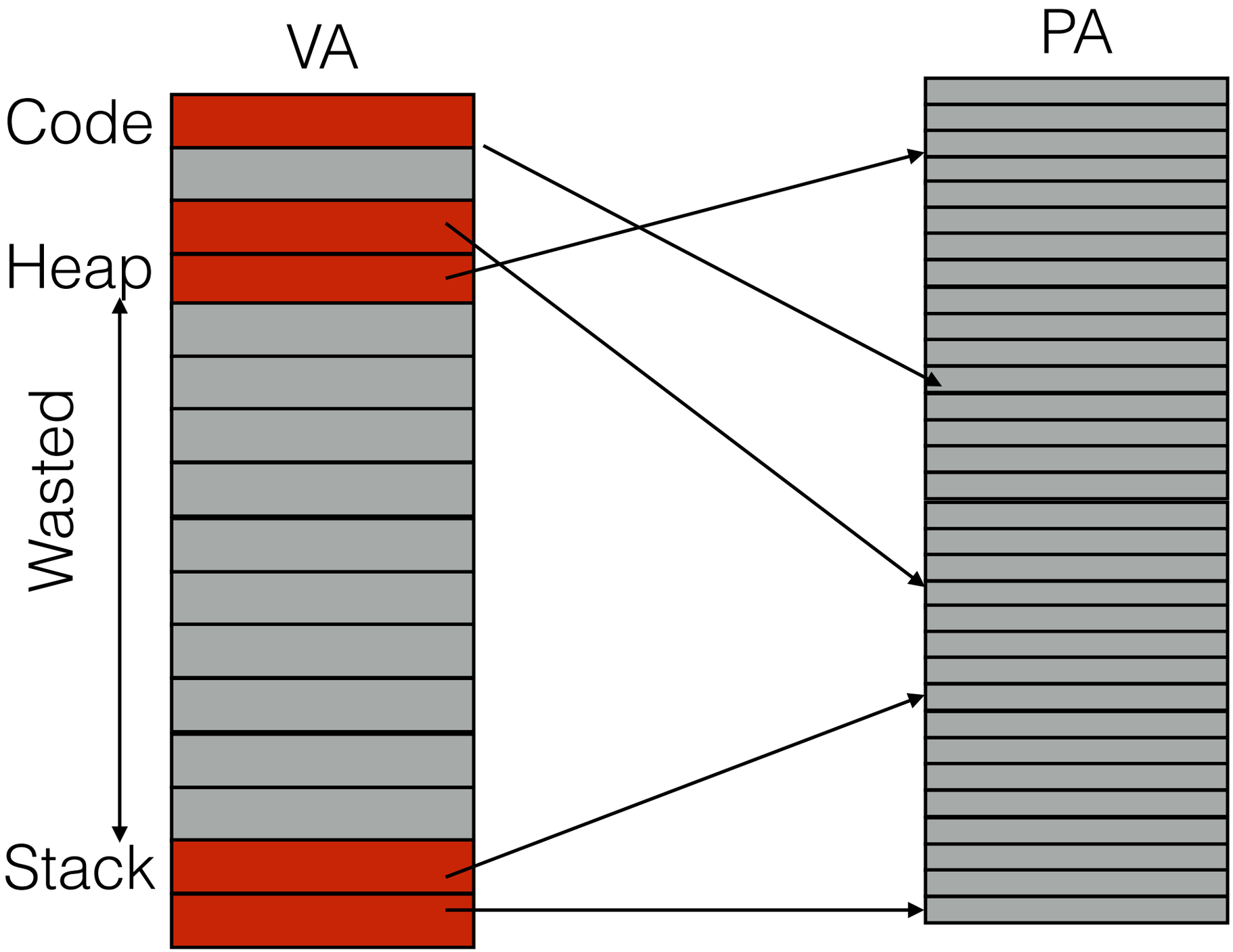
Convert



Reducing Memory Overheads of Paging

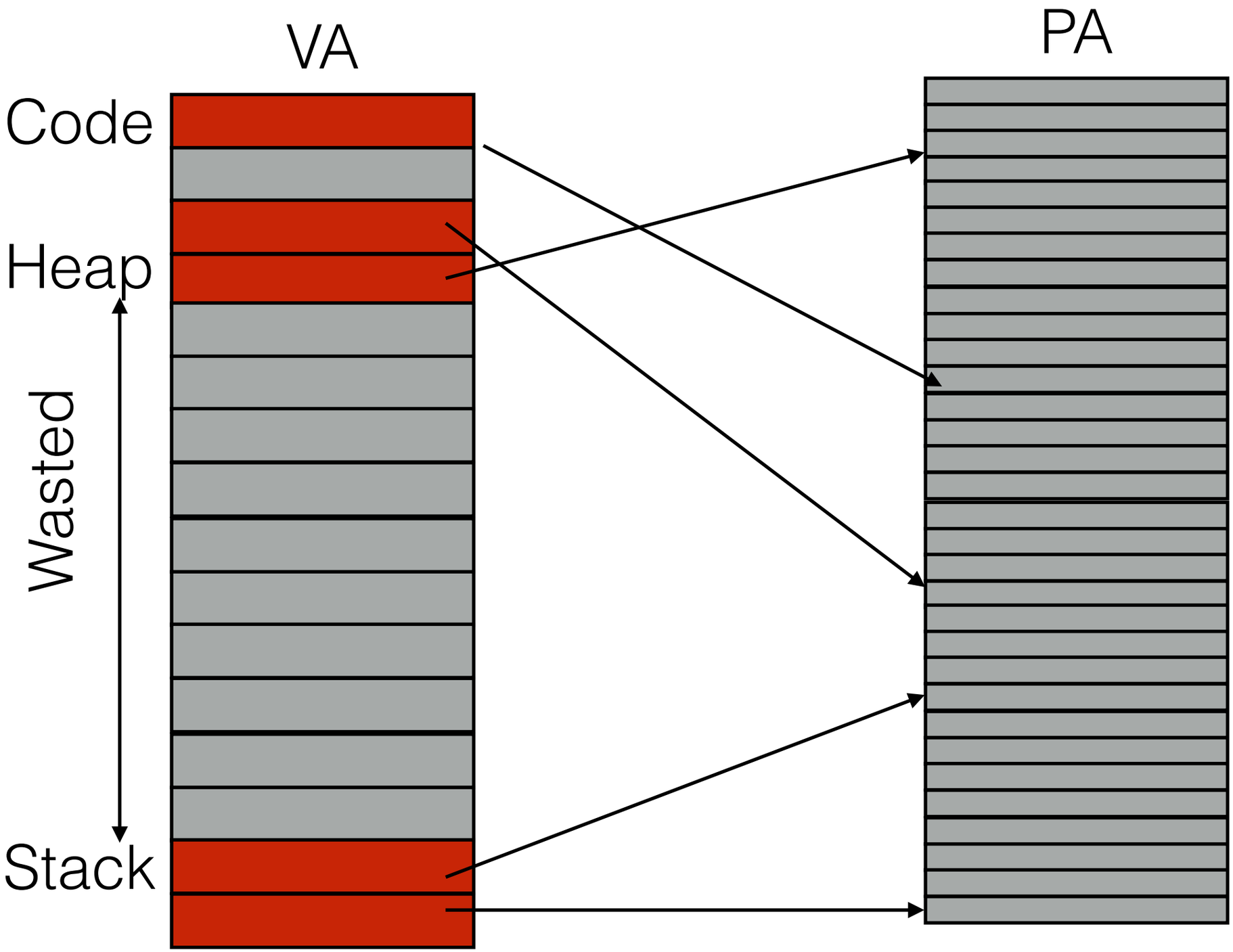


Reducing Memory Overheads of Paging



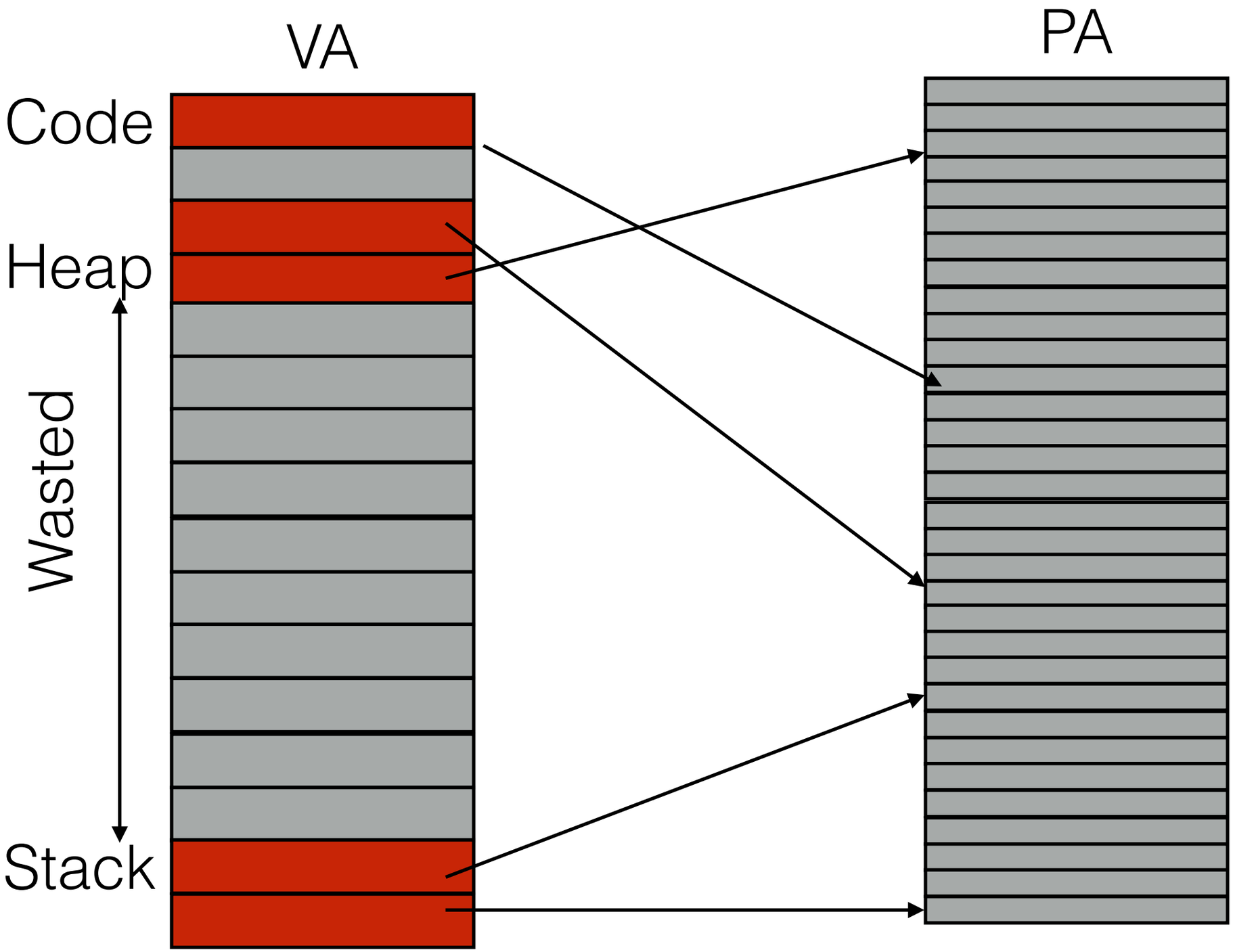
How did we fill holes in PA space earlier?

Reducing Memory Overheads of Paging



How did we fill holes in PA space earlier?

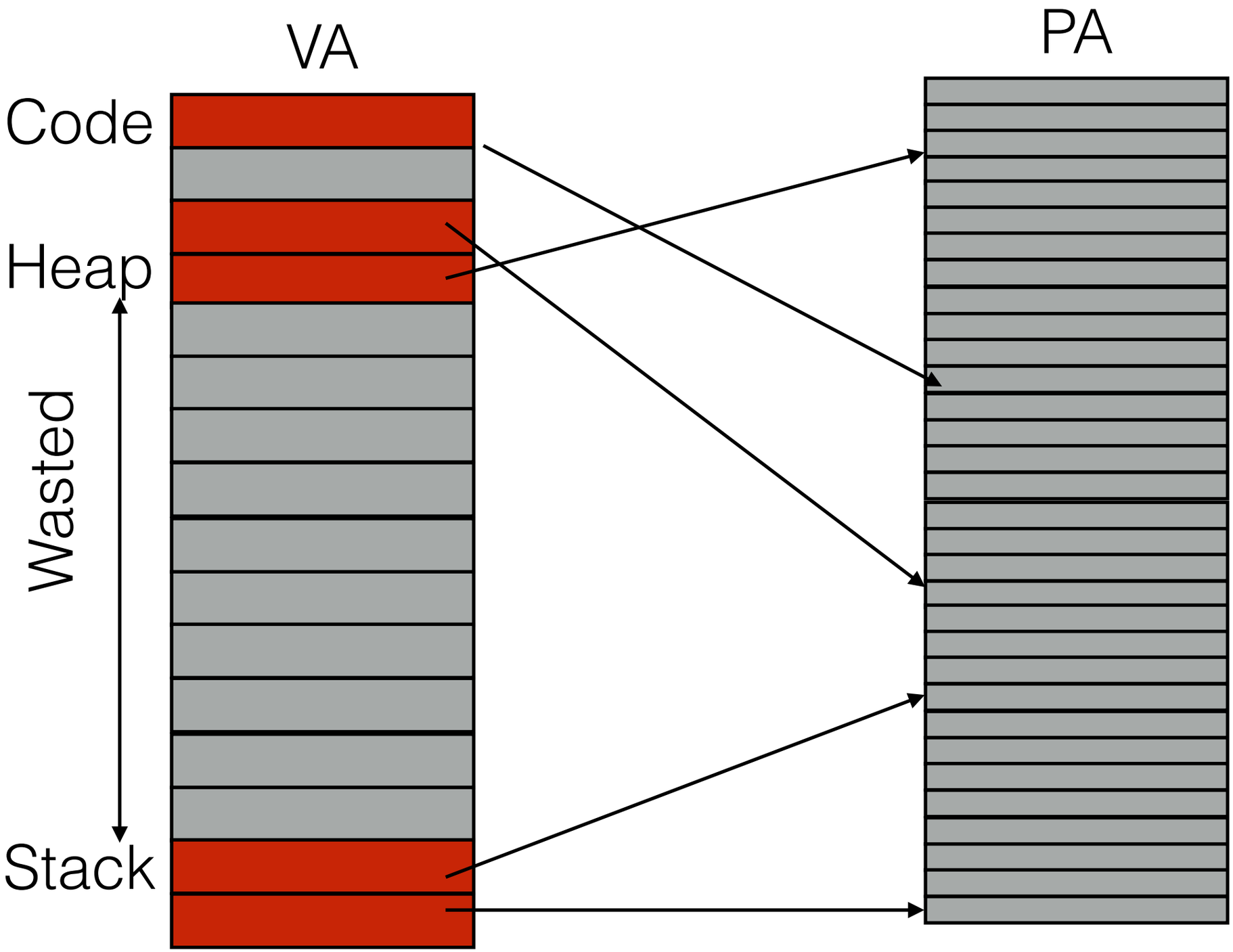
Reducing Memory Overheads of Paging



How did we fill holes in PA space earlier?

1. Segmentation

Reducing Memory Overheads of Paging



How did we fill holes in PA space earlier?

1. Segmentation
2. Paging

Reducing Memory Overheads of Paging - Segmentation + PT

Reducing Memory Overheads of Paging - Segmentation + PT

Idea: use different page tables for heap, stack, etc

Reducing Memory Overheads of Paging - Segmentation + PT

Idea: use different page tables for heap, stack, etc

Reducing Memory Overheads of Paging - Segmentation + PT

Idea: use different page tables for heap, stack, etc

- Each PT can be different size

Reducing Memory Overheads of Paging - Segmentation + PT

Idea: use different page tables for heap, stack, etc

- Each PT can be different size
- Each PT has base & bounds

Reducing Memory Overheads of Paging - Segmentation + PT

Idea: use different page tables for heap, stack, etc

- Each PT can be different size
- Each PT has base & bounds
  - Base & Bounds stored in :

Reducing Memory Overheads of Paging - Segmentation + PT

Idea: use different page tables for heap, stack, etc

- Each PT can be different size
- Each PT has base & bounds
  - Base & Bounds stored in :
  - MMU

Reducing Memory Overheads of Paging - Segmentation + PT

Idea: use different page tables for heap, stack, etc

- Each PT can be different size
- Each PT has base & bounds
  - Base & Bounds stored in :
    - MMU
- What did Base store in regular segmentation?

Reducing Memory Overheads of Paging - Segmentation + PT

Idea: use different page tables for heap, stack, etc

- Each PT can be different size
- Each PT has base & bounds
  - Base & Bounds stored in :
    - MMU
- What did Base store in regular segmentation?
  - PA where segment resided

Reducing Memory Overheads of Paging - Segmentation + PT

Idea: use different page tables for heap, stack, etc

- Each PT can be different size
- Each PT has base & bounds
  - Base & Bounds stored in :
    - MMU
- What did Base store in regular segmentation?
  - PA where segment resided
- What would Base refer here?

Reducing Memory Overheads of Paging - Segmentation + PT

Idea: use different page tables for heap, stack, etc

- Each PT can be different size
- Each PT has base & bounds
  - Base & Bounds stored in :
    - MMU
- What did Base store in regular segmentation?
  - PA where segment resided
- What would Base refer here?
  - PA of PT for segment

Reducing Memory Overheads of Paging - Segmentation + PT

Idea: use different page tables for heap, stack, etc

- Each PT can be different size
- Each PT has base & bounds
  - Base & Bounds stored in :
    - MMU
- What did Base store in regular segmentation?
  - PA where segment resided
- What would Base refer here?
  - PA of PT for segment
- What would Bounds refer to here?

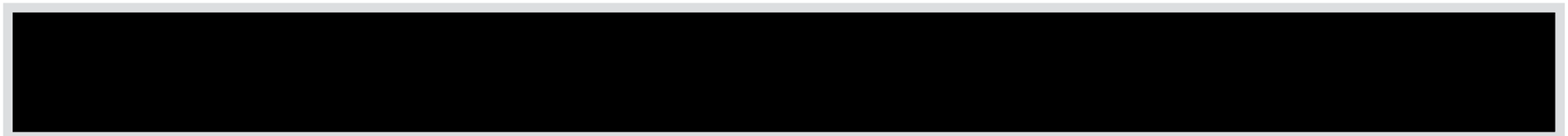
Reducing Memory Overheads of Paging - Segmentation + PT

Idea: use different page tables for heap, stack, etc

- Each PT can be different size
- Each PT has base & bounds
  - Base & Bounds stored in :
    - MMU
- What did Base store in regular segmentation?
  - PA where segment resided
- What would Base refer here?
  - PA of PT for segment
- What would Bounds refer to here?
  - Number of valid pages/End of page table

Reducing Memory Overheads of Paging - Segmentation + PT

32 bit VA space



32 bit VA space with 4KB pages

32 bit VA space with 4KB pages for 4 segments

Reducing Memory Overheads of Paging - Segmentation + PT

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Reducing Memory Overheads of Paging - Segmentation + PT

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

PFN	Valid	…
10	1	..
..	1	

Reducing Memory Overheads of Paging - Segmentation + PT

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Code PT

PFN	Valid	…
10	1	..
..	1	

Reducing Memory Overheads of Paging - Segmentation + PT

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Code PT
Base = 0

PFN	Valid	…
10	1	..
..	1	

Reducing Memory Overheads of Paging - Segmentation + PT

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Code PT
Base = 0
Bounds = 2

PFN	Valid	…
10	1	..
..	1	

Reducing Memory Overheads of Paging - Segmentation + PT

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Code PT
Base = 0
Bounds = 2

PFN	Valid	…
10	1	..
..	1	

PFN	Valid	…
23	1	..
..	1	

Reducing Memory Overheads of Paging - Segmentation + PT

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Code PT
Base = 0
Bounds = 2

PFN	Valid	…
10	1	..
..	1	

Heap PT

PFN	Valid	…
23	1	..
..	1	

Reducing Memory Overheads of Paging - Segmentation + PT

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Code PT
Base = 0
Bounds = 2

PFN	Valid	…
10	1	..
..	1	

Heap PT
Base = 4

PFN	Valid	…
23	1	..
..	1	

Reducing Memory Overheads of Paging - Segmentation + PT

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Code PT
Base = 0
Bounds = 2

PFN	Valid	…
10	1	..
..	1	

Heap PT
Base = 4
Bounds = 2

PFN	Valid	…
23	1	..
..	1	

Reducing Memory Overheads of Paging - Segmentation + PT

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Code PT
Base = 0
Bounds = 2

PFN	Valid	…
10	1	..
..	1	

Heap PT
Base = 4
Bounds = 2

PFN	Valid	…
23	1	..
..	1	

Stack PT

Reducing Memory Overheads of Paging - Segmentation + PT

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Code PT
Base = 0
Bounds = 2

PFN	Valid	…
10	1	..
..	1	

Heap PT
Base = 4
Bounds = 2

PFN	Valid	…
23	1	..
..	1	

Stack PT
Base = ?

Reducing Memory Overheads of Paging - Segmentation + PT

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Code PT
Base = 0
Bounds = 2

PFN	Valid	…
10	1	..
..	1	

Heap PT
Base = 4
Bounds = 2

PFN	Valid	…
23	1	..
..	1	

Stack PT
Base = ?
Bounds = ?

Reducing Memory Overheads of Paging - Segmentation + PT

Reducing Memory Overheads of Paging - Segmentation + PT

Reducing Memory Overheads of Paging - Segmentation + PT

- Pros:

Reducing Memory Overheads of Paging - Segmentation + PT

- Pros:
  - Leads to memory saving (Large gaps between segments)

Reducing Memory Overheads of Paging - Segmentation + PT

- Pros:
  - Leads to memory saving (Large gaps between segments)
- Cons:

Reducing Memory Overheads of Paging - Segmentation + PT

- Pros:
  - Leads to memory saving (Large gaps between segments)
- Cons:
  - Uses segmentation

Reducing Memory Overheads of Paging - Segmentation + PT

- Pros:
  - Leads to memory saving (Large gaps between segments)
- Cons:
  - Uses segmentation
  - Assumes certain usage pattern of address space

Reducing Memory Overheads of Paging - Segmentation + PT

- Pros:
  - Leads to memory saving (Large gaps between segments)
- Cons:
  - Uses segmentation
  - Assumes certain usage pattern of address space
  - Sparsely used segments (sub-segment internal fragmentation) have same space waste issue

Reducing Memory Overheads of Paging - Segmentation + PT

- Pros:
  - Leads to memory saving (Large gaps between segments)
- Cons:
  - Uses segmentation
  - Assumes certain usage pattern of address space
  - Sparsely used segments (sub-segment internal fragmentation) have same space waste issue
    - How to address this?

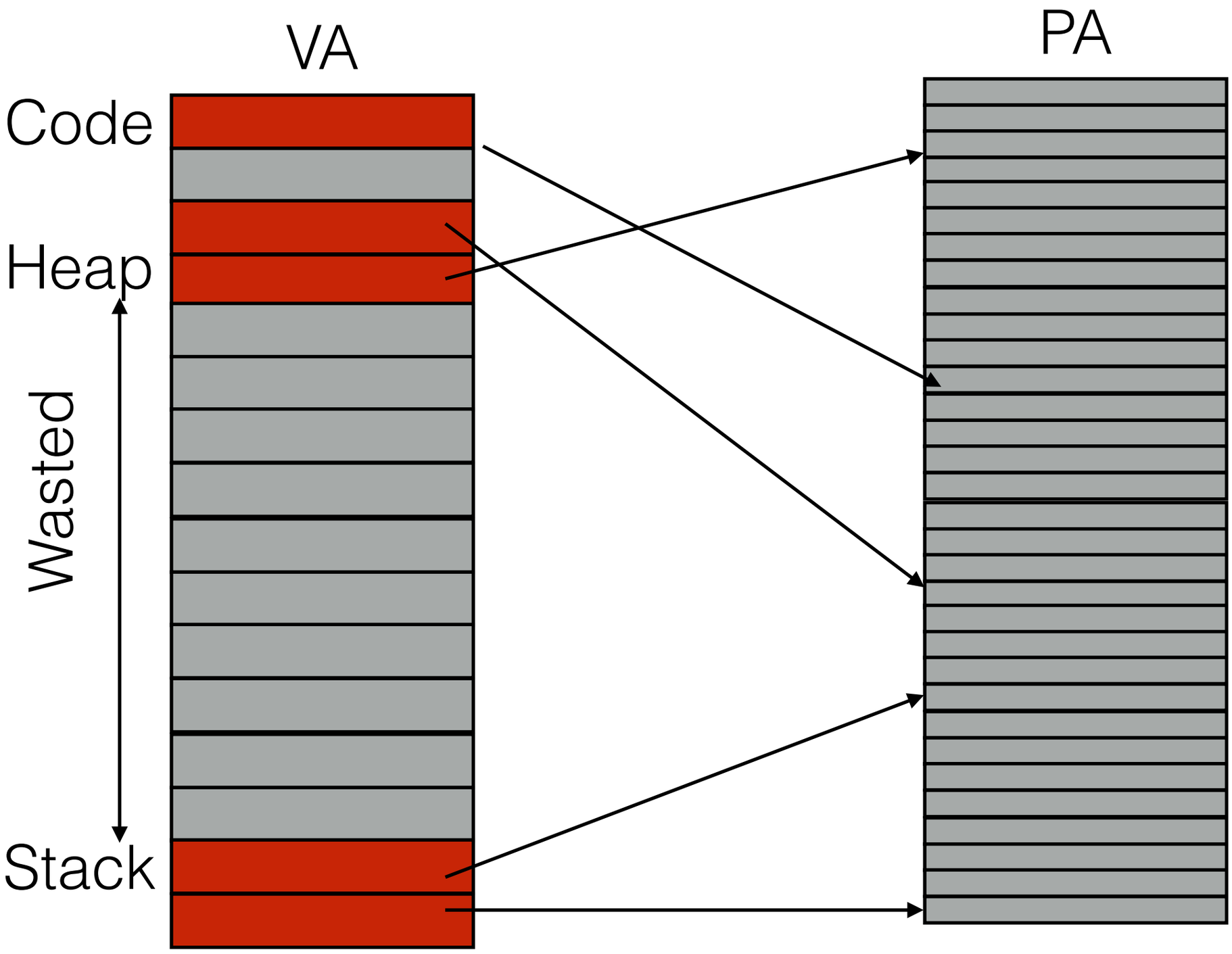
Reducing Memory Overheads of Paging - Segmentation + PT

- Pros:
  - Leads to memory saving (Large gaps between segments)
- Cons:
  - Uses segmentation
  - Assumes certain usage pattern of address space
  - Sparsely used segments (sub-segment internal fragmentation) have same space waste issue
    - How to address this?
      - LinkedList! Getting complex now.

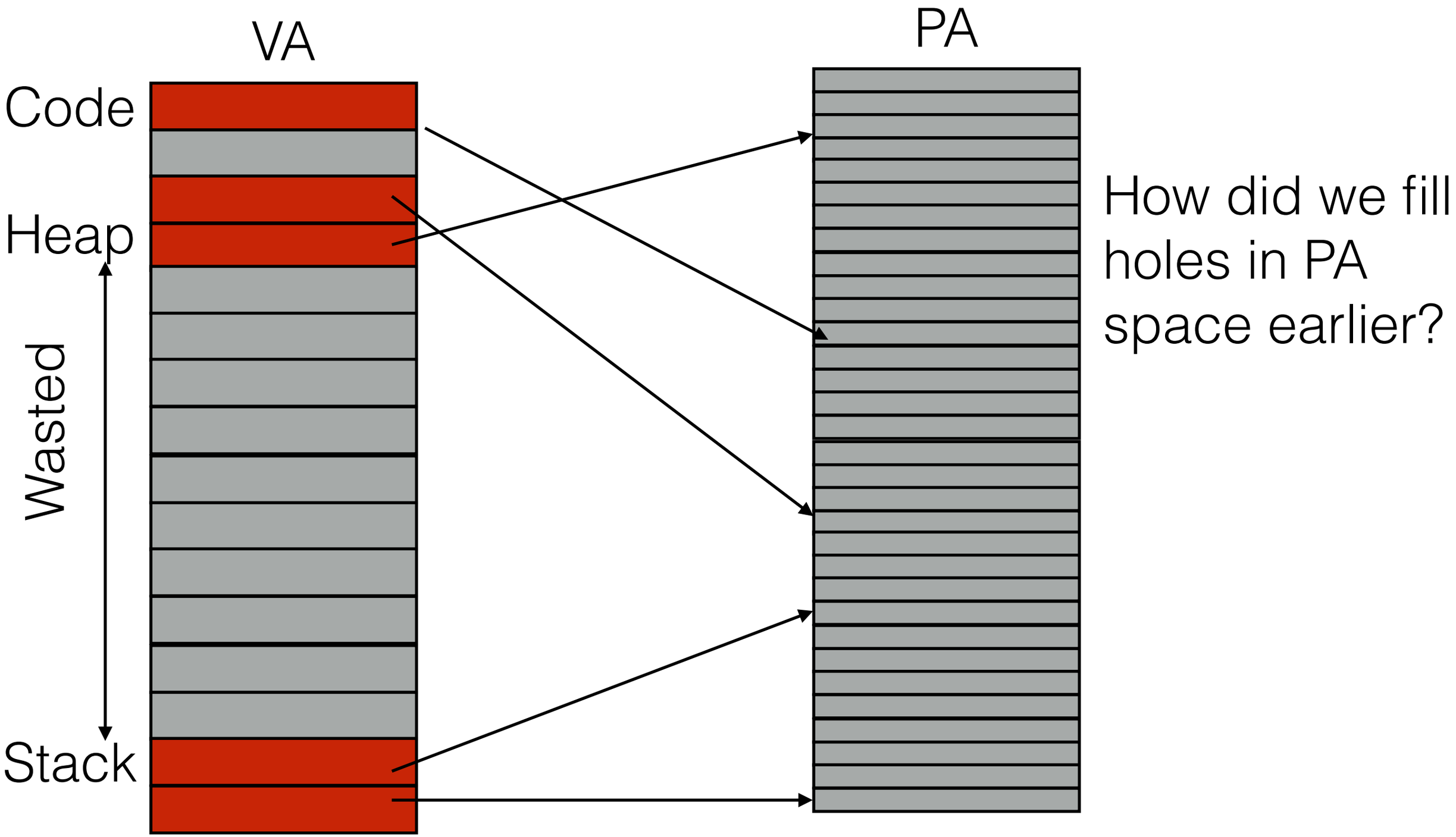
Reducing Memory Overheads of Paging - Segmentation + PT

- Pros:
  - Leads to memory saving (Large gaps between segments)
- Cons:
  - Uses segmentation
  - Assumes certain usage pattern of address space
  - Sparsely used segments (sub-segment internal fragmentation) have same space waste issue
    - How to address this?
      - LinkedList! Getting complex now.
    - Variable size page tables —> Can lead to fragmentation

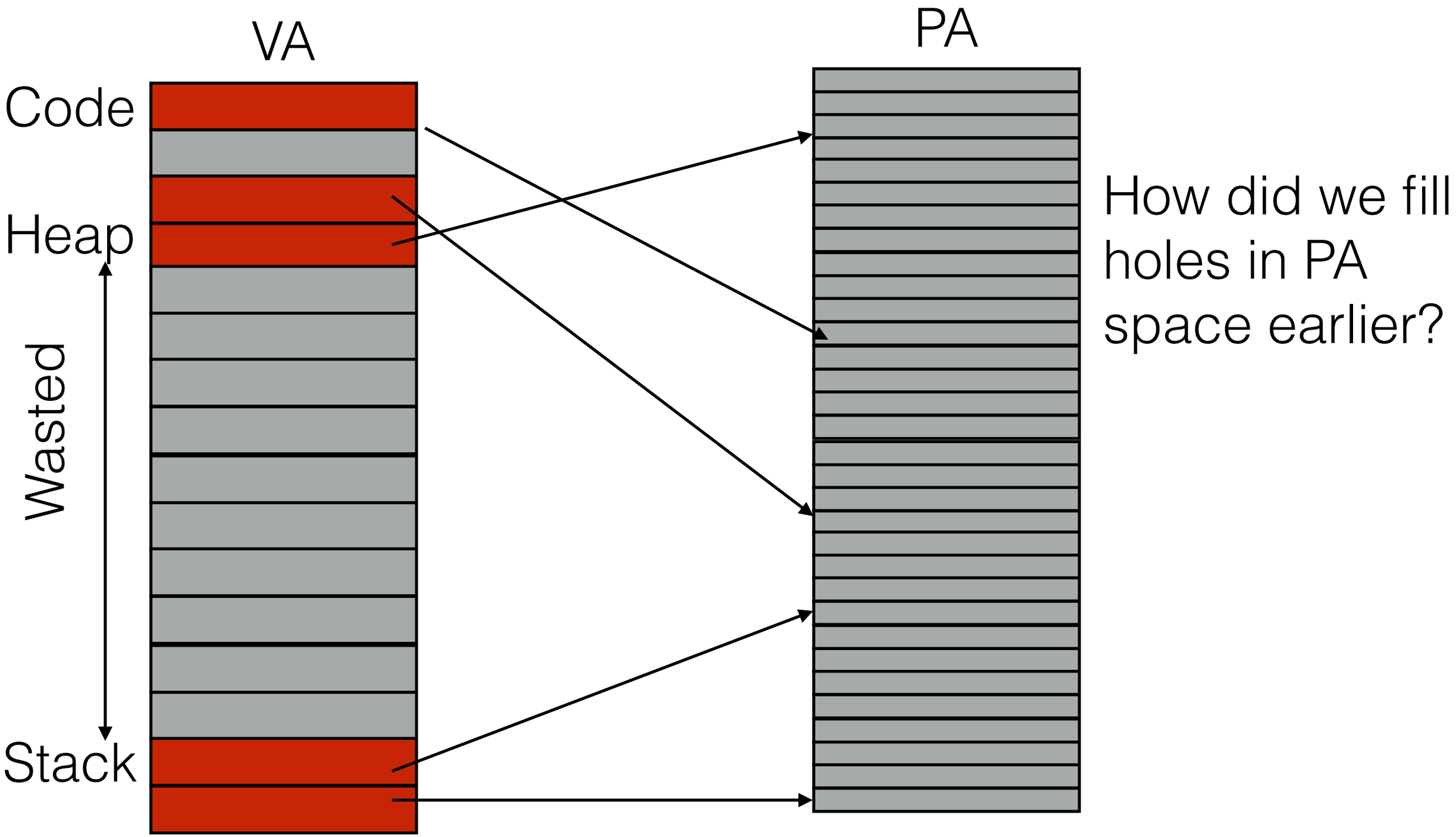
Reducing Memory Overheads of Paging



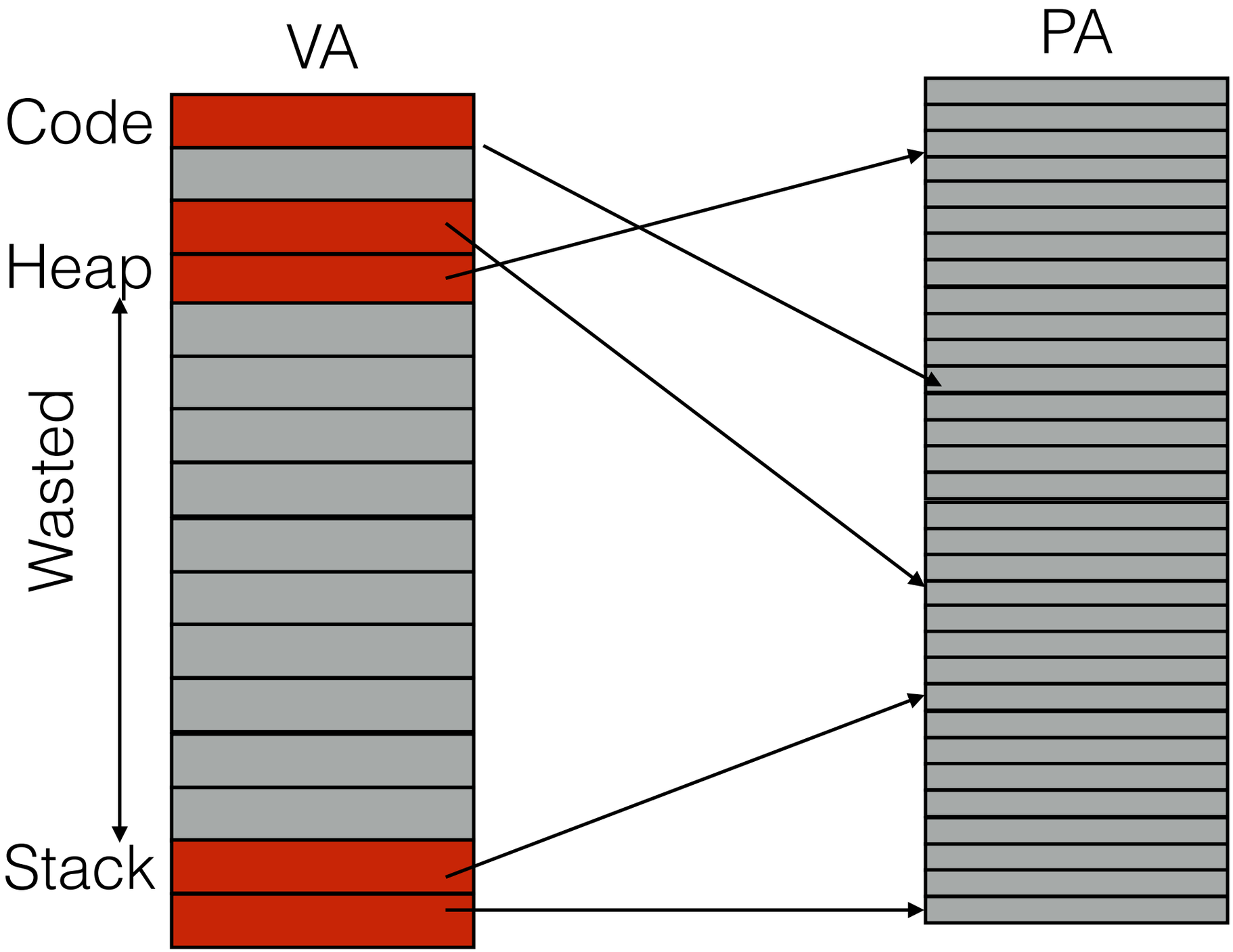
Reducing Memory Overheads of Paging



Reducing Memory Overheads of Paging



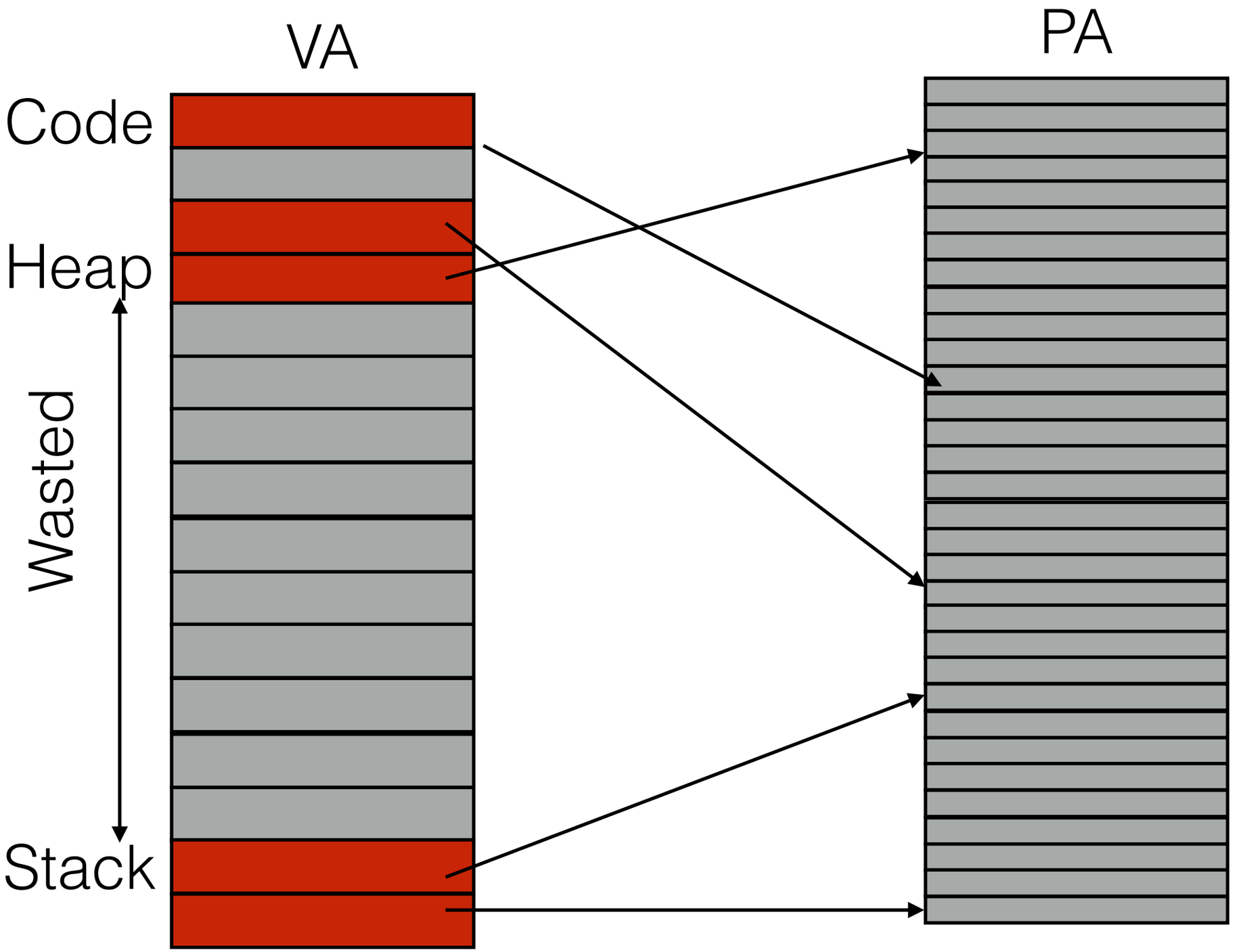
Reducing Memory Overheads of Paging



How did we fill holes in PA space earlier?

1. Segmentation

Reducing Memory Overheads of Paging



How did we fill holes in PA space earlier?

1. Segmentation
2. **Paging**

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging)

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging)

Idea: break PT itself into pages

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging)

Idea: break PT itself into pages

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging)

Idea: break PT itself into pages

- A Page Directory refers to pieces

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging)

Idea: break PT itself into pages

- A Page Directory refers to pieces
- Only have pieces with >0 valid entries

Reducing Memory Overheads of Paging - Segmentation + PT

	PFN	Valid	…
PFN = 200	10	1	..
	-	0	
	-	0	
	-	0	
PFN = 201	23	1	
	-	0	
	-	0	
PFN = 202	-	0	
	-	0	
	-	0	
	-	0	
	-	0	
PFN = 203	-	0	
	-	0	
	28	1	
	4	1	

Total entries = 16

Reducing Memory Overheads of Paging - Segmentation + PT

	PFN	Valid	…
PFN = 200	10	1	..
	-	0	
	-	0	
	-	0	
PFN = 201	23	1	
	-	0	
	-	0	
PFN = 202	-	0	
	-	0	
	-	0	
	-	0	
	-	0	
PFN = 203	-	0	
	-	0	
	28	1	
	4	1	

Total entries = 16

Reducing Memory Overheads of Paging - Segmentation + PT

	PFN	Valid	…
PFN = 200	10	1	..
	-	0	
	-	0	
	-	0	
PFN = 201	23	1	
	-	0	
	-	0	
PFN = 202	-	0	
	-	0	
	-	0	
	-	0	
	-	0	
PFN = 203	-	0	
	-	0	
	28	1	
	4	1	

Total entries = 16

PFN	Valid	…
10	1	..
-	0	
-	0	
23	1	…

Reducing Memory Overheads of Paging - Segmentation + PT

PFN = 200

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	

PFN = 201

23	1	
-	0	
-	0	

PFN = 202

-	0	
-	0	
-	0	
-	0	

PFN = 203

-	0	
-	0	
28	1	
4	1	

Total entries = 16

PFN	Valid	…
10	1	..
-	0	
-	0	
23	1	…

PFN	Valid	…
-	0	..
-	0	
-	0	
-	0	…

Reducing Memory Overheads of Paging - Segmentation + PT

PFN = 200

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	

PFN = 201

23	1	
-	0	
-	0	

PFN = 202

-	0	
-	0	
-	0	
-	0	

PFN = 203

-	0	
-	0	
28	1	
4	1	

Total entries = 16

PFN	Valid	…
10	1	..
-	0	
-	0	
23	1	…

PFN	Valid	…
-	0	..
-	0	
-	0	
-	0	…

PFN	Valid	…
-	0	..
-	0	
-	0	
-	0	…

Reducing Memory Overheads of Paging - Segmentation + PT

PFN = 200

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	

PFN = 201

23	1	
-	0	
-	0	
-	0	

PFN = 202

-	0	
-	0	
-	0	
-	0	

PFN = 203

-	0	
-	0	
28	1	
4	1	

Total entries = 16

PFN	Valid	…
10	1	..
-	0	
-	0	
23	1	…

PFN	Valid	…
-	0	..
-	0	
-	0	
-	0	…

PFN	Valid	…
-	0	..
-	0	
-	0	
-	0	…

PFN	Valid	…
-	0	..
-	0	
28	1	
4	1	…

Reducing Memory Overheads of Paging - Segmentation + PT

PFN = 200

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	

PFN = 201

23	1	
-	0	
-	0	

PFN = 202

-	0	
-	0	
-	0	
-	0	

PFN = 203

-	0	
-	0	
28	1	
4	1	

Total entries = 16

PFN	Valid	…
201	1	..
202	0	
203	0	
204	1	…

PFN	Valid	…
10	1	..
-	0	
-	0	
23	1	…

PFN	Valid	…
-	0	..
-	0	
-	0	
-	0	…

PFN	Valid	…
-	0	..
-	0	
28	1	
4	1	…

Reducing Memory Overheads of Paging - Segmentation + PT

PFN = 200

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	…
-	0	..
-	0	
-	0	
-	0	…
-	0	..
-	0	
-	0	
-	0	…
-	0	..
-	0	
28	1	
4	1	…

PFN = 201

PFN	Valid	…
201	1	..
202	0	
203	0	
204	1	…

PFN = 202

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
-	0	
23	1	…
-	0	..
-	0	
-	0	
-	0	…
-	0	..
-	0	
-	0	
-	0	…
-	0	..
-	0	
28	1	
4	1	…

PFN = 203

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	…
-	0	..
-	0	
-	0	
-	0	…
-	0	..
-	0	
-	0	
-	0	…
-	0	..
-	0	
28	1	
4	1	…

Total entries = 16

Reducing Memory Overheads of Paging - Segmentation + PT

PFN = 200

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	

PFN = 201

PFN	Valid	…
23	1	
-	0	
-	0	
-	0	

PFN = 202

PFN	Valid	…
-	0	
-	0	
-	0	
-	0	

PFN = 203

PFN	Valid	…
-	0	
-	0	
28	1	
4	1	

Total entries = 16

PFN = 200

PFN	Valid	…
201	1	..
202	0	
203	0	
204	1	…

PFN = 201

PFN	Valid	…
10	1	..
-	0	
-	0	
23	1	…

PFN	Valid	…
-	0	..
-	0	
-	0	
-	0	…

PFN	Valid	…
-	0	..
-	0	
-	0	
-	0	…

PFN	Valid	…
-	0	..
-	0	
28	1	
4	1	…

Reducing Memory Overheads of Paging - Segmentation + PT

PFN = 200

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	

PFN = 201

PFN	Valid	…
23	1	
-	0	
-	0	
-	0	

PFN = 202

PFN	Valid	…
-	0	
-	0	
-	0	
-	0	

PFN = 203

PFN	Valid	…
-	0	
-	0	
28	1	
4	1	

Total entries = 16

PFN = 200

PFN	Valid	…
201	1	..
202	0	
203	0	
204	1	…

PFN = 201

PFN	Valid	…
10	1	..
-	0	
-	0	
23	1	…

PFN = 202

PFN	Valid	…
-	0	..
-	0	
-	0	
-	0	…

PFN	Valid	…
-	0	..
-	0	
-	0	
-	0	…

PFN	Valid	…
-	0	..
-	0	
28	1	
4	1	…

Reducing Memory Overheads of Paging - Segmentation + PT

PFN = 200

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	

PFN = 201

PFN	Valid	…
23	1	
-	0	
-	0	
-	0	

PFN = 202

PFN	Valid	…
-	0	
-	0	
-	0	
-	0	

PFN = 203

PFN	Valid	…
-	0	
-	0	
28	1	
4	1	

Total entries = 16

PFN = 200

PFN	Valid	…
201	1	..
202	0	
203	0	
204	1	…

PFN = 201

PFN	Valid	…
10	1	..
-	0	
-	0	
23	1	…

PFN = 202

PFN	Valid	…
-	0	..
-	0	
-	0	
-	0	…

PFN = 203

PFN	Valid	…
-	0	..
-	0	
-	0	
-	0	…

PFN	Valid	…
-	0	..
-	0	
28	1	
4	1	…

Reducing Memory Overheads of Paging - Segmentation + PT

PFN = 200

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	

PFN = 201

PFN	Valid	…
23	1	
-	0	
-	0	
-	0	

PFN = 202

PFN	Valid	…
-	0	
-	0	
-	0	
-	0	

PFN = 203

PFN	Valid	…
-	0	
-	0	
28	1	
4	1	

Total entries = 16

PFN = 200

PFN	Valid	…
201	1	..
202	0	
203	0	
204	1	…

PFN = 201

PFN	Valid	…
10	1	..
-	0	
-	0	
23	1	…

PFN = 202

PFN	Valid	…
-	0	..
-	0	
-	0	
-	0	…

PFN = 203

PFN	Valid	…
-	0	..
-	0	
-	0	
-	0	…

PFN = 204

PFN	Valid	…
-	0	..
-	0	
28	1	
4	1	…

Reducing Memory Overheads of Paging - Segmentation + PT

PFN = 200

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	

PFN = 201

PFN	Valid	…
23	1	
-	0	
-	0	
-	0	

PFN = 202

PFN	Valid	…
-	0	
-	0	
-	0	
-	0	

PFN = 203

PFN	Valid	…
-	0	
-	0	
28	1	
4	1	

Total entries = 16

PFN = 200

PFN	Valid	…
201	1	..
202	0	
203	0	
204	1	…

PFN = 201

PFN	Valid	…
10	1	..
-	0	
-	0	
23	1	…

PFN = 202

PFN	Valid	…
-	0	..
-	0	
-	0	
-	0	…

PFN = 203

PFN	Valid	…
-	0	..
-	0	
-	0	
-	0	…

PFN = 204

PFN	Valid	…
-	0	..
-	0	
28	1	
4	1	…

Reducing Memory Overheads of Paging - Segmentation + PT

PFN = 200

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	

PFN = 201

PFN	Valid	…
23	1	
-	0	
-	0	
-	0	

PFN = 202

PFN	Valid	…
-	0	
-	0	
-	0	
-	0	

PFN = 203

PFN	Valid	…
-	0	
-	0	
28	1	
4	1	

Total entries = 16

PFN = 200

PFN	Valid	…
201	1	..
202	0	
203	0	
204	1	…

PFN = 201

PFN	Valid	…
10	1	..
-	0	
-	0	
23	1	…

PFN = 202

PFN	Valid	…
-	0	..
-	0	
-	0	
-	0	…

PFN = 203

PFN	Valid	…
-	0	..
-	0	
-	0	
-	0	…

PFN = 204

PFN	Valid	…
-	0	..
-	0	
28	1	
4	1	…

Reducing Memory Overheads of Paging - Segmentation + PT

PFN = 200

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Total entries = 16

PFN = 200

PFN	Valid	…
201	1	..
202	0	
203	0	
204	1	…

PFN = 201

PFN	Valid	…
10	1	..
-	0	
-	0	
23	1	…

PFN = 202

PFN	Valid	…
-	0	..
-	0	
-	0	
-	0	…

PFN = 203

PFN	Valid	…
-	0	..
-	0	
-	0	
-	0	…

PFN = 204

PFN	Valid	…
-	0	..
-	0	
28	1	
4	1	…

Reducing Memory Overheads of Paging - Segmentation + PT

PFN = 200

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Total entries = 16

PFN = 200

PFN	Valid	…
201	1	..
202	0	
203	0	
204	1	…

PFN = 201

PFN	Valid	…
10	1	..
-	0	
-	0	
23	1	…

PFN = 202

PFN	Valid	…
-	0	..
-	0	
-	0	
-	0	…

PFN = 203

PFN	Valid	…
-	0	..
-	0	
-	0	
-	0	…

PFN = 204

PFN	Valid	…
-	0	..
-	0	
28	1	
4	1	…

Reducing Memory Overheads of Paging - Segmentation + PT

PFN = 200

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Total entries = 16

PFN = 200

PFN	Valid	…
201	1	..
202	0	
203	0	
204	1	…

Total entries = 16 + 4

PFN = 201

PFN	Valid	…
10	1	..
-	0	
-	0	
23	1	…

PFN = 202

PFN	Valid	…
-	0	..
-	0	
-	0	
-	0	…

PFN = 203

PFN	Valid	…
-	0	..
-	0	
-	0	
-	0	…

PFN = 204

PFN	Valid	…
-	0	..
-	0	
28	1	
4	1	…

Reducing Memory Overheads of Paging - Segmentation + PT

PFN = 200

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Total entries = 16

PFN = 200

PFN	Valid	…
201	1	..
202	0	
203	0	
204	1	…

Total entries = 16 + 4

PFN = 201

PFN	Valid	…
10	1	..
-	0	
-	0	
23	1	…

PFN = 202

PFN	Valid	…
-	0	..
-	0	
-	0	
-	0	…

PFN = 203

PFN	Valid	…
-	0	..
-	0	
-	0	
-	0	…

PFN = 204

PFN	Valid	…
-	0	..
-	0	
28	1	
4	1	…

Reducing Memory Overheads of Paging - Segmentation + PT

PFN = 200

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	

PFN = 201

PFN	Valid	…
23	1	
-	0	
-	0	
-	0	

PFN = 202

PFN	Valid	…
-	0	
-	0	
-	0	
-	0	

PFN = 203

PFN	Valid	…
-	0	
-	0	
28	1	
4	1	

Total entries = 16

PFN = 200

PFN	Valid	…
201	1	..
202	0	
203	0	
204	1	…

Total entries = 16 + 4

PFN = 201

PFN	Valid	…
10	1	..
-	0	
-	0	
23	1	…

PFN = 202

PFN	Valid	…
-	0	..
-	0	
-	0	
-	0	…

PFN = 203

PFN	Valid	…
-	0	..
-	0	
-	0	
-	0	…

PFN = 204

PFN	Valid	…
-	0	..
-	0	
28	1	
4	1	…

Reducing Memory Overheads of Paging - Segmentation + PT

PFN = 200

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	

PFN = 201

PFN	Valid	…
23	1	
-	0	
-	0	
-	0	

PFN = 202

PFN	Valid	…
-	0	
-	0	
-	0	
-	0	

PFN = 203

PFN	Valid	…
-	0	
-	0	
28	1	
4	1	

Total entries = 16

PFN = 200

PFN	Valid	…
201	1	..
202	0	
203	0	
204	1	…

Total entries = 16 + 4

PFN = 201

PFN	Valid	…
10	1	..
-	0	
-	0	
23	1	…

PFN = 202

PFN = 203

PFN	Valid	…
-	0	..
-	0	
-	0	
-	0	…

PFN = 204

PFN	Valid	…
-	0	..
-	0	
28	1	
4	1	…

Reducing Memory Overheads of Paging - Segmentation + PT

PFN = 200

PFN = 201

PFN = 202

PFN = 203

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Total entries = 16

PFN = 200

PFN	Valid	…
201	1	..
202	0	
203	0	
204	1	…

Total entries = 16 + 4

PFN = 201

PFN	Valid	…
10	1	..
-	0	
-	0	
23	1	…

PFN = 202

PFN = 203

PFN = 204

PFN	Valid	…
-	0	..
-	0	
28	1	
4	1	…

Reducing Memory Overheads of Paging - Segmentation + PT

PFN = 200

PFN = 201

PFN = 202

PFN = 203

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Total entries = 16

PFN = 200

PFN	Valid	…
201	1	..
202	0	
203	0	
204	1	…

Total entries = 16 + 4

PFN = 201

PFN	Valid	…
10	1	..
-	0	
-	0	
23	1	…

PFN = 203

PFN = 204

PFN	Valid	…
-	0	..
-	0	
28	1	
4	1	…

Reducing Memory Overheads of Paging - Segmentation + PT

PFN = 200

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	

PFN = 201

PFN	Valid	…
23	1	
-	0	
-	0	
-	0	

PFN = 202

PFN	Valid	…
-	0	
-	0	
-	0	
-	0	

PFN = 203

PFN	Valid	…
-	0	
-	0	
28	1	
4	1	

Total entries = 16

PFN = 200

PFN	Valid	…
201	1	..
202	0	
203	0	
204	1	…

Total entries = 16 + 4

PFN = 201

PFN	Valid	…
10	1	..
-	0	
-	0	
23	1	…

PFN = 204

PFN	Valid	…
-	0	..
-	0	
28	1	
4	1	…

Reducing Memory Overheads of Paging - Segmentation + PT

PFN = 200

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	

PFN = 201

PFN	Valid	…
23	1	
-	0	
-	0	
-	0	

PFN = 202

PFN	Valid	…
-	0	
-	0	
-	0	
-	0	

PFN = 203

PFN	Valid	…
-	0	
-	0	
28	1	
4	1	

Total entries = 16

PFN = 200

PFN	Valid	…
201	1	..
202	0	
203	0	
204	1	…

PFN = 201

PFN	Valid	…
10	1	..
-	0	
-	0	
23	1	…

PFN = 204

PFN	Valid	…
-	0	..
-	0	
28	1	
4	1	…

Reducing Memory Overheads of Paging - Segmentation + PT

PFN = 200

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	

PFN = 201

PFN	Valid	…
23	1	
-	0	
-	0	
-	0	

PFN = 202

PFN	Valid	…
-	0	
-	0	
-	0	
-	0	

PFN = 203

PFN	Valid	…
-	0	
-	0	
28	1	
4	1	

Total entries = 16

PFN = 200

PFN	Valid	…
201	1	..
202	0	
203	0	
204	1	…

Total entries = 16 + 4 - 8

PFN = 201

PFN	Valid	…
10	1	..
-	0	
-	0	
23	1	…

PFN = 204

PFN	Valid	…
-	0	..
-	0	
28	1	
4	1	…

Reducing Memory Overheads of Paging - Segmentation + PT

PFN = 200

PFN = 201

PFN = 202

PFN = 203

PFN	Valid	…
10	1	..
-	0	
-	0	
-	0	
23	1	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
-	0	
28	1	
4	1	

Total entries = 16

Page Directory Entry (PDE)

PFN = 200

PFN	Valid	…
201	1	..
202	0	
203	0	
204	1	…

Total entries = 16 + 4 - 8

PFN = 201

PFN	Valid	…
10	1	..
-	0	
-	0	
23	1	…

PFN = 204

PFN	Valid	…
-	0	..
-	0	
28	1	
4	1	…

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging)

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging)

- Multi-level paging allocates memory proportional to requirement

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging)

- Multi-level paging allocates memory proportional to requirement
  - Sparse address spaces well supported

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging)

- Multi-level paging allocates memory proportional to requirement
  - Sparse address spaces well supported
- Previously, we needed 4 MB contiguous space for PT memory

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging)

- Multi-level paging allocates memory proportional to requirement
  - Sparse address spaces well supported
- Previously, we needed 4 MB contiguous space for PT memory
  - Now?

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging)

- Multi-level paging allocates memory proportional to requirement
  - Sparse address spaces well supported
- Previously, we needed 4 MB contiguous space for PT memory
  - Now?
    - Can place Page Tables anywhere in memory with multi-level paging…

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

- Address space = 16 KB

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

- Address space = 16 KB
  - Bits needed = 14 bits

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

- Address space = 16 KB
  - Bits needed = 14 bits
- Page size = 64 bytes (Offset)

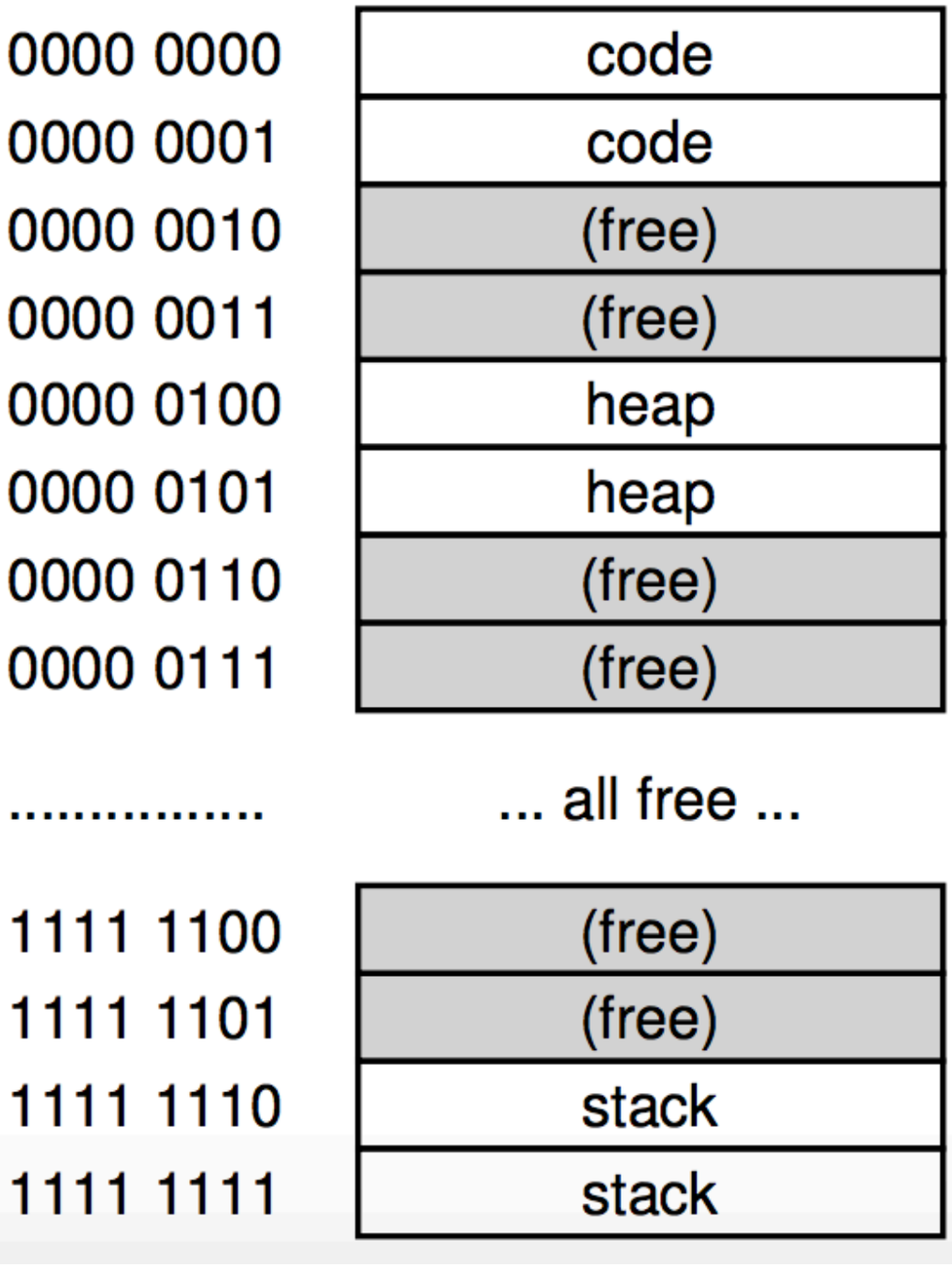
Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

- Address space = 16 KB
  - Bits needed = 14 bits
- Page size = 64 bytes (Offset)
  - 6 bits

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

- Address space = 16 KB
  - Bits needed = 14 bits
- Page size = 64 bytes (Offset)
  - 6 bits
- # Pages = 2^(14-6) = 256 (VPN)

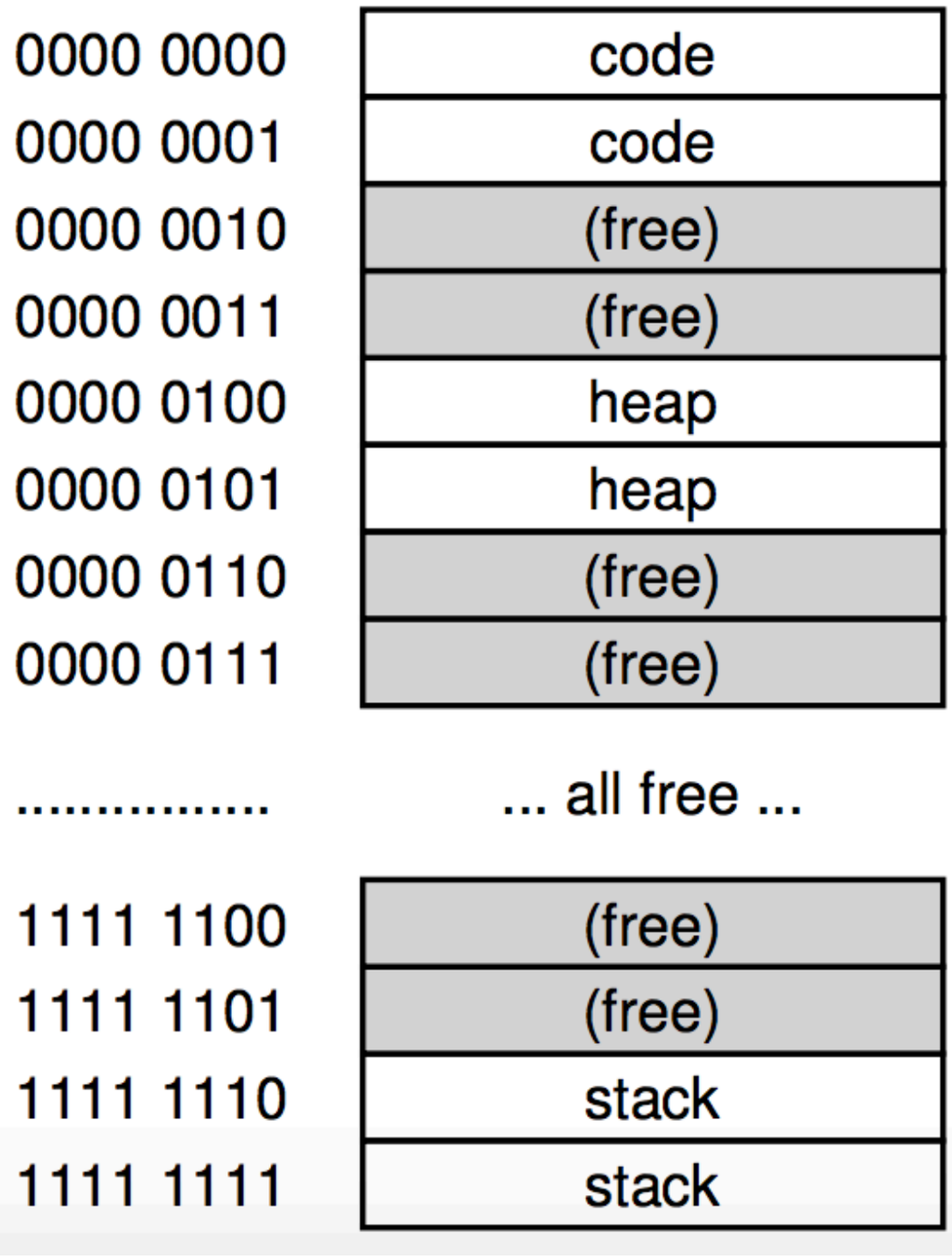
Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example



Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

Page Table

VPN	PFN	Valid	…
0	10	1	..
1	23	1	
	-	0	
	-	0	
4	80	1	
5	59	1	
…	..	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
254	55	1	
255	45	1	



Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

Page Table

VPN	PFN	Valid	…
0	10	1	..
1	23	1	
	-	0	
	-	0	
4	80	1	
5	59	1	
…	..	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
254	55	1	
255	45	1	

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

Page Table

VPN	PFN	Valid	…
0	10	1	..
1	23	1	
	-	0	
	-	0	
4	80	1	
5	59	1	
…	..	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
254	55	1	
255	45	1	

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

Page Table

VPN	PFN	Valid	…
0	10	1	..
1	23	1	
	-	0	
	-	0	
4	80	1	
5	59	1	
…	..	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
254	55	1	
255	45	1	

PTE = 4 bytes

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

Page Table

PT size = 256*4 bytes = 1 KB

VPN	PFN	Valid	…
0	10	1	..
1	23	1	
	-	0	
	-	0	
4	80	1	
5	59	1	
…	..	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
254	55	1	
255	45	1	

PTE = 4 bytes

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

Page Table

PT size = 256*4 bytes = 1 KB

VPN	PFN	Valid	…
0	10	1	..
1	23	1	
	-	0	
	-	0	
4	80	1	
5	59	1	
…	..	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
254	55	1	
255	45	1	

PTE = 4 bytes

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

Page Table

VPN	PFN	Valid	…
0	10	1	..
1	23	1	
	-	0	
	-	0	
4	80	1	
5	59	1	
…	..	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
254	55	1	
255	45	1	

PTE = 4 bytes

PT size = 256*4 bytes = 1 KB

Page size = 64 bytes = 16 PTE

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

Page Table

VPN	PFN	Valid	…
0	10	1	..
1	23	1	
	-	0	
	-	0	
4	80	1	
5	59	1	
…	..	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
254	55	1	
255	45	1	

PT size = 256*4 bytes = 1 KB

PTE = 4 bytes

Page size = 64 bytes = 16 PTE

Total PT fits in 256/16 = 16 pages

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

Page Table

VPN	PFN	Valid	…
0	10	1	..
1	23	1	
	-	0	
	-	0	
4	80	1	
5	59	1	
…	..	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
254	55	1	
255	45	1	

Total PT fits in 256/16 = 16 pages

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

Page Table

VPN	PFN	Valid	…
0	10	1	..
1	23	1	
	-	0	
	-	0	
4	80	1	
5	59	1	
…	..	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
254	55	1	
255	45	1	

Total PT fits in 256/16 = 16 pages

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

Page Table

VPN	PFN	Valid	…
0	10	1	..
1	23	1	
	-	0	
	-	0	
4	80	1	
5	59	1	
…	..	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
254	55	1	
255	45	1	

PFN = 100

Total PT fits in 256/16 = 16 pages

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

Page Table

VPN	PFN	Valid	…
0	10	1	..
1	23	1	
	-	0	
	-	0	
4	80	1	
5	59	1	
…	..	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
254	55	1	
255	45	1	

PFN = 100

PFN = 101

Total PT fits in 256/16 = 16 pages

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

PFN	Valid	…
100	1	..
-	0	
-	0	
-	0	
-	0	
-	0	
..	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
-	0	
101	1	

Page Table

VPN	PFN	Valid	…
0	10	1	..
1	23	1	
	-	0	
	-	0	
4	80	1	
5	59	1	
…	..	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
254	55	1	
255	45	1	

PFN = 100

Total PT fits in 256/16 = 16 pages

PFN = 101

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

Page Directory

PFN	Valid	…
100	1	..
-	0	
-	0	
-	0	
-	0	
-	0	
..	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
-	0	
101	1	

Page Table

VPN	PFN	Valid	…
0	10	1	..
1	23	1	
	-	0	
	-	0	
4	80	1	
5	59	1	
…	..	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
254	55	1	
255	45	1	

→ PFN = 100

→ PFN = 101

Total PT fits in 256/16 = 16 pages

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

PFN	Valid	…
100	1	..
-	0	
-	0	
-	0	
-	0	
-	0	
..	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
-	0	
101	1	

PFN	Valid
10	1
23	1
-	0
-	0
80	1
59	1
..	0
…	0
…	0

PFN	Valid
-	0
-	0
-	0
-	0
-	0
-	0
..	0
55	1
45	1

Page Table

VPN	PFN	Valid	…
0	10	1	..
1	23	1	
	-	0	
	-	0	
4	80	1	
5	59	1	
…	..	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
254	55	1	
255	45	1	

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

Page Directory

PFN	Valid	…
100	1	..
-	0	
-	0	
-	0	
-	0	
-	0	
..	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
-	0	
101	1	

PFN	Valid
10	1
23	1
-	0
-	0
80	1
59	1
..	0
…	0
…	0

PFN	Valid
-	0
-	0
-	0
-	0
-	0
-	0
..	0
55	1
45	1

Page Table

VPN	PFN	Valid	…
0	10	1	..
1	23	1	
	-	0	
	-	0	
4	80	1	
5	59	1	
…	..	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
254	55	1	
255	45	1	

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

Page Directory

PFN	Valid	…
100	1	..
-	0	
-	0	
-	0	
-	0	
-	0	
..	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
-	0	
101	1	

PFN = 100

PFN	Valid
10	1
23	1
-	0
-	0
80	1
59	1
..	0
…	0
…	0

PFN	Valid
-	0
-	0
-	0
-	0
-	0
-	0
..	0
55	1
45	1

Page Table

VPN	PFN	Valid	…
0	10	1	..
1	23	1	
	-	0	
	-	0	
4	80	1	
5	59	1	
…	..	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
254	55	1	
255	45	1	

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

Page Directory

PFN	Valid	…
100	1	..
-	0	
-	0	
-	0	
-	0	
-	0	
..	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
-	0	
101	1	

PFN = 100

PFN	Valid
10	1
23	1
-	0
-	0
80	1
59	1
..	0
…	0
…	0

PFN = 101

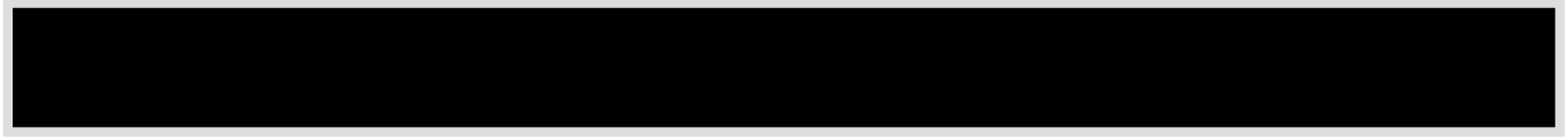
PFN	Valid
-	0
-	0
-	0
-	0
-	0
-	0
..	0
55	1
45	1

Page Table

VPN	PFN	Valid	…
0	10	1	..
1	23	1	
	-	0	
	-	0	
4	80	1	
5	59	1	
…	..	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
…	…	0	
254	55	1	
255	45	1	

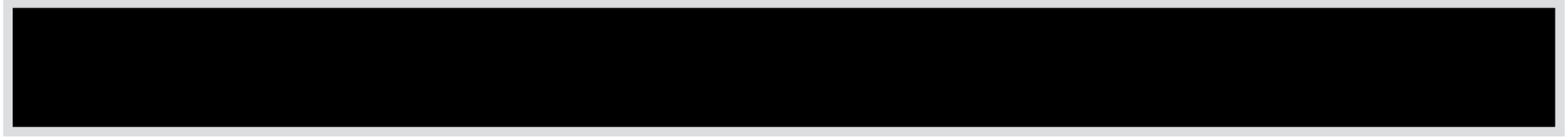
Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

14 bit VA space



Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

14 bit VA space

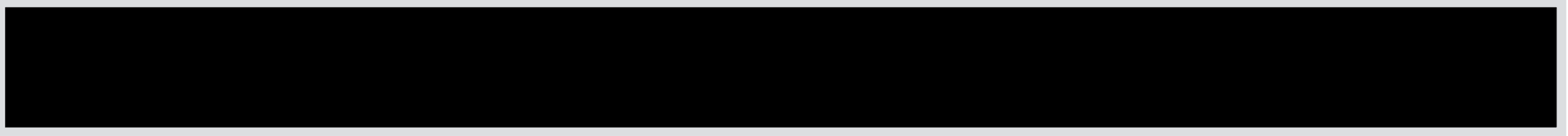


8 bit VPN

6 bit Offset

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

14 bit VA space



8 bit VPN

6 bit Offset

4 bit PD Index

4 bit PT Index

6 bit Offset

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

Page Directory

PFN	Valid	…
100	1	..
-	0	
-	0	
-	0	
-	0	
-	0	
..	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
-	0	
101	1	

PFN = 100

PFN	Valid
10	1
23	1
-	0
-	0
80	1
59	1
..	0
…	0
…	0
…	0

PFN = 101

PFN	Valid
-	0
-	0
-	0
-	0
-	0
-	0
..	0
55	1
45	1

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

Page Directory

PFN	Valid	…
100	1	..
-	0	
-	0	
-	0	
-	0	
-	0	
..	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
-	0	
101	1	

PFN = 100

PFN	Valid
10	1
23	1
-	0
-	0
80	1
59	1
..	0
…	0
…	0
…	0

PFN = 101

PFN	Valid
-	0
-	0
-	0
-	0
-	0
-	0
..	0
55	1
45	1

- Translate 0x3F80 VA to PA

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

Page Directory

PFN	Valid	…
100	1	..
-	0	
-	0	
-	0	
-	0	
-	0	
..	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
-	0	
101	1	

PFN = 100

PFN	Valid
10	1
23	1
-	0
-	0
80	1
59	1
..	0
…	0
…	0

PFN = 101

PFN	Valid
-	0
-	0
-	0
-	0
-	0
-	0
..	0
55	1
45	1

- Translate 0x3F80 VA to PA
- 0x3F80 = (11)(1111)(1000)(0000)

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

Page Directory

PFN	Valid	…
100	1	..
-	0	
-	0	
-	0	
-	0	
-	0	
..	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
-	0	
101	1	

PFN = 100

PFN	Valid
10	1
23	1
-	0
-	0
80	1
59	1
..	0
…	0
…	0
…	0

PFN = 101

PFN	Valid
-	0
-	0
-	0
-	0
-	0
-	0
..	0
55	1
45	1

- Translate 0x3F80 VA to PA
- 0x3F80 = (11)(1111)(1000)(0000)
- **(11)(11**11)(1000)(0000) ->PD Index

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

Page Directory

PFN	Valid	…
100	1	..
-	0	
-	0	
-	0	
-	0	
-	0	
..	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
-	0	
101	1	

PFN = 100

PFN	Valid
10	1
23	1
-	0
-	0
80	1
59	1
..	0
…	0
…	0
…	0

PFN = 101

PFN	Valid
-	0
-	0
-	0
-	0
-	0
-	0
..	0
55	1
45	1

- Translate 0x3F80 VA to PA
- 0x3F80 = (11)(1111)(1000)(0000)
- **(11)(11**11)(1000)(0000) ->PD Index
- PD index = 1111 -> PFN = 101

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

Page Directory

PFN	Valid	…
100	1	..
-	0	
-	0	
-	0	
-	0	
-	0	
..	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
-	0	
101	1	

PFN = 100

PFN	Valid
10	1
23	1
-	0
-	0
80	1
59	1
..	0
…	0
…	0
…	0

PFN = 101

PFN	Valid
-	0
-	0
-	0
-	0
-	0
-	0
..	0
55	1
45	1

- Translate 0x3F80 VA to PA
- 0x3F80 = (11)(1111)(1000)(0000)
- **(11)(11**11)(1000)(0000) ->PD Index
- PD index = 1111 -> PFN = 101

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

Page Directory

PFN	Valid	…
100	1	..
-	0	
-	0	
-	0	
-	0	
-	0	
..	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
-	0	
101	1	

PFN = 100

PFN	Valid
10	1
23	1
-	0
-	0
80	1
59	1
..	0
…	0
…	0
…	0

PFN = 101

PFN	Valid
-	0
-	0
-	0
-	0
-	0
-	0
..	0
55	1
45	1

- Translate 0x3F80 VA to PA
- 0x3F80 = (11)(1111)(1000)(0000)
- **(11)(11**11)(1000)(0000) ->PD Index
- PD index = 1111 -> PFN = 101

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

Page Directory

PFN	Valid	…
100	1	..
-	0	
-	0	
-	0	
-	0	
-	0	
..	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
-	0	
101	1	

PFN = 100

PFN	Valid
10	1
23	1
-	0
-	0
80	1
59	1
..	0
…	0
…	0

PFN = 101

PFN	Valid
-	0
-	0
-	0
-	0
-	0
-	0
..	0
55	1
45	1

- Translate 0x3F80 VA to PA
- 0x3F80 = (11)(1111)(1000)(0000)
- **(11)(11**11)(1000)(0000) ->PD Index
- PD index = 1111 -> PFN = 101
- Next 4 bits = PT index = 1110 = 14 decimal —> last PTE in PFN = 101 —> PFN = 55

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

Page Directory

PFN	Valid	…
100	1	..
-	0	
-	0	
-	0	
-	0	
-	0	
..	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
-	0	
101	1	

PFN = 100

PFN	Valid
10	1
23	1
-	0
-	0
80	1
59	1
..	0
…	0
…	0

PFN = 101

PFN	Valid
-	0
-	0
-	0
-	0
-	0
-	0
..	0
55	1
45	1

- Translate 0x3F80 VA to PA
- 0x3F80 = (11)(1111)(1000)(0000)
- **(11)(11**11)(1000)(0000) ->PD Index
- PD index = 1111 -> PFN = 101
- Next 4 bits = PT index = 1110 = 14 decimal —> last PTE in PFN = 101 —> PFN = 55
- Offset = last 6 digits = 0

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

Page Directory

PFN	Valid	…
100	1	..
-	0	
-	0	
-	0	
-	0	
-	0	
..	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
-	0	
101	1	

PFN = 100

PFN	Valid
10	1
23	1
-	0
-	0
80	1
59	1
..	0
…	0
…	0

PFN = 101

PFN	Valid
-	0
-	0
-	0
-	0
-	0
-	0
..	0
55	1
45	1

- Translate 0x3F80 VA to PA
- 0x3F80 = (11)(1111)(1000)(0000)
- **(11)(11**11)(1000)(0000) ->PD Index
- PD index = 1111 -> PFN = 101
- Next 4 bits = PT index = 1110 = 14 decimal —> last PTE in PFN = 101 —> PFN = 55
- Offset = last 6 digits = 0
- PA = 55 <<SHIFT + OFFSET = 55<6 + 000000 = 0x0DC0

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

Page Directory

PFN	Valid	…
100	1	..
-	0	
-	0	
-	0	
-	0	
-	0	
..	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
-	0	
101	1	

PFN = 100

PFN	Valid
10	1
23	1
-	0
-	0
80	1
59	1
..	0
…	0
…	0

PFN = 101

PFN	Valid
-	0
-	0
-	0
-	0
-	0
-	0
..	0
55	1
45	1

- Translate 0x3F80 VA to PA
- 0x3F80 = (11)(1111)(1000)(0000)
- **(11)(11**11)(1000)(0000) ->PD Index
- PD index = 1111 -> PFN = 101
- Next 4 bits = PT index = 1110 = 14 decimal —> last PTE in PFN = 101 —> PFN = 55
- Offset = last 6 digits = 0
- PA = 55 <<SHIFT + OFFSET = 55<6 + 000000 = 0x0DC0

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

Page Directory

PFN	Valid	…
100	1	..
-	0	
-	0	
-	0	
-	0	
-	0	
..	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
-	0	
101	1	

PFN = 100

PFN	Valid
10	1
23	1
-	0
-	0
80	1
59	1
..	0
…	0
…	0

PFN = 101

PFN	Valid
-	0
-	0
-	0
-	0
-	0
-	0
..	0
55	1
45	1

- Translate 0x3F80 VA to PA
- 0x3F80 = (11)(1111)(1000)(0000)
- **(11)(11**11)(1000)(0000) ->PD Index
- PD index = 1111 -> PFN = 101
- Next 4 bits = PT index = 1110 = 14 decimal —> last PTE in PFN = 101 —> PFN = 55
- Offset = last 6 digits = 0
- PA = 55 <<SHIFT + OFFSET = 55<6 + 000000 = 0x0DC0

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

Page Directory

PFN	Valid	…
100	1	..
-	0	
-	0	
-	0	
-	0	
-	0	
..	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
-	0	
101	1	

PFN = 100

PFN	Valid
10	1
23	1
-	0
-	0
80	1
59	1
..	0
…	0
…	0

PFN = 101

PFN	Valid
-	0
-	0
-	0
-	0
-	0
-	0
..	0
55	1
45	1

- Translate 0x3F80 VA to PA
- 0x3F80 = (11)(1111)(1000)(0000)
- **(11)(11**11)(1000)(0000) ->PD Index
- PD index = 1111 -> PFN = 101
- Next 4 bits = PT index = 1110 = 14 decimal —> last PTE in PFN = 101 —> PFN = 55
- Offset = last 6 digits = 0
- PA = 55 <<SHIFT + OFFSET = 55<6 + 000000 = 0x0DC0

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example

Page Directory

PFN	Valid	…
100	1	..
-	0	
-	0	
-	0	
-	0	
-	0	
..	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
…	0	
-	0	
101	1	

PFN = 100

PFN	Valid
10	1
23	1
-	0
-	0
80	1
59	1
..	0
…	0
…	0

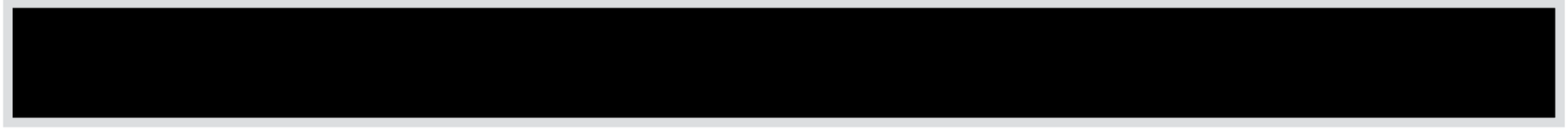
PFN = 101

PFN	Valid
-	0
-	0
-	0
-	0
-	0
-	0
..	0
55	1
45	1

- Translate 0x3F80 VA to PA
- 0x3F80 = (11)(1111)(1000)(0000)
- **(11)(11**11)(1000)(0000) ->PD Index
- PD index = 1111 -> PFN = 101
- Next 4 bits = PT index = 1110 = 14 decimal —> last PTE in PFN = 101 —> PFN = 55
- Offset = last 6 digits = 0
- PA = 55 <<SHIFT + OFFSET = 55<6 + 000000 = 0x0DC0

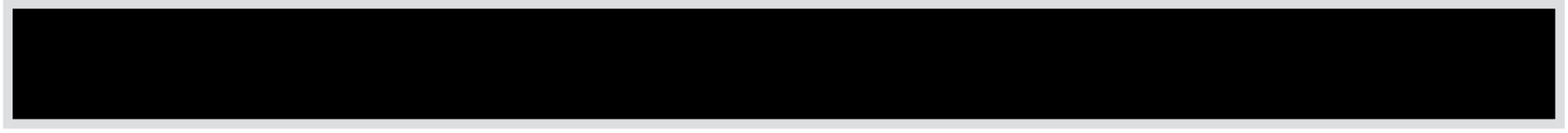
Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example 2

30 bit VA space



Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example 2

30 bit VA space



512 byte page, 4 byte PTE

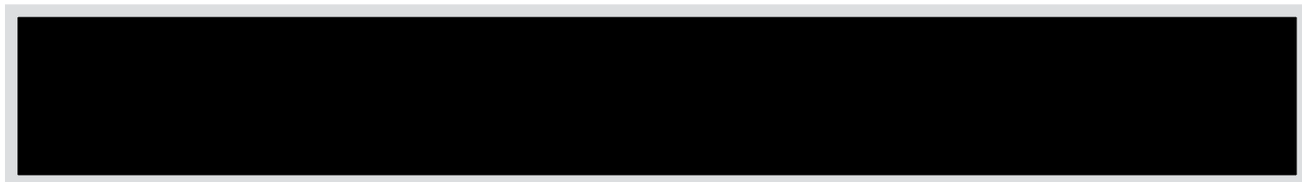
Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example 2

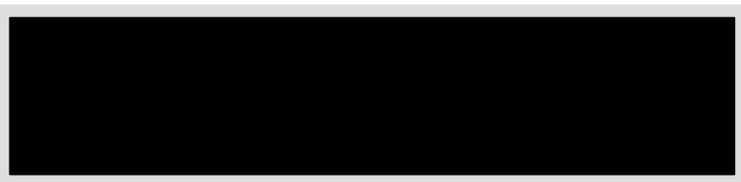
30 bit VA space

512 byte page, 4 byte PTE

21 bit VPN

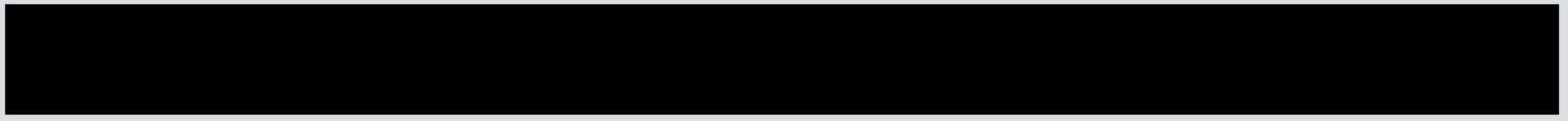
9 bit Offset





Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example 2

30 bit VA space



512 byte page, 4 byte PTE

21 bit VPN

9 bit Offset

14 bit PD Index

7 bit PT Index

6 bit Offset

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example 2

30 bit VA space

512 byte page, 4 byte PTE

21 bit VPN

9 bit Offset

128 PTE per page

14 bit PD Index

7 bit PT Index

6 bit Offset

Reducing Memory Overheads of Paging - PT + PT (Multi-level Paging) Example 2

30 bit VA space

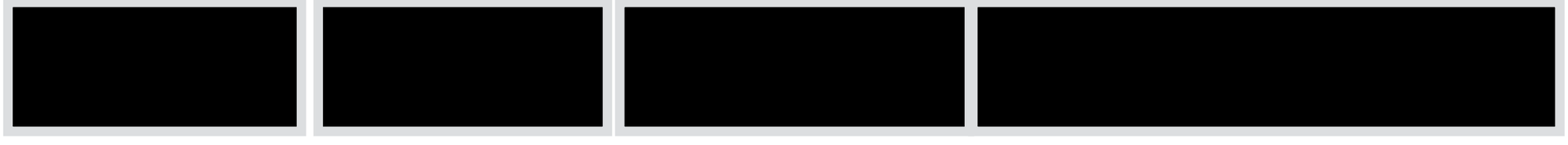
512 byte page, 4 byte PTE

21 bit VPN | 9 bit Offset

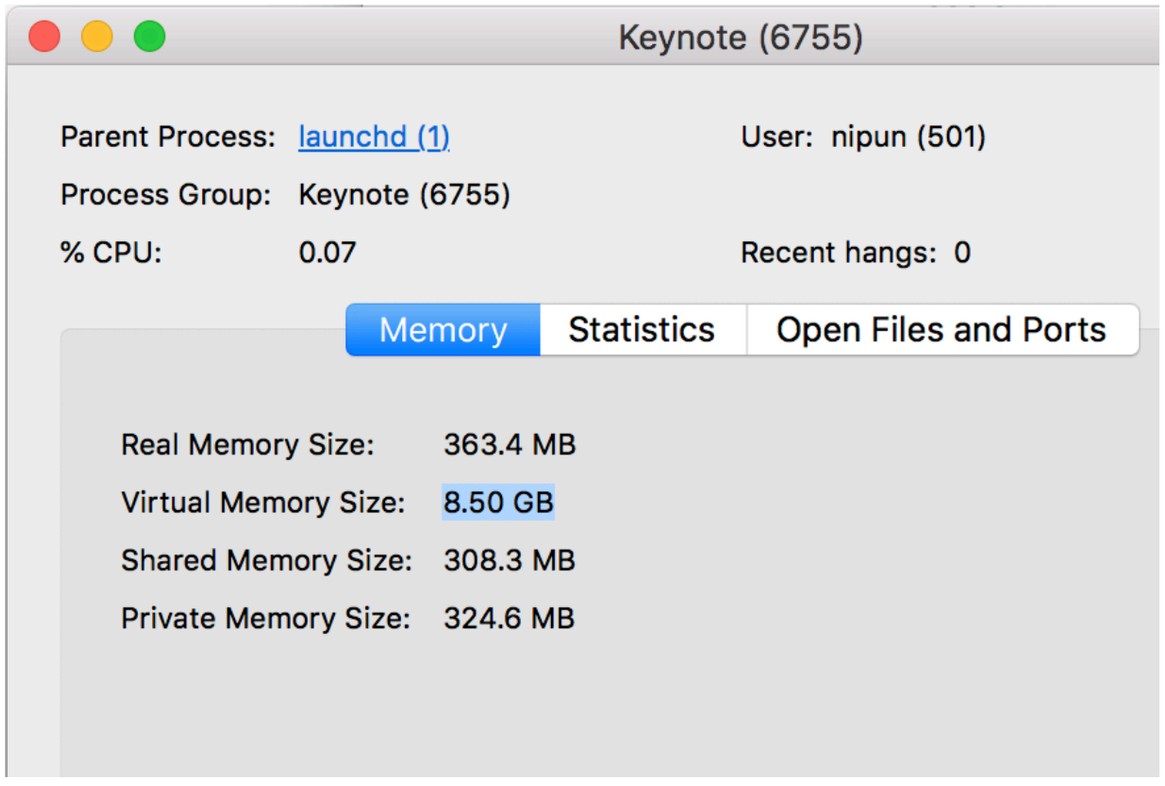
128 PTE per page

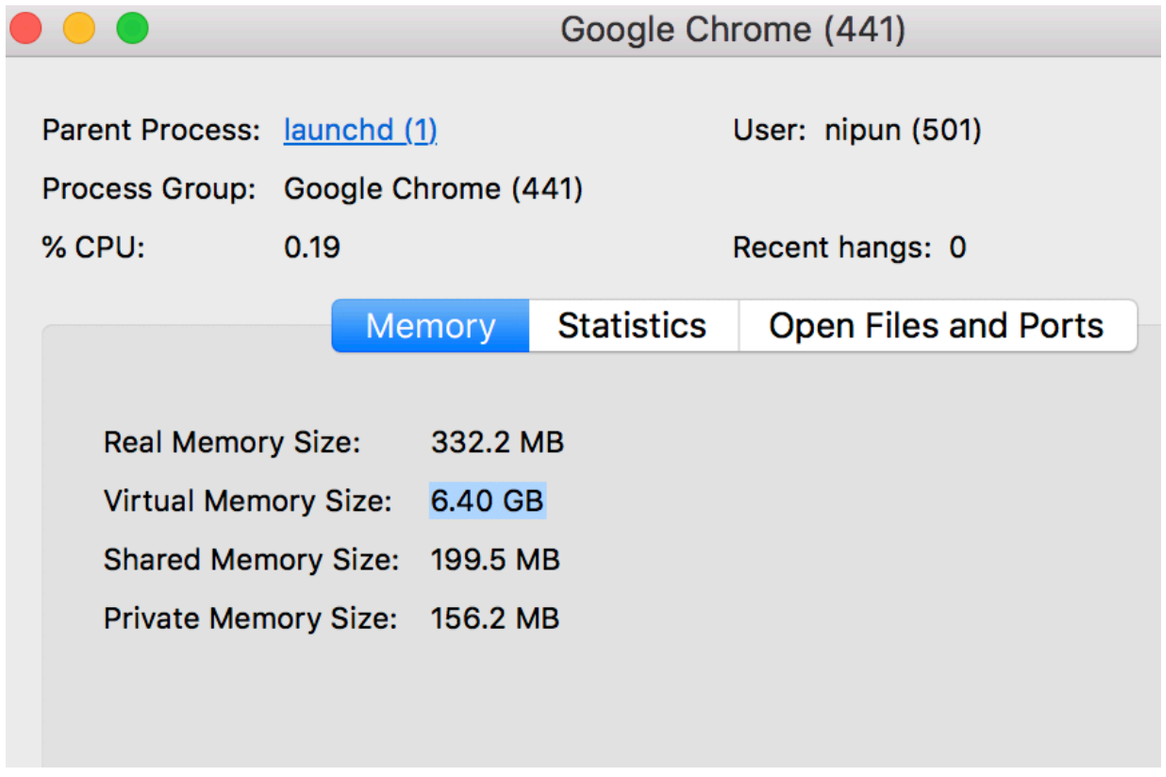
14 bit PD Index | 7 bit PT Index | 6 bit Offset

7 bit PD2 Index | 7 bit PD1 Index | 7 bit PT Index | 6 bit Offset



Beyond Physical Memory





Beyond Physical Memory

scikit-learn.org/stable/modules/scaling_strategies.html

folder | New folder | Google Analytics | Outlook Web App | imac - Google Sear...

scikit learn

Home | Installation | Documentation | Examples | Google Custom Search

Previous 5.6.6. RCV1 dataset | Next 7. Computatio.. | Up User Guide

scikit-learn v0.19.2
Other versions

Please cite us if you use the software.

6. Strategies to scale computationally: bigger data
6.1. Scaling with instances using out-of-core learning
- 6.1.1. Streaming instances
- 6.1.2. Extracting features
- 6.1.3. Incremental learning
- 6.1.4. Examples
- 6.1.5. Notes

6. Strategies to scale computationally: bigger data

For some applications the amount of examples, features (or both) and/or the speed at which they need to be processed are challenging for traditional approaches. In these cases scikit-learn has a number of options you can consider to make your system scale.

6.1. Scaling with instances using out-of-core learning

Out-of-core (or "external memory") learning is a technique used to learn from data that cannot fit in a computer's main memory (RAM).

Here is sketch of a system designed to achieve this goal:

1. a way to stream instances
2. a way to extract features from instances
3. an incremental algorithm

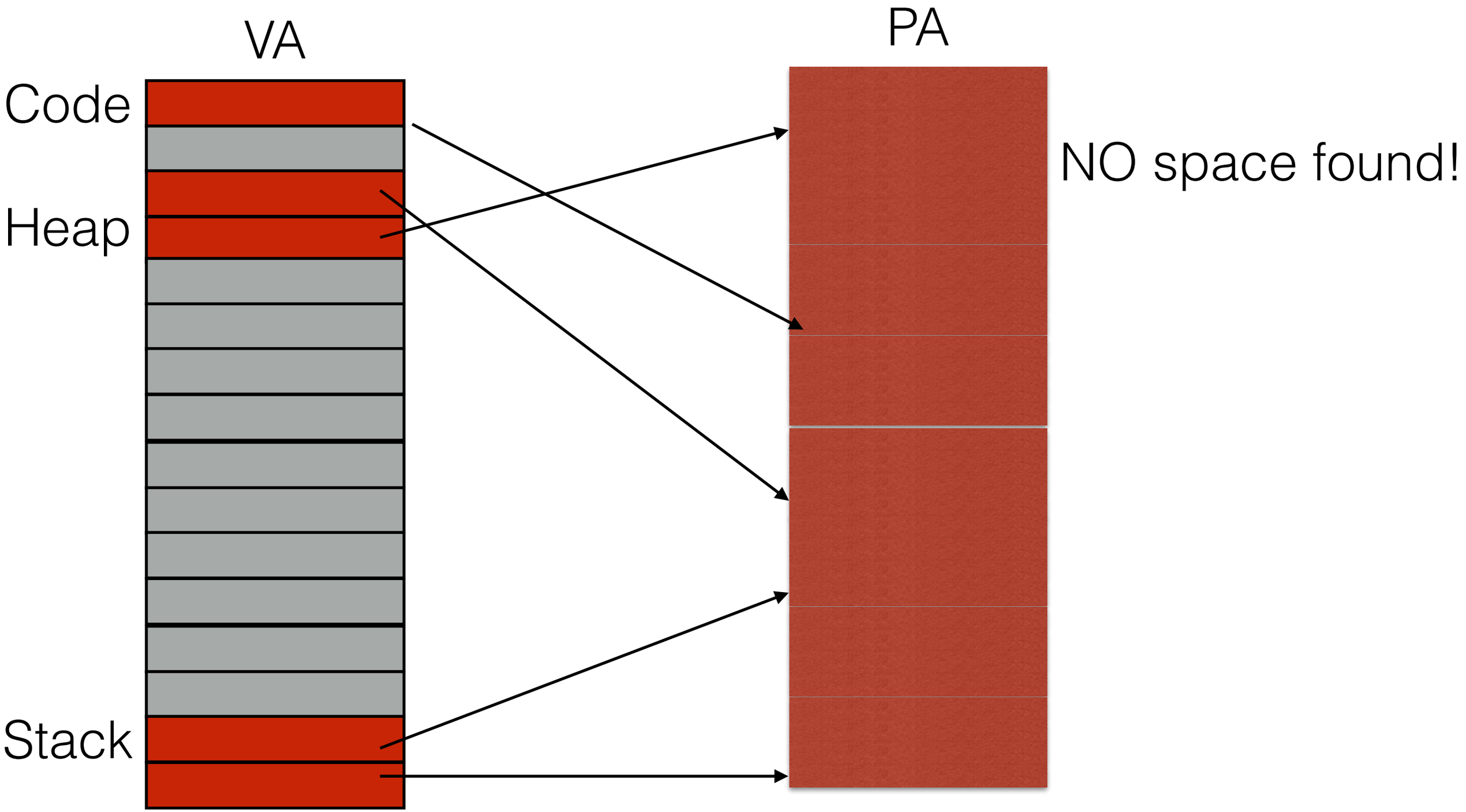
6.1.1. Streaming instances

Basically, 1. may be a reader that yields instances from files on a hard drive, a database, from a network stream etc. However, details on how to achieve this are beyond the scope of this documentation.

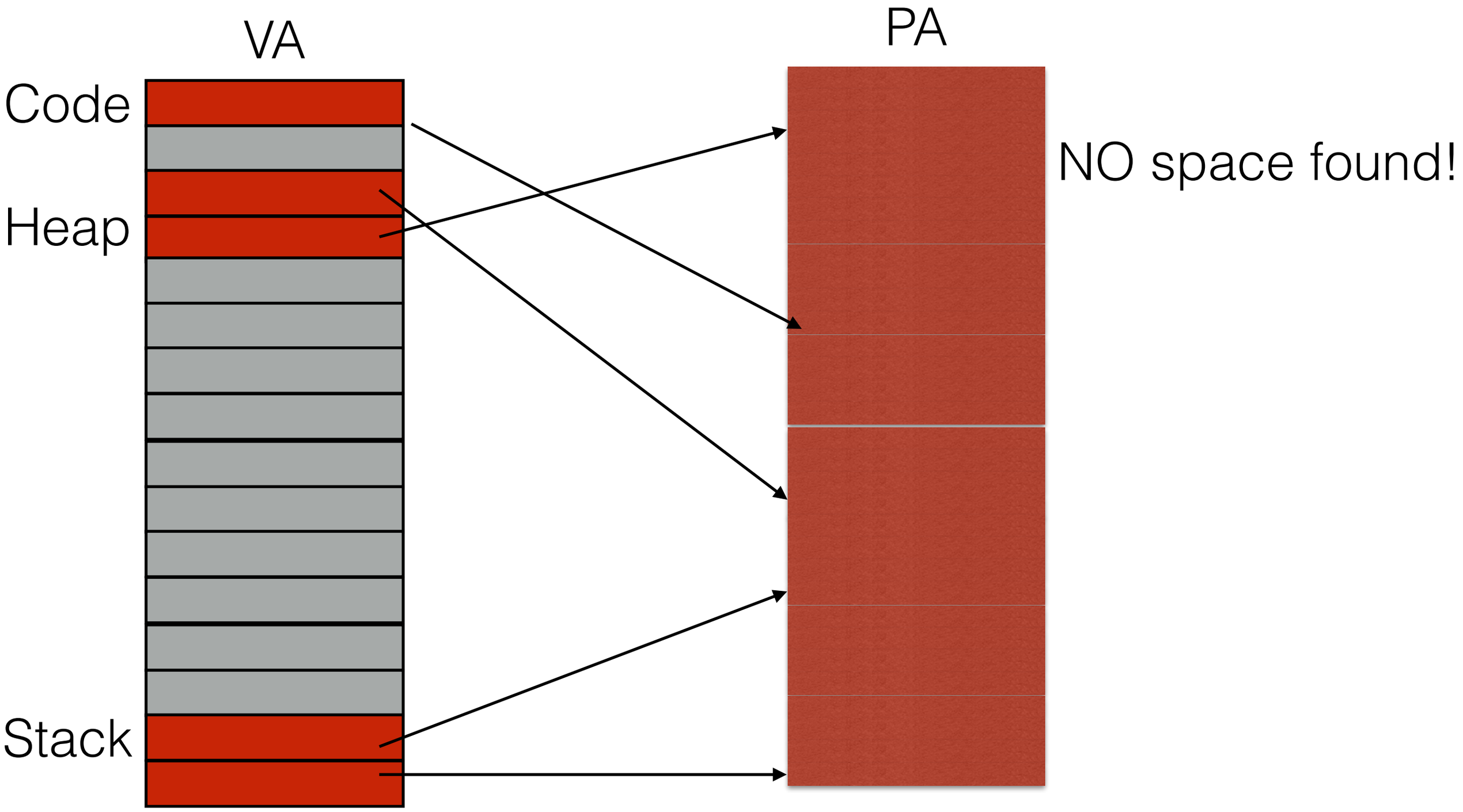
6.1.2. Extracting features

2. could be any relevant way to extract features among the different feature extraction methods supported by scikit-learn. However, when working with data that needs vectorization and where the set of features or values is not known in advance one should take explicit care. A good example is text classification where unknown terms are likely to be found during training. It is possible to use a stateful vectorizer if making multiple passes over the data is reasonable from an application point of view. Otherwise, one can turn up the difficulty by using a stateless feature extractor. Currently the preferred way to do this

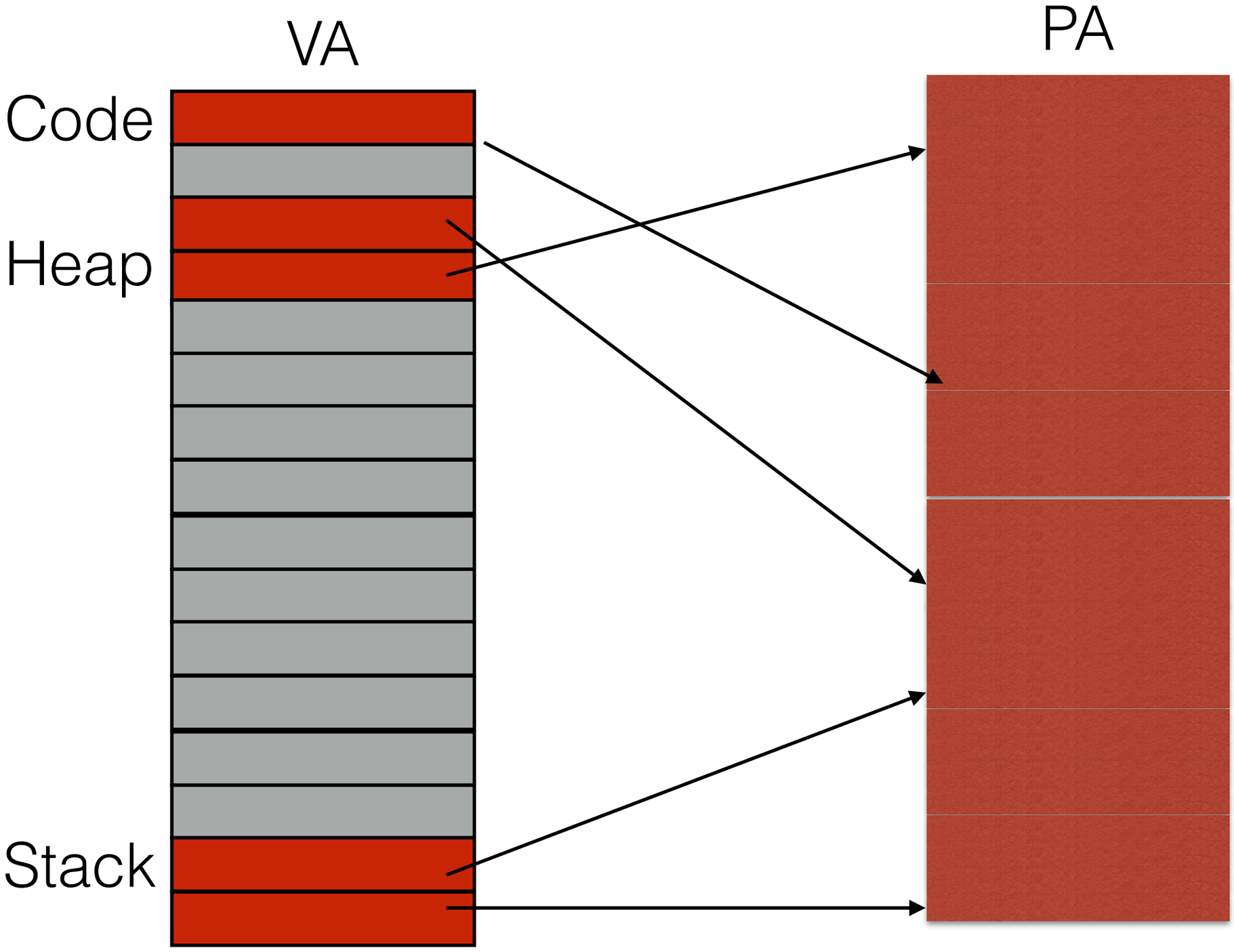
Out of PA space



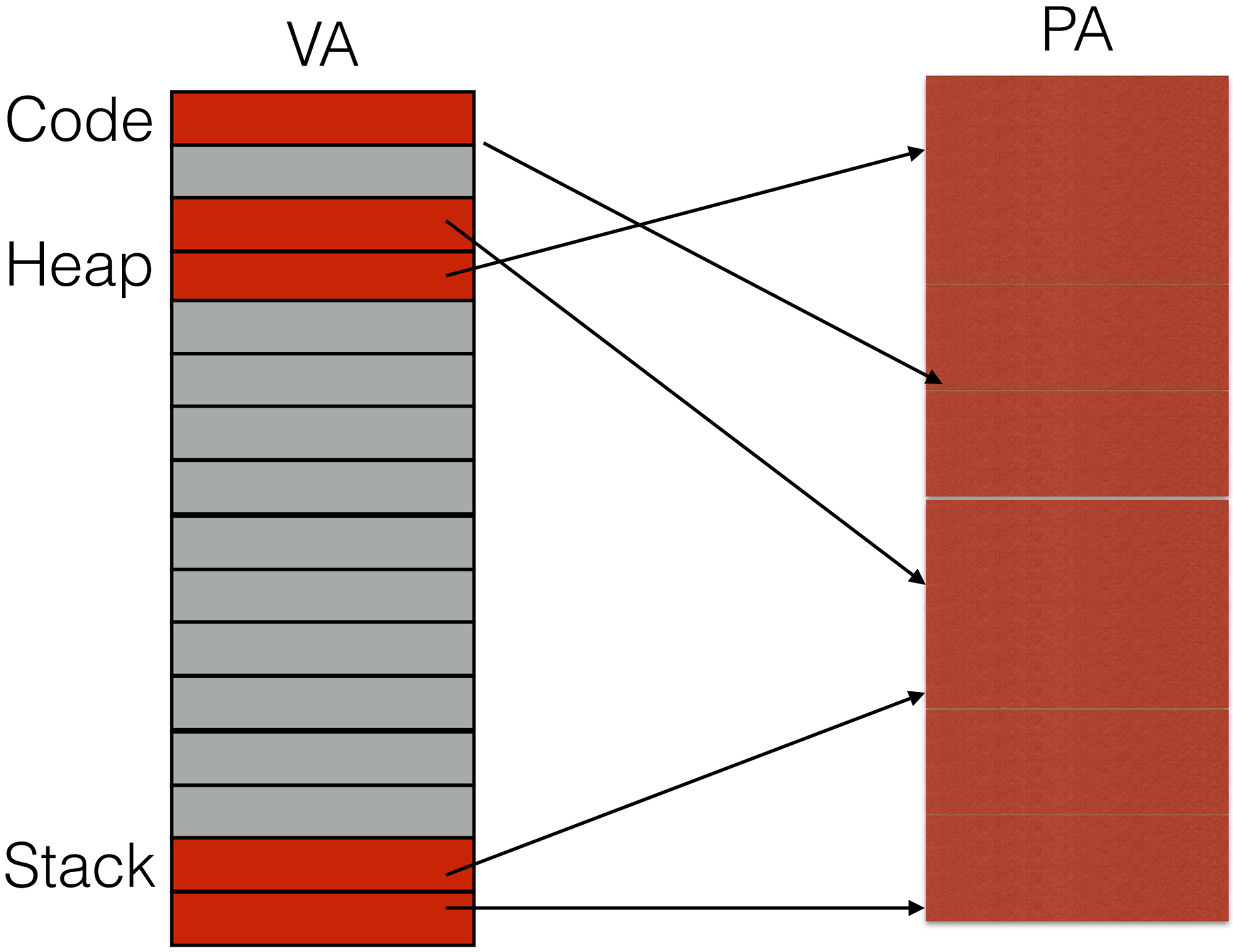
Out of PA space



Out of PA space



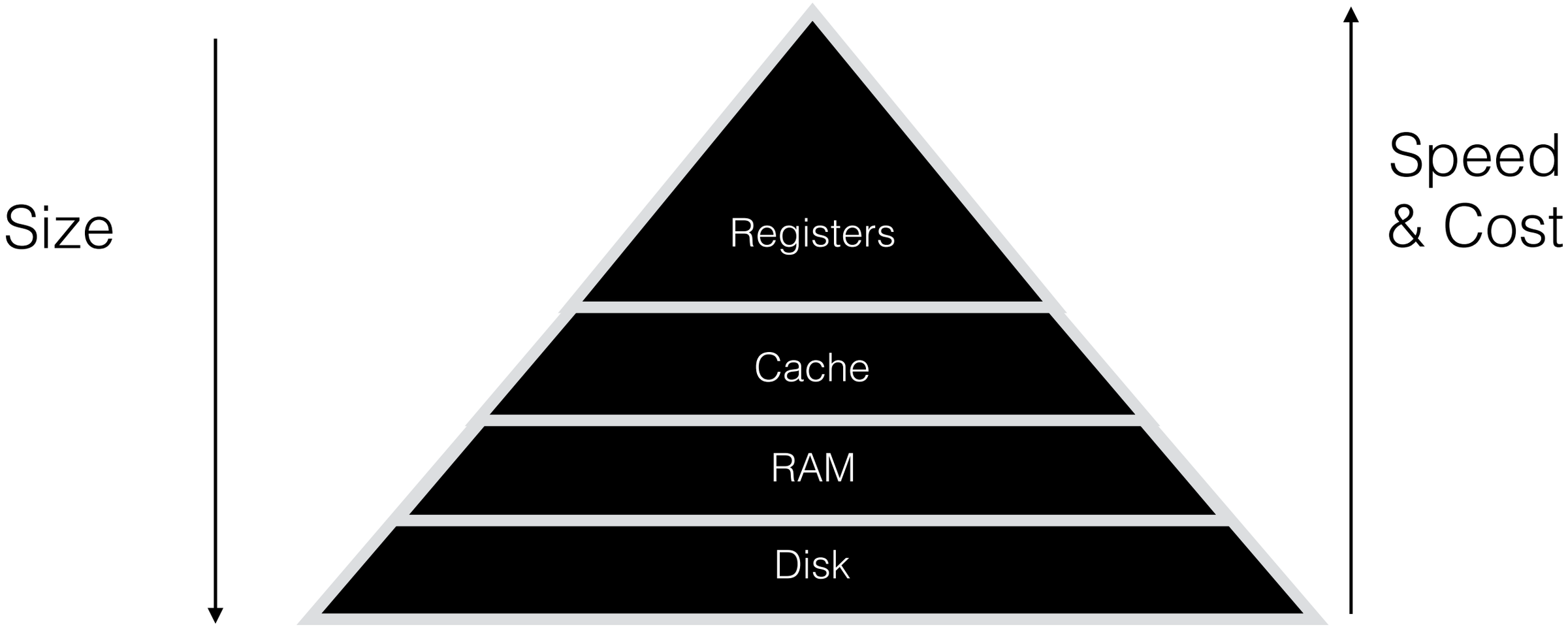
Out of PA space



NO space found!

1. Fail - Kill the process
2. Create more space - Preserving memory contents

Out of PA space - Memory hierarchy



Out of PA space - Virtualisation

Out of PA space - Virtualisation

1. Does the user know whether the PFN came from TLB or memory?

Out of PA space - Virtualisation

1. Does the user know whether the PFN came from TLB or memory?
   - No!

Out of PA space - Virtualisation

1. Does the user know whether the PFN came from TLB or memory?
   - No!
   - Does the user even know if paging is used?

Out of PA space - Virtualisation

1. Does the user know whether the PFN came from TLB or memory?
   - No!
   - Does the user even know if paging is used?
2. Should the user know if the page came from memory or TLB or disk?

Out of PA space - Virtualisation

1. Does the user know whether the PFN came from TLB or memory?
   - No!
   - Does the user even know if paging is used?
2. Should the user know if the page came from memory or TLB or disk?
   - No!

Out of PA space - Virtualisation

1. Does the user know whether the PFN came from TLB or memory?
   - No!
   - Does the user even know if paging is used?
2. Should the user know if the page came from memory or TLB or disk?
   - No!
   - The last time the process used the virtual address, it behaved like memory.

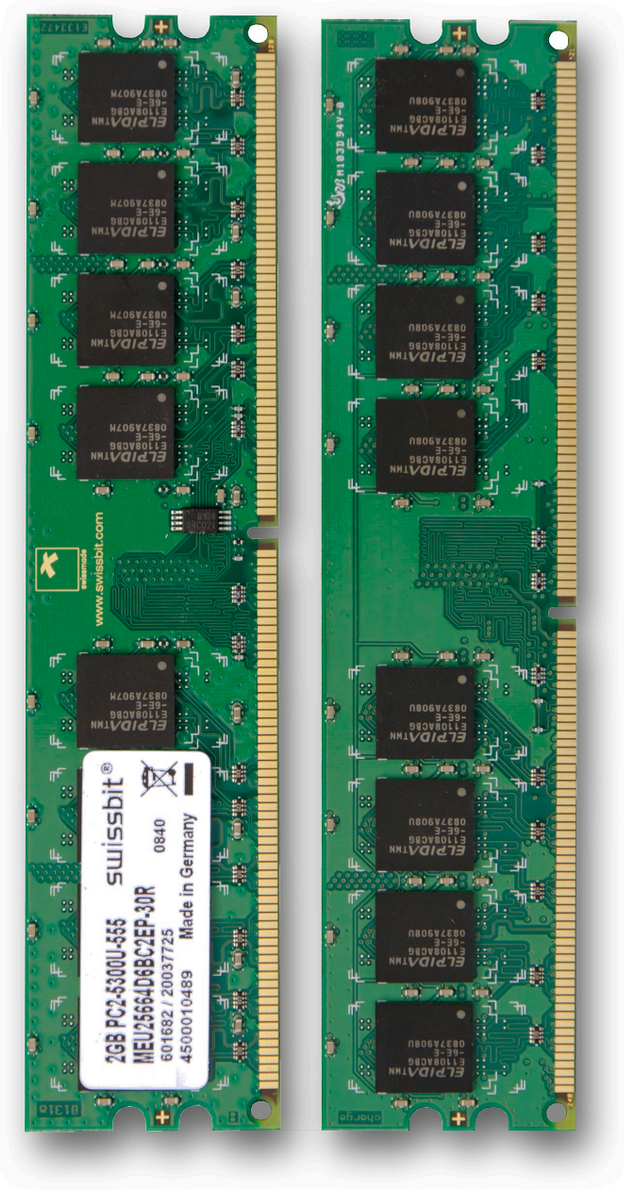
Out of PA space - Virtualisation

1. Does the user know whether the PFN came from TLB or memory?
   - No!
   - Does the user even know if paging is used?
2. Should the user know if the page came from memory or TLB or disk?
   - No!
   - The last time the process used the virtual address, it behaved like memory.
   - The next time the process uses the virtual address, it behaves like memory.

Out of PA space - Virtualisation

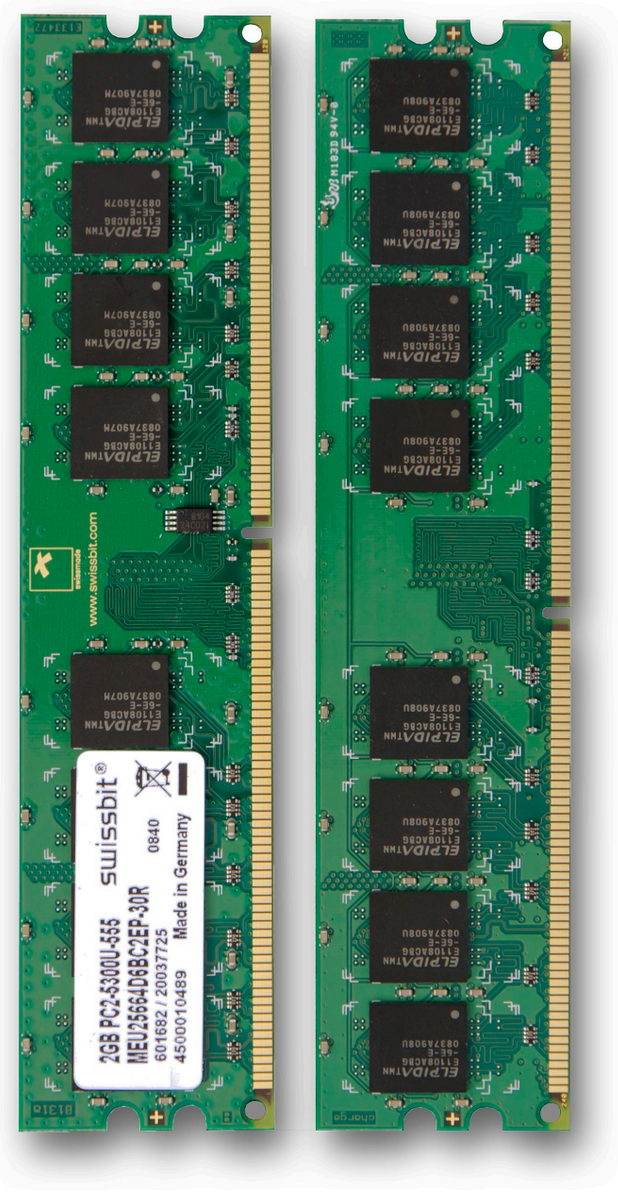
1. Does the user know whether the PFN came from TLB or memory?
   - No!
   - Does the user even know if paging is used?
2. Should the user know if the page came from memory or TLB or disk?
   - No!
   - The last time the process used the virtual address, it behaved like memory.
   - The next time the process uses the virtual address, it behaves like memory.
   - In between, whatever data was stored at that address must be preserved.

Swapping

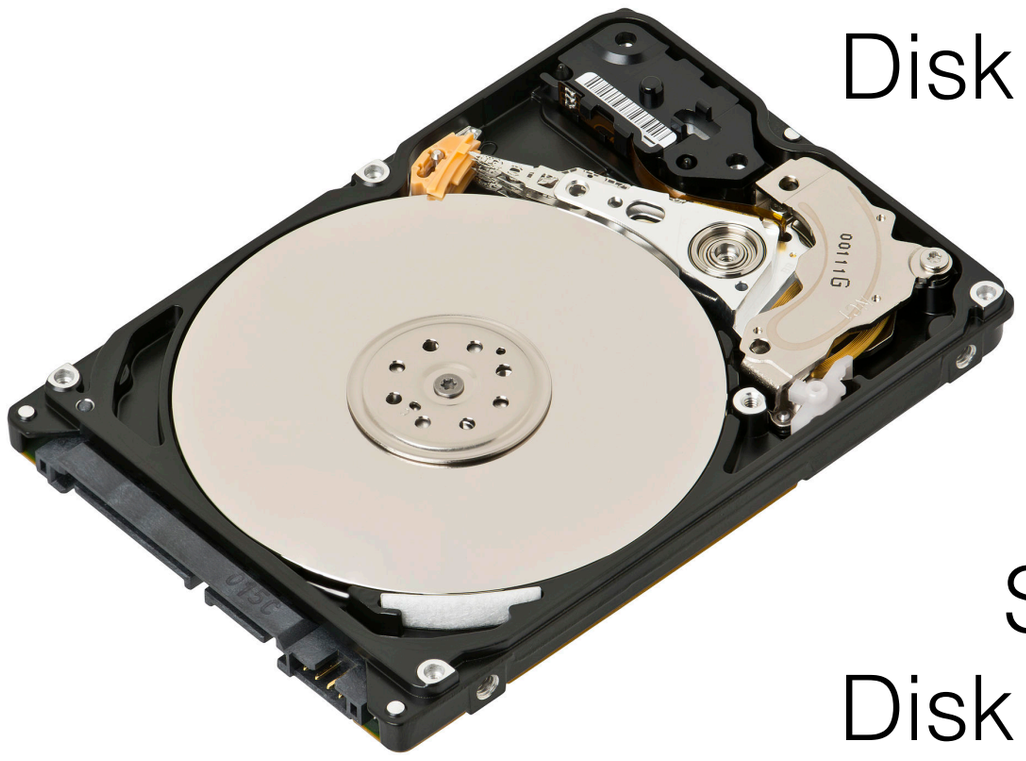

www.swissbit.com
2GB PC2-5300U-555
MEU25664D6BC2EP-30R
601682 / 20037725
4500010489
swissbit®
0840
Made in Germany

Swapping

Swap in
Disk —> Memory

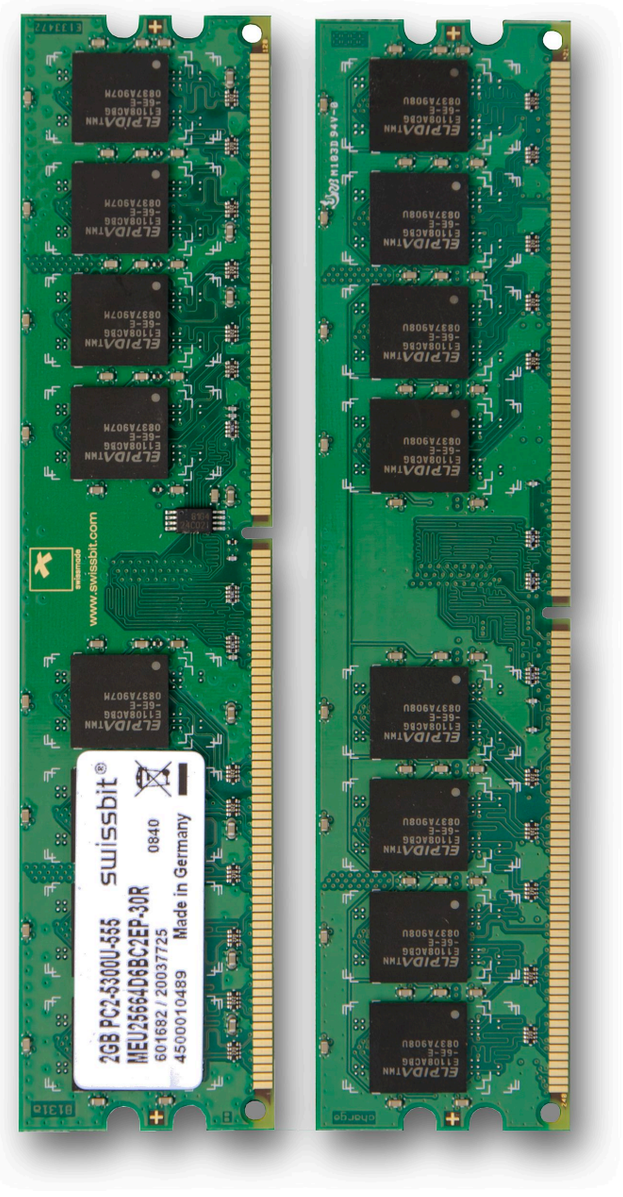


Swapping

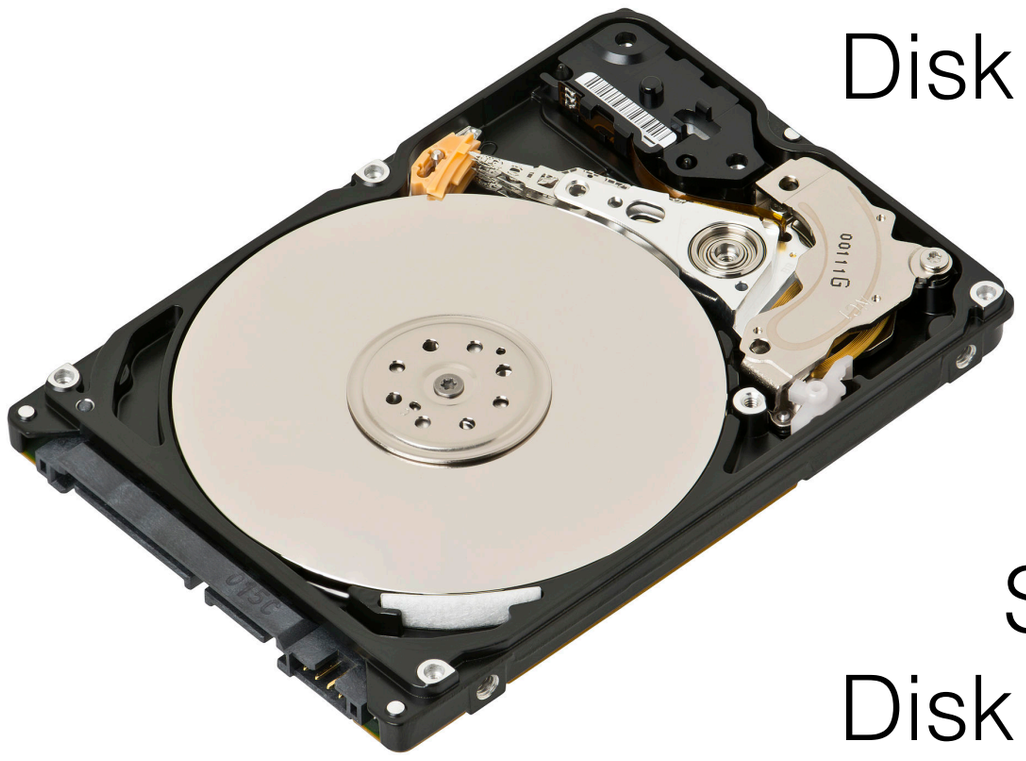


Swap in
Disk —> Memory

Swap out
Disk <— Memory

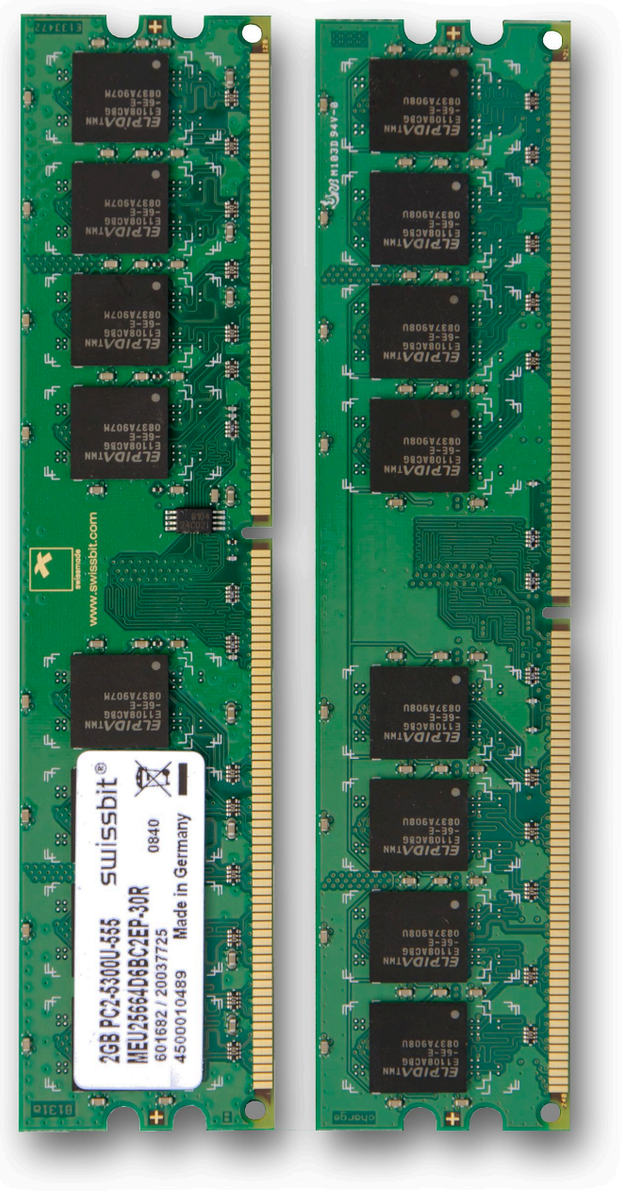


Swapping



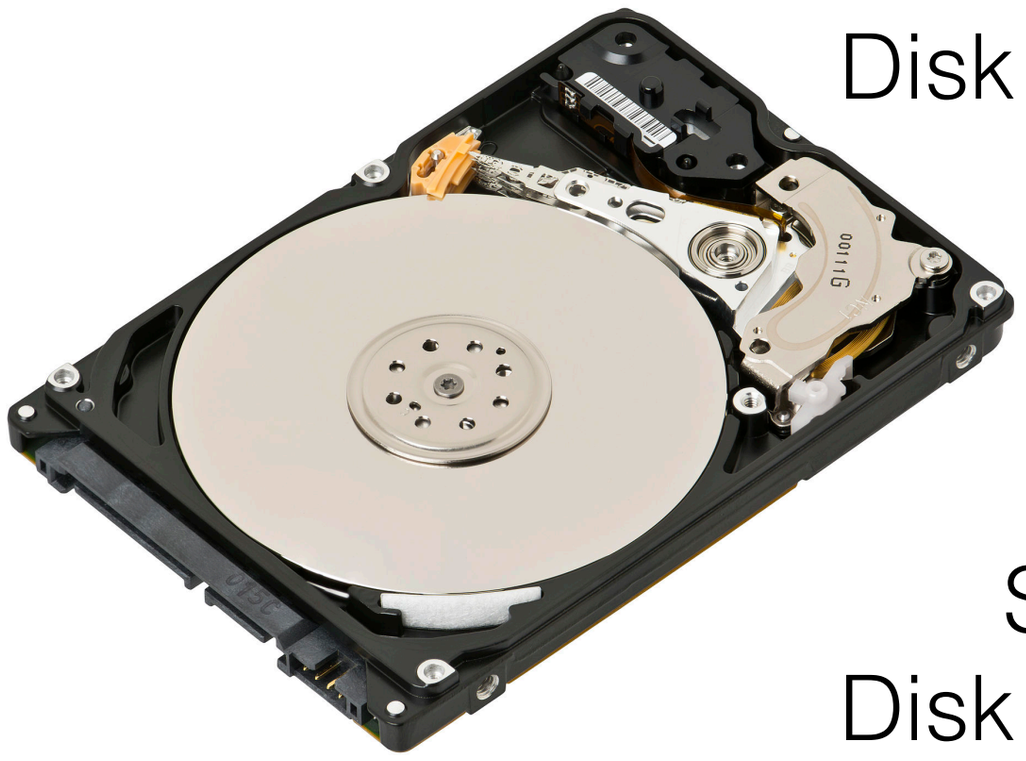
Swap in
Disk —> Memory

Swap out
Disk <— Memory



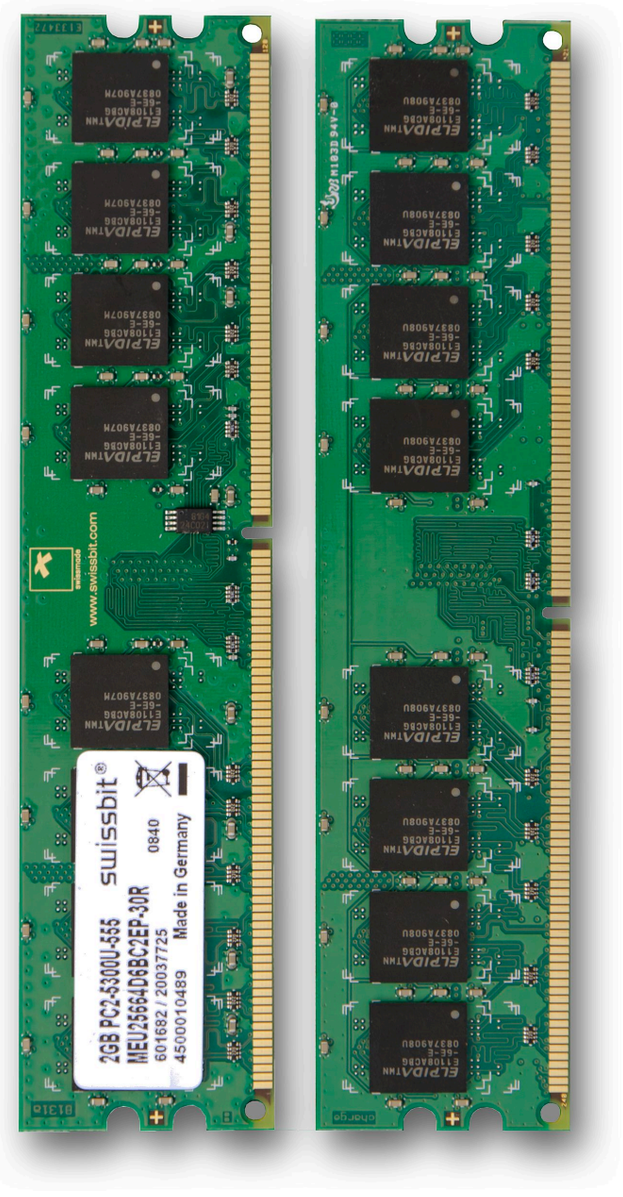
Done well : Memory as large as disk, as fast as RAM

Swapping



Swap in
Disk —> Memory

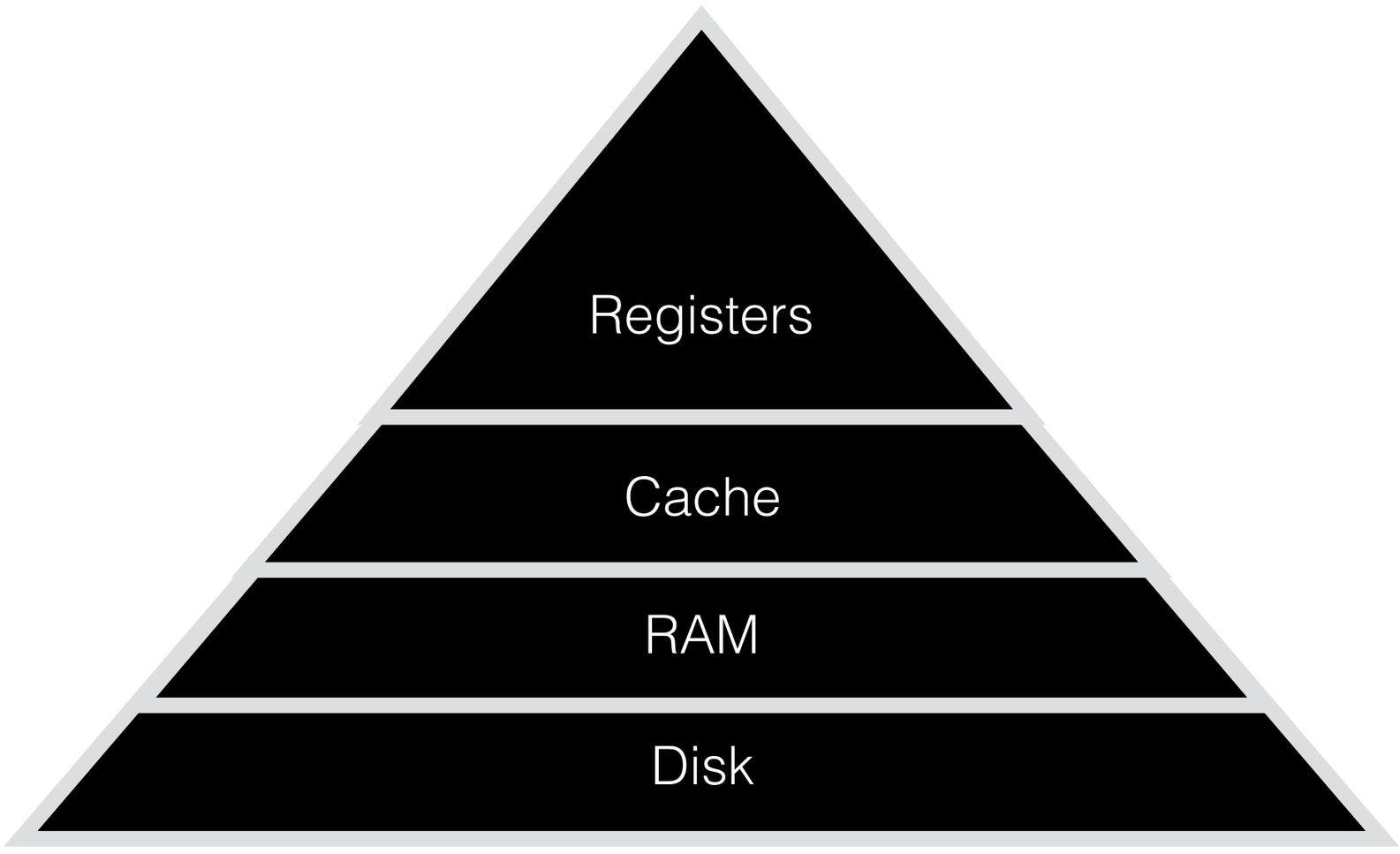
Swap out
Disk <— Memory



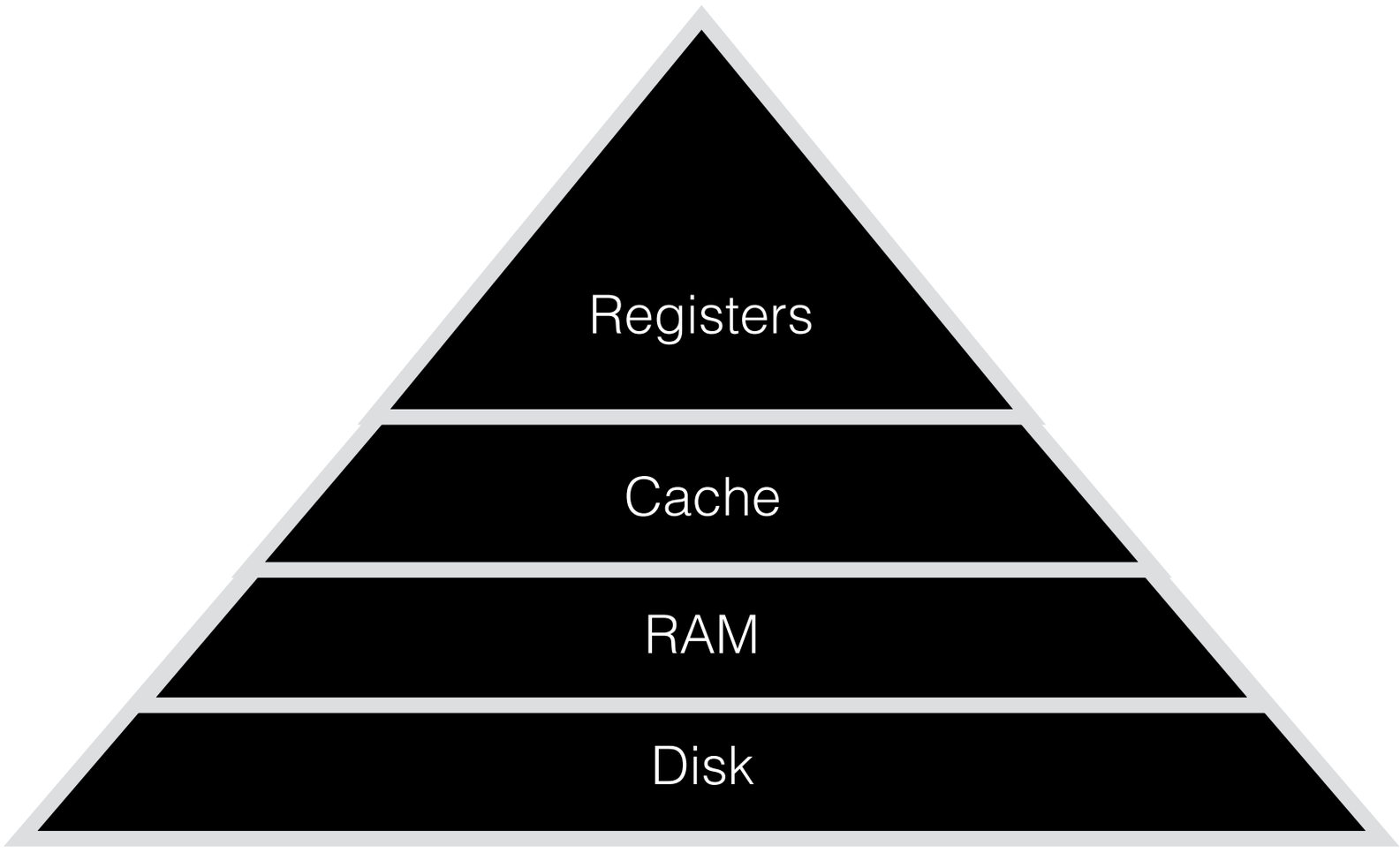
Done well : Memory as large as disk, as fast as RAM

Done bad : Memory as small as RAM, as slow as disk

TLB miss v/s Page Fault

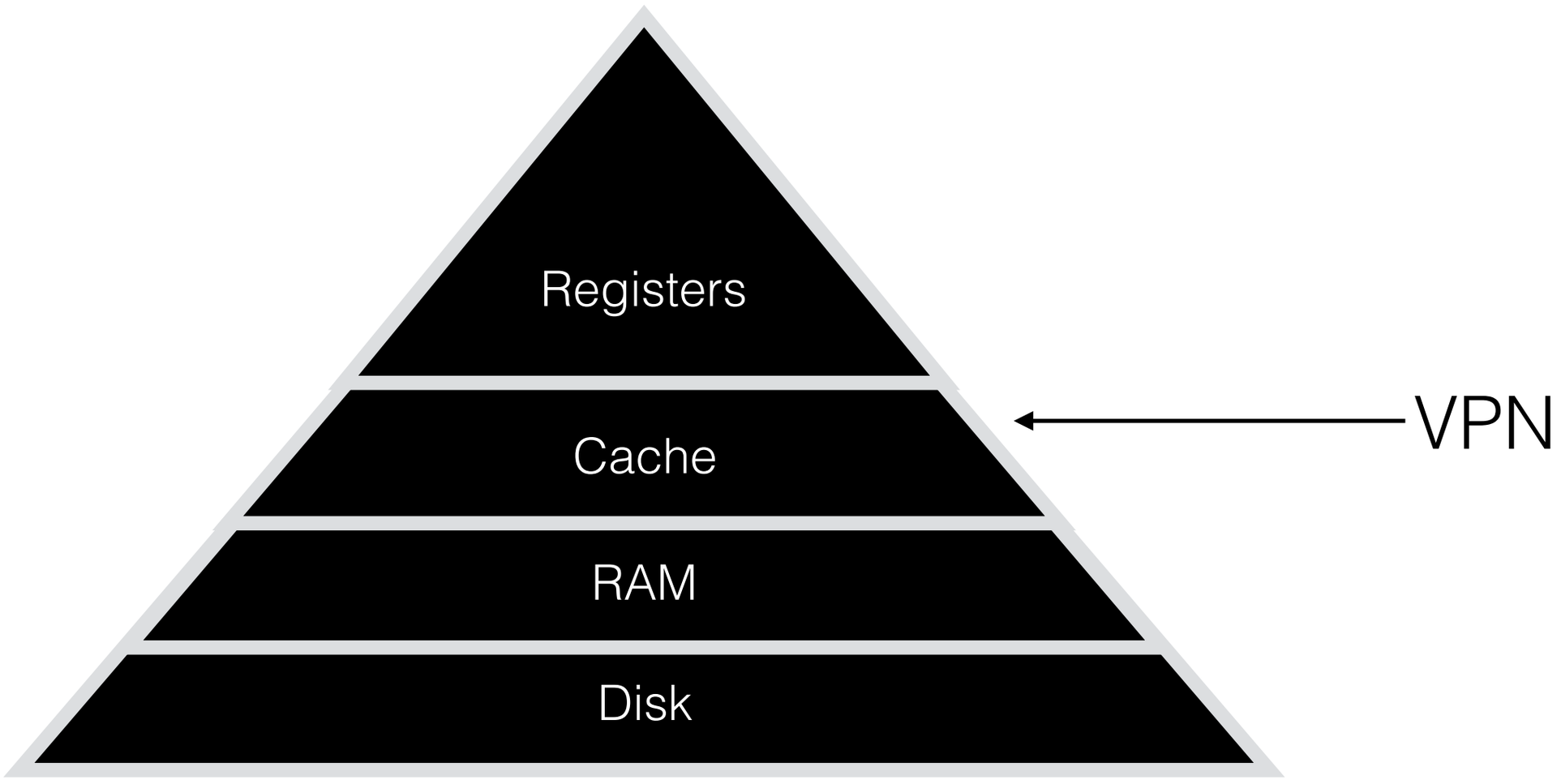


TLB miss v/s Page Fault

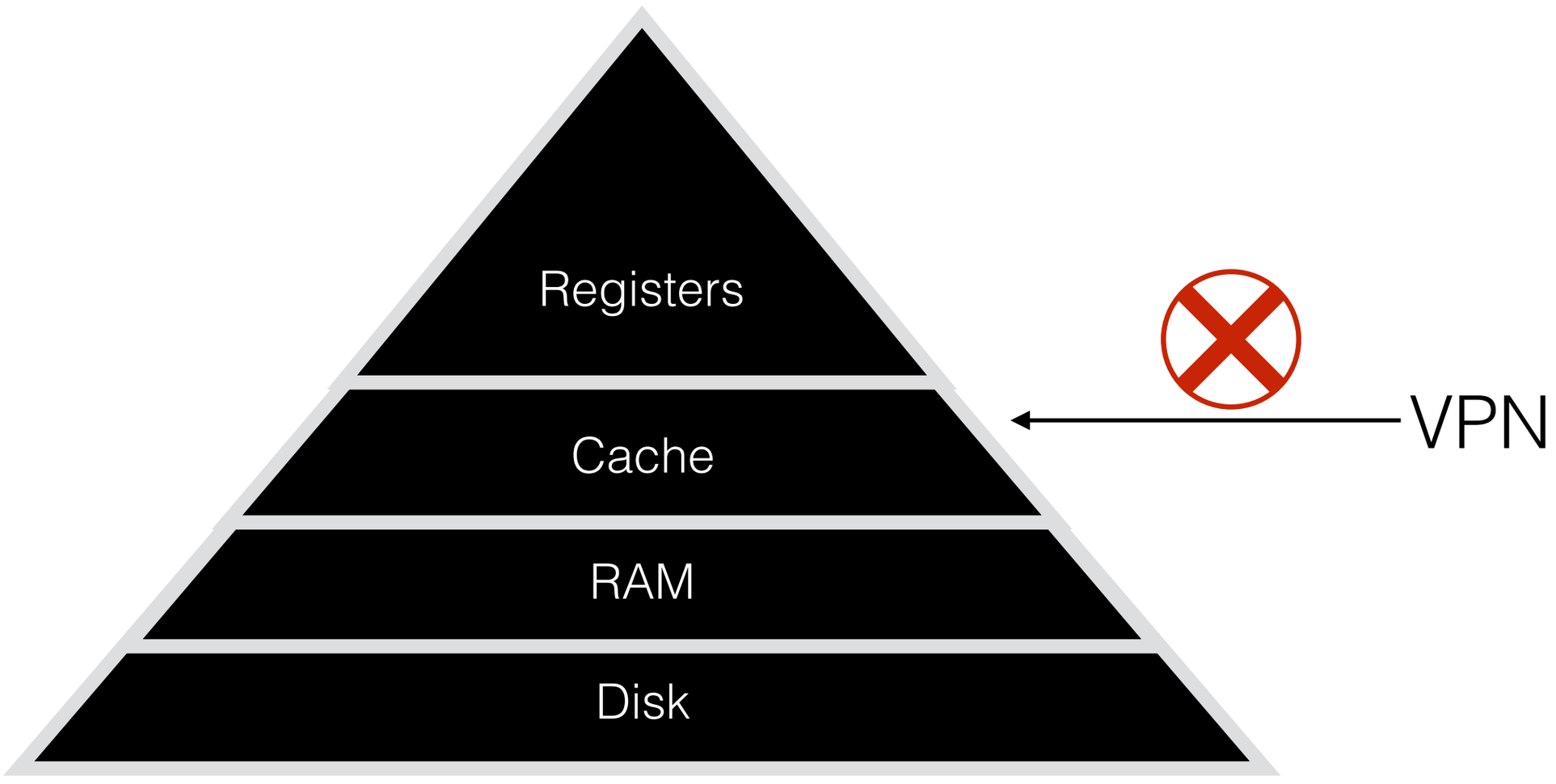


VPN

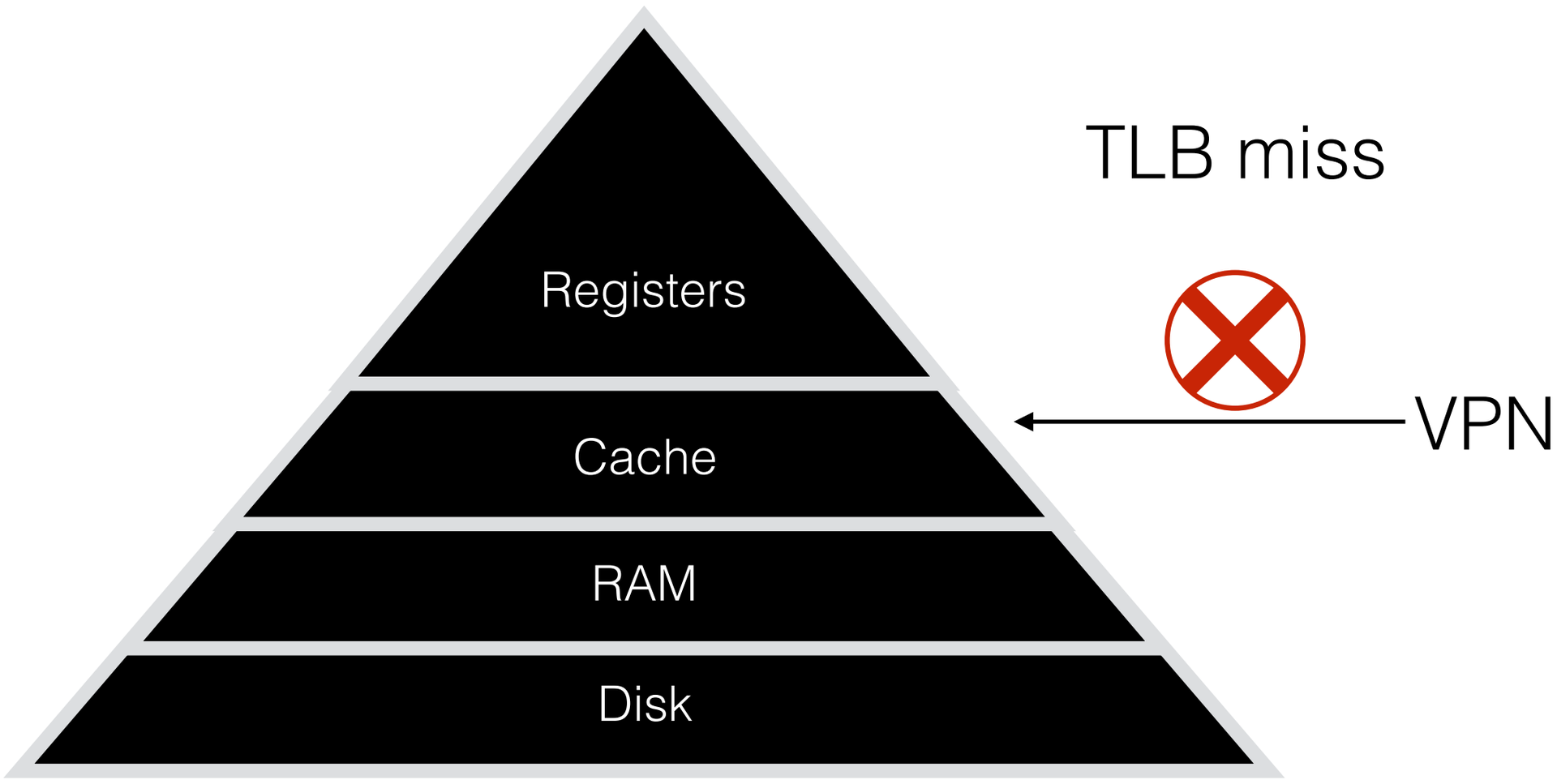
TLB miss v/s Page Fault



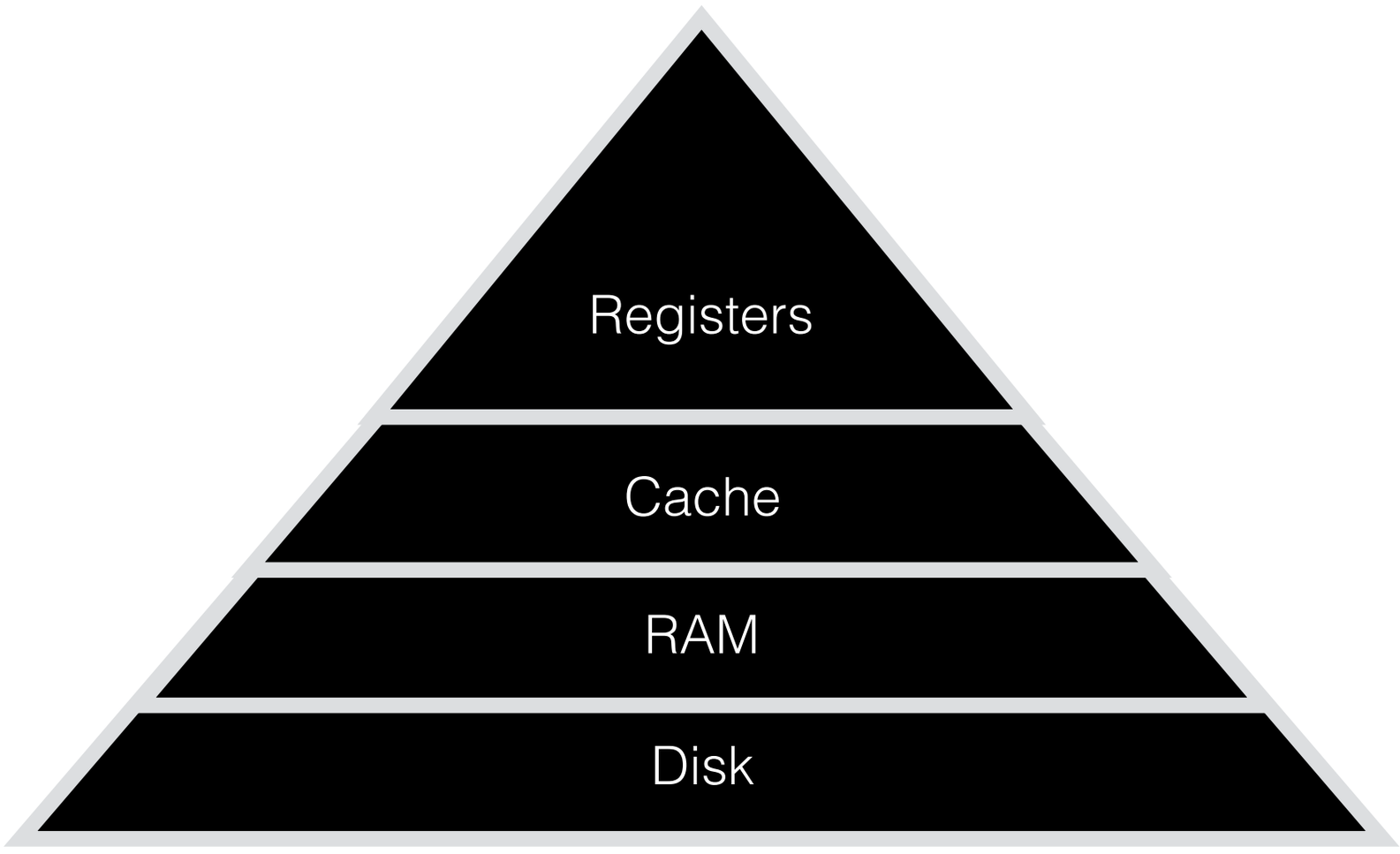
TLB miss v/s Page Fault



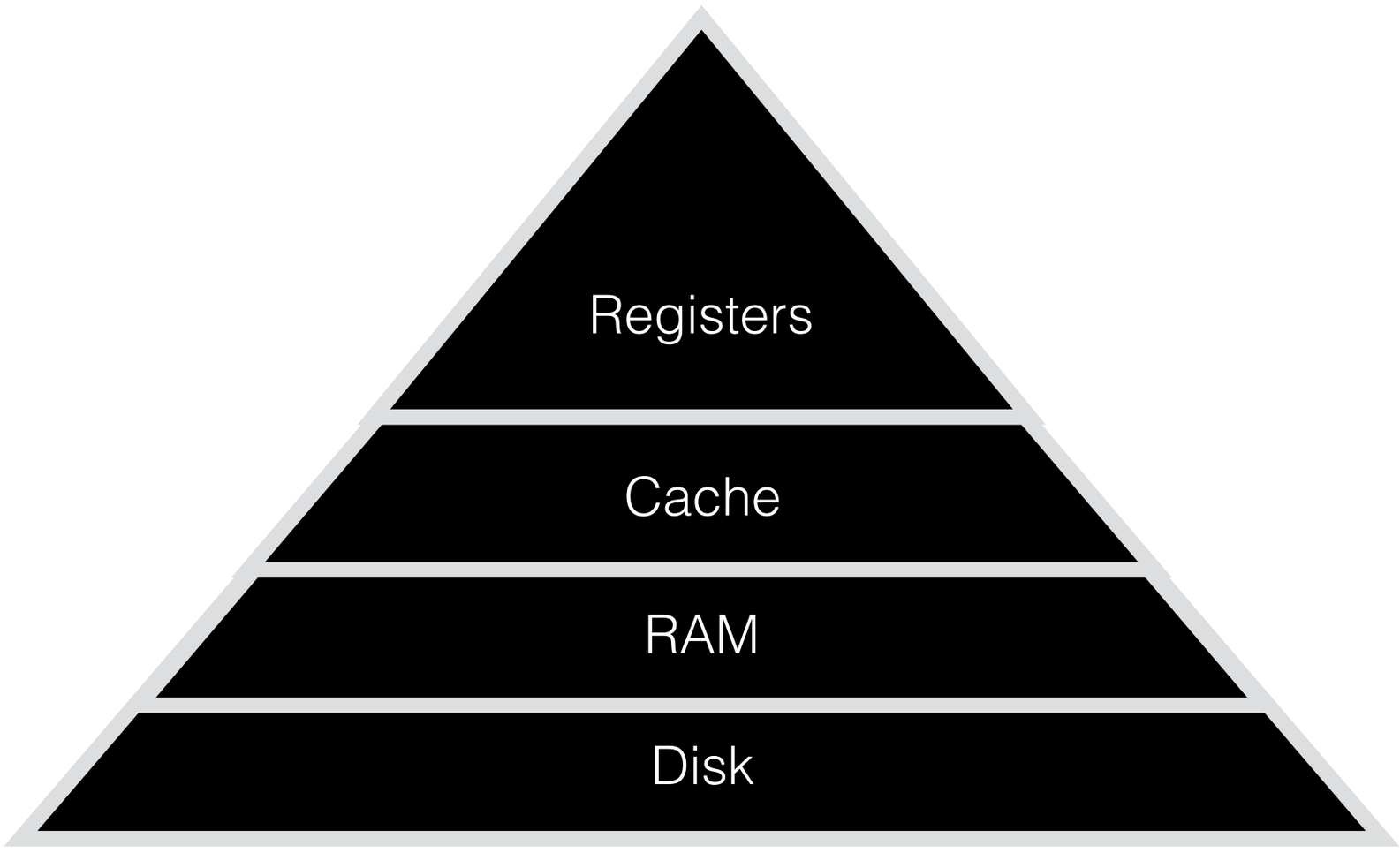
TLB miss v/s Page Fault



TLB miss v/s Page Fault

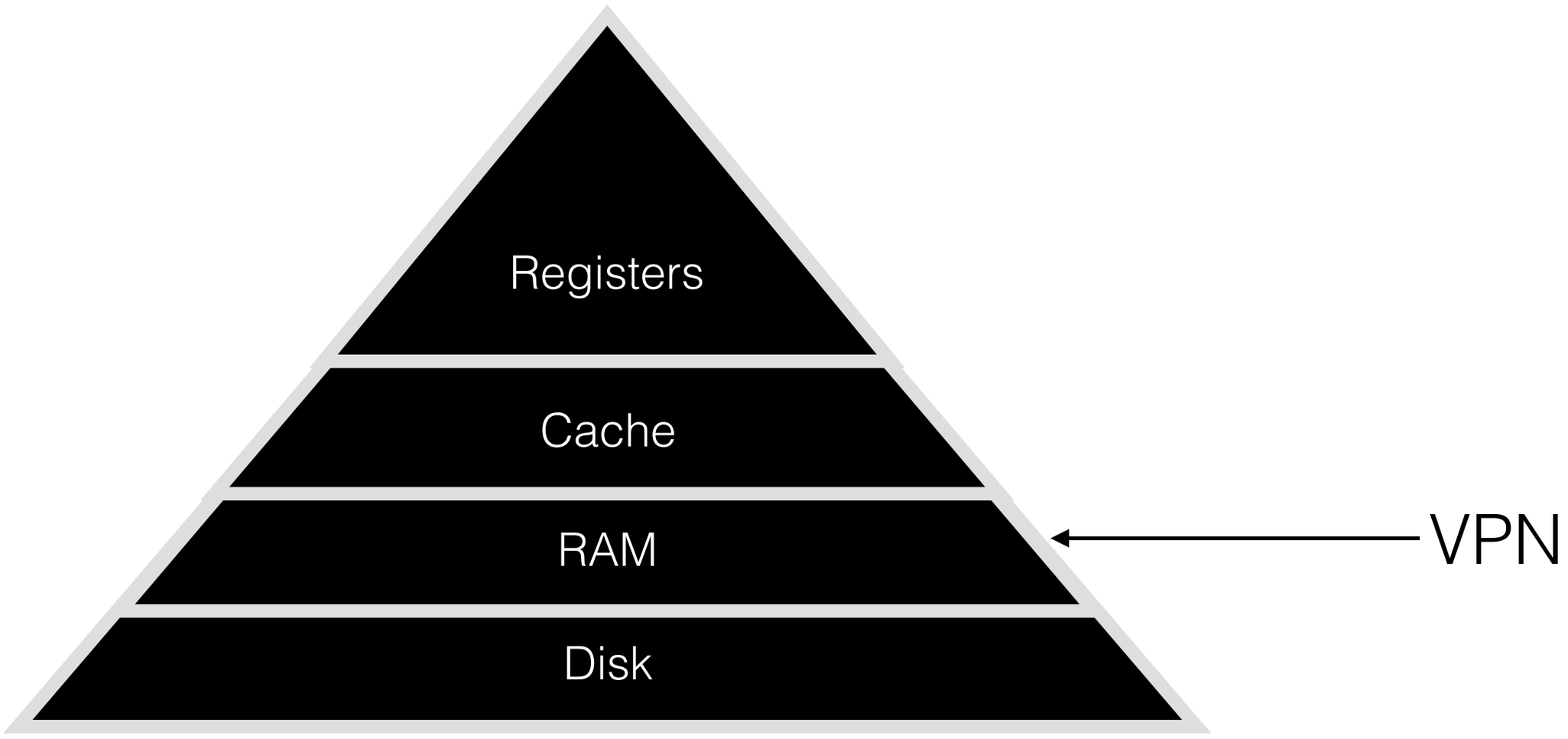


TLB miss v/s Page Fault

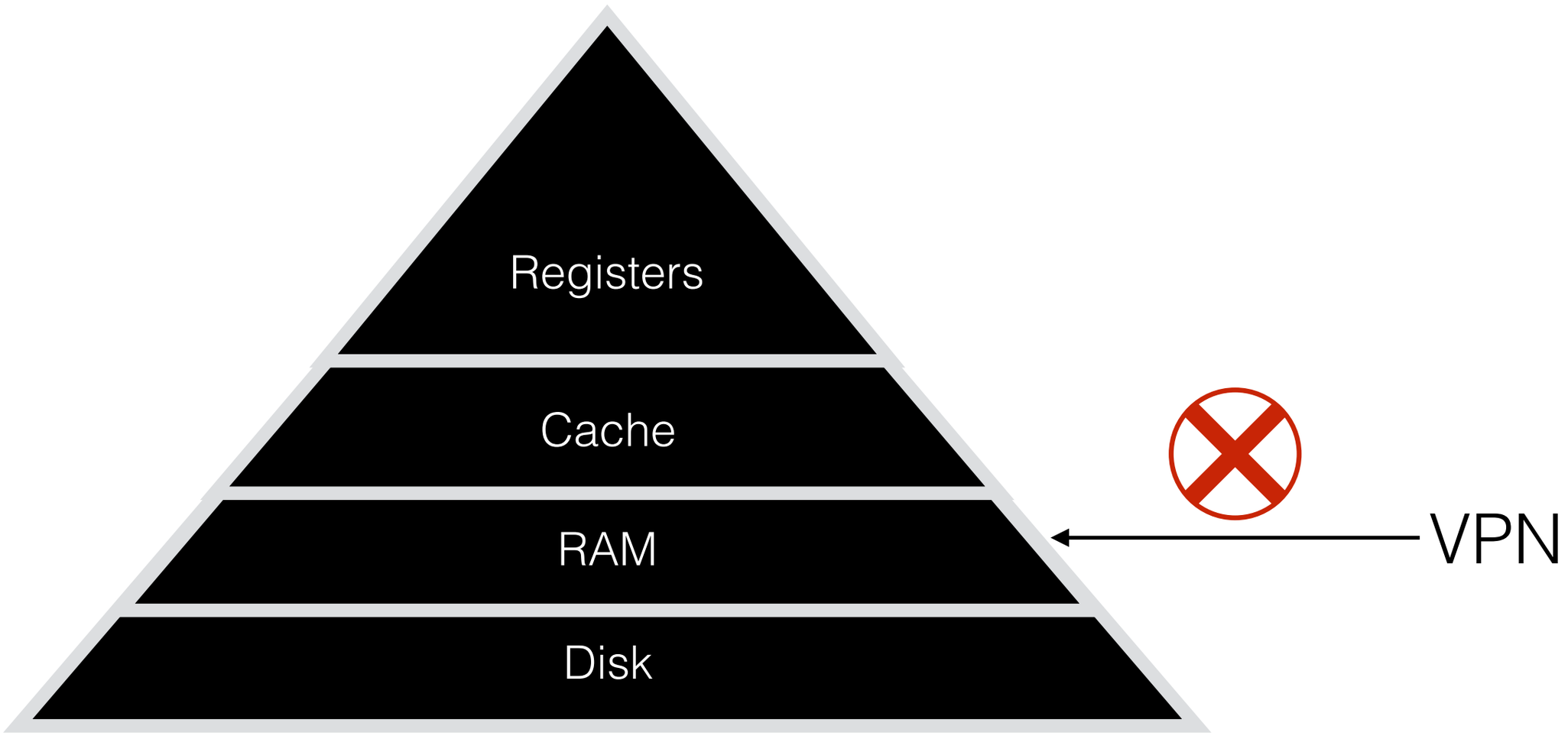


VPN

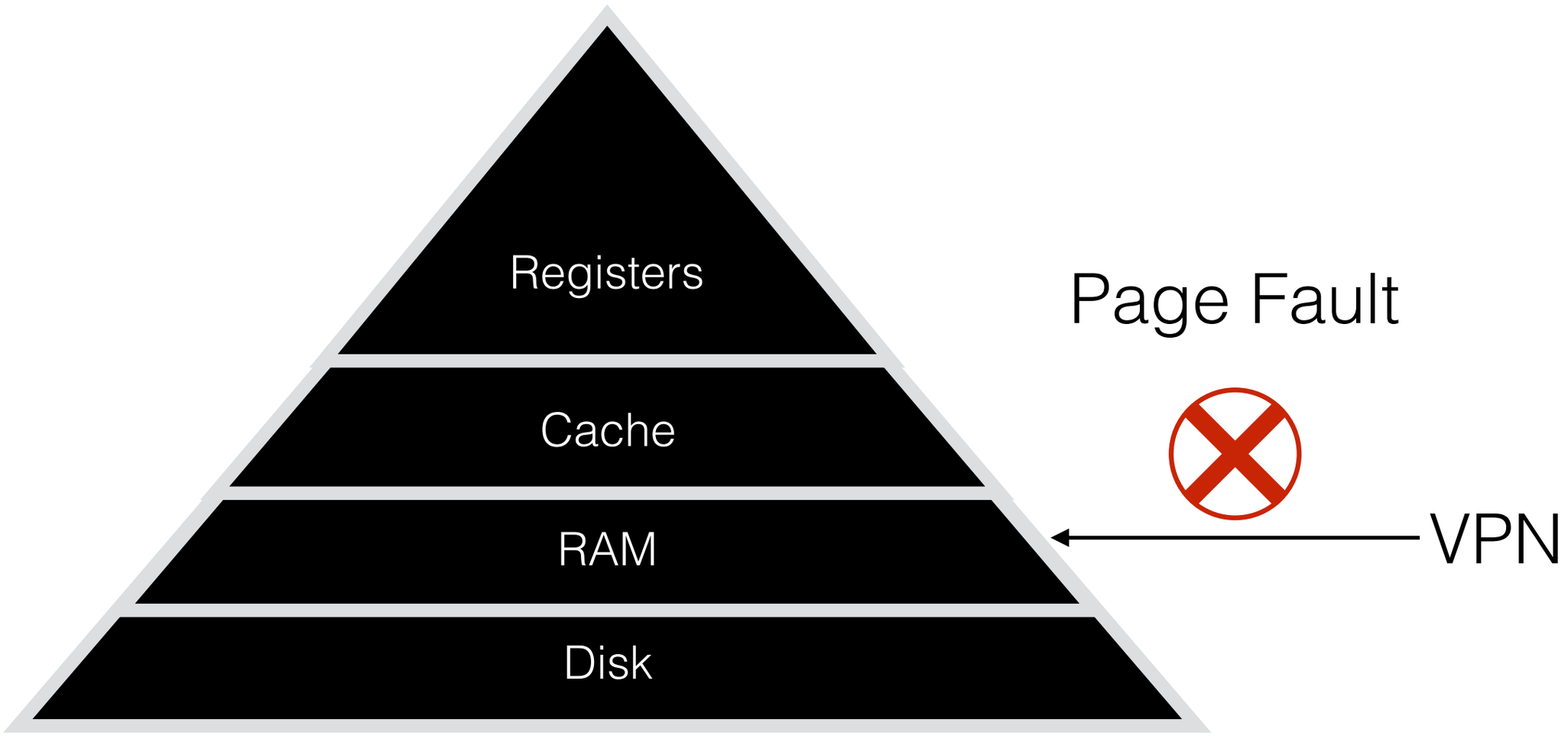
TLB miss v/s Page Fault



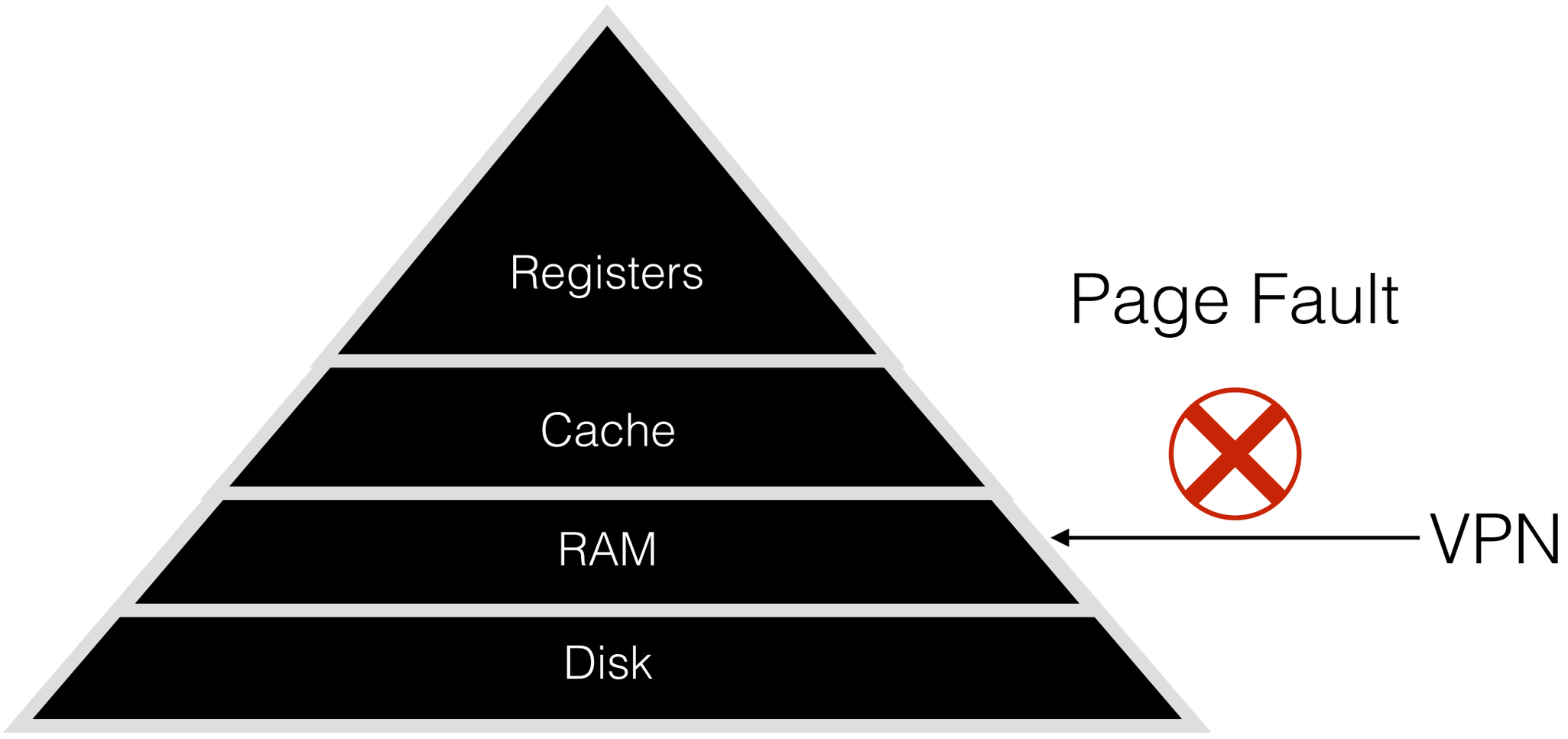
TLB miss v/s Page Fault



TLB miss v/s Page Fault

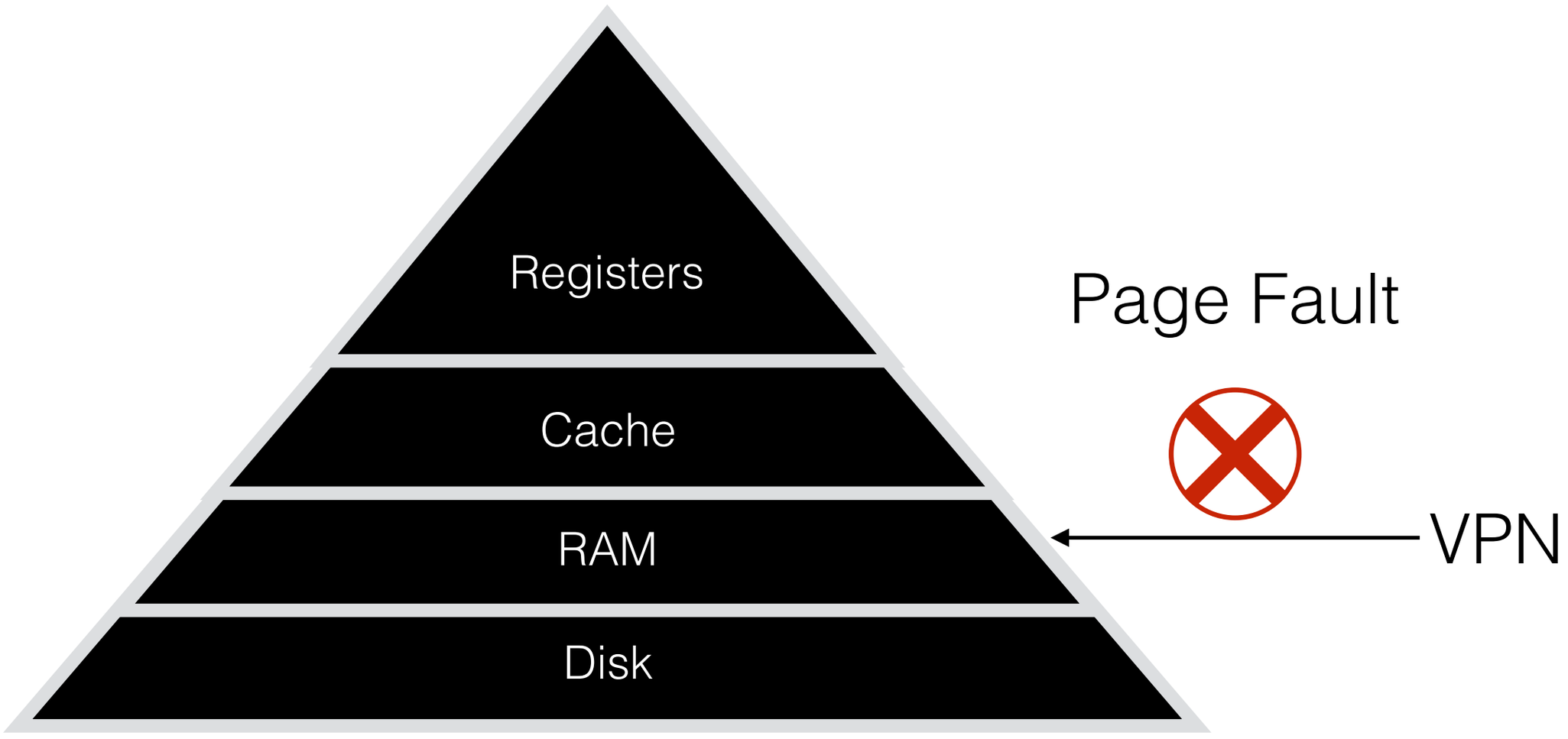


TLB miss v/s Page Fault



- Every page fault preceded by a TLB miss

TLB miss v/s Page Fault



- Every page fault preceded by a TLB miss
- Every TLB miss does not generate a page fault