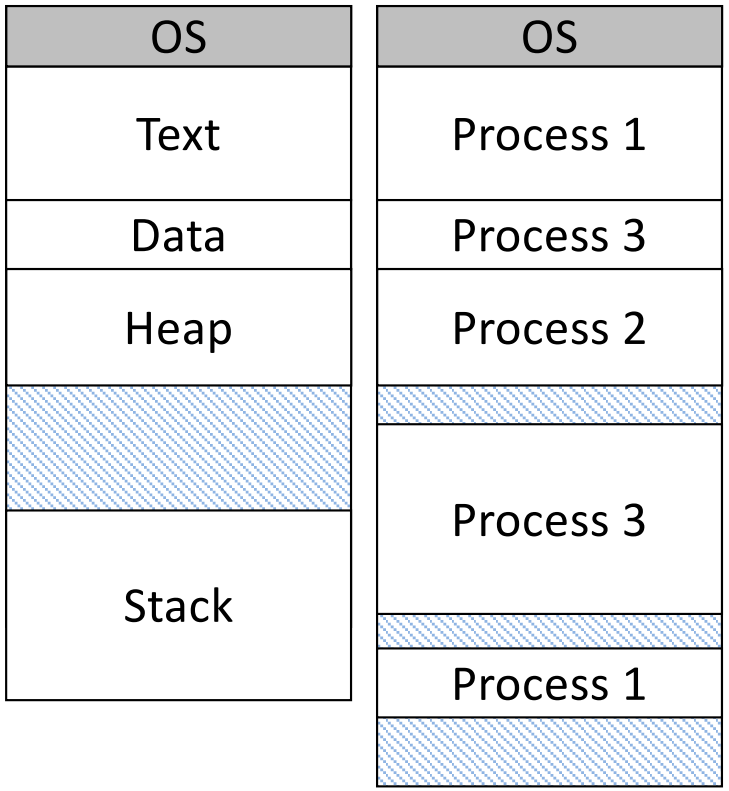
CS 31: Introduction to Computer Systems

26-27: Virtual Memory

30 April, 2020

Memory

- Abstraction goal: make every process think it has the same memory layout.
  - MUCH simpler for compiler if the stack always starts at 0xFFFFFFFF, etc.
- Reality: there's only so much memory to go around, and no two processes should use the same (physical) memory addresses.

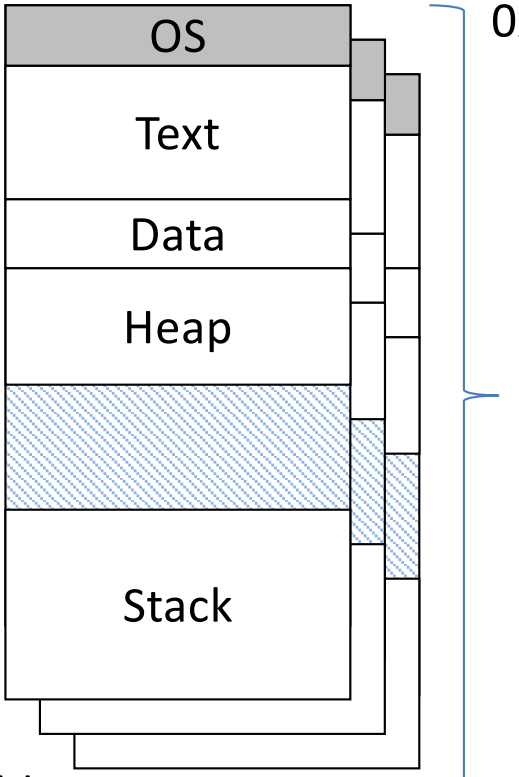


OS (with help from hardware) will keep track of who's using each memory region.

Memory Terminology

Virtual (logical) Memory: The abstract view of memory given to processes. Each process gets an independent view of the memory.

Physical Memory: The contents of the hardware (RAM) memory. Managed by OS. Only ONE of these for the entire machine!



0x0

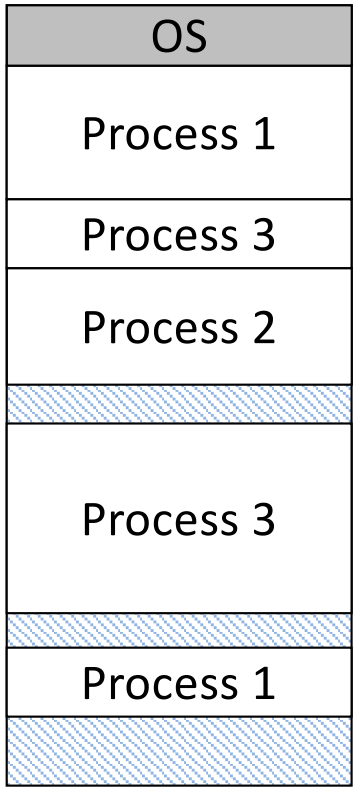
0xFFFFFFFF

Virtual address space (VAS): fixed size.

Address Space: Range of addresses for a region of memory.

The set of available storage locations.

0x0



0x…

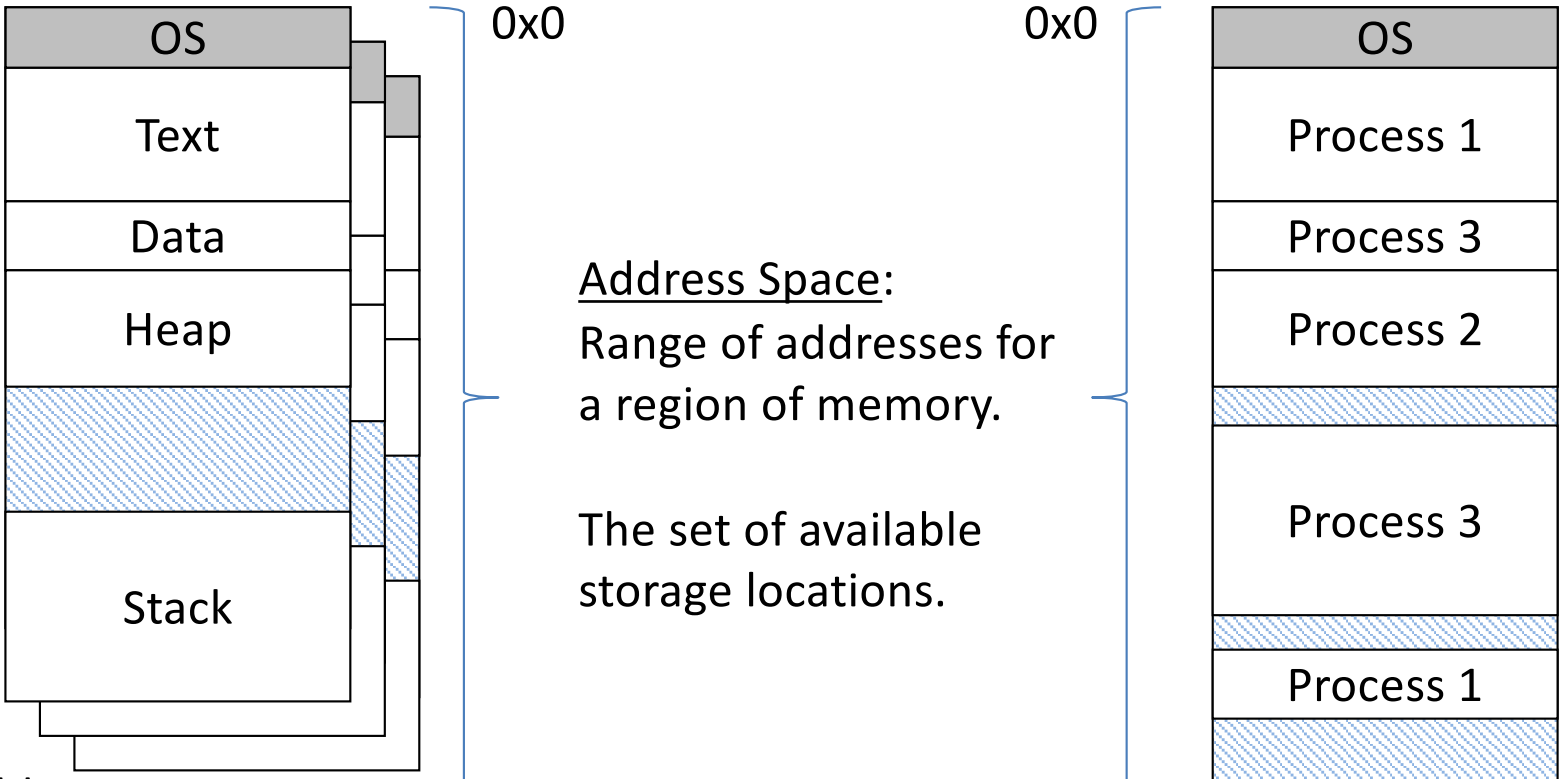
(Determined by amount of installed RAM.)

Memory Terminology

Note: It is common for VAS to appear larger than physical memory.

32-bit (IA32): Can address up to 4 GB, might have less installed

64-bit (X86-64): Our lab machines have 48-bit VAS (256 TB), 36-bit PAS (64 GB)



Virtual address space (VAS): fixed size.

(Determined by amount of installed RAM.)

Cohabitating Physical Memory

- If process is given CPU, must also be in memory.
- Problem
  - Context-switching time (CST): 10 µsec
  - Loading from disk: 10 MB/s
  - To load 1 MB process: 100 msec = 10,000 x CST
  - Too much overhead! Breaks illusion of simultaneity
- Solution: keep multiple processes in memory
  - Context switch only between processes in memory

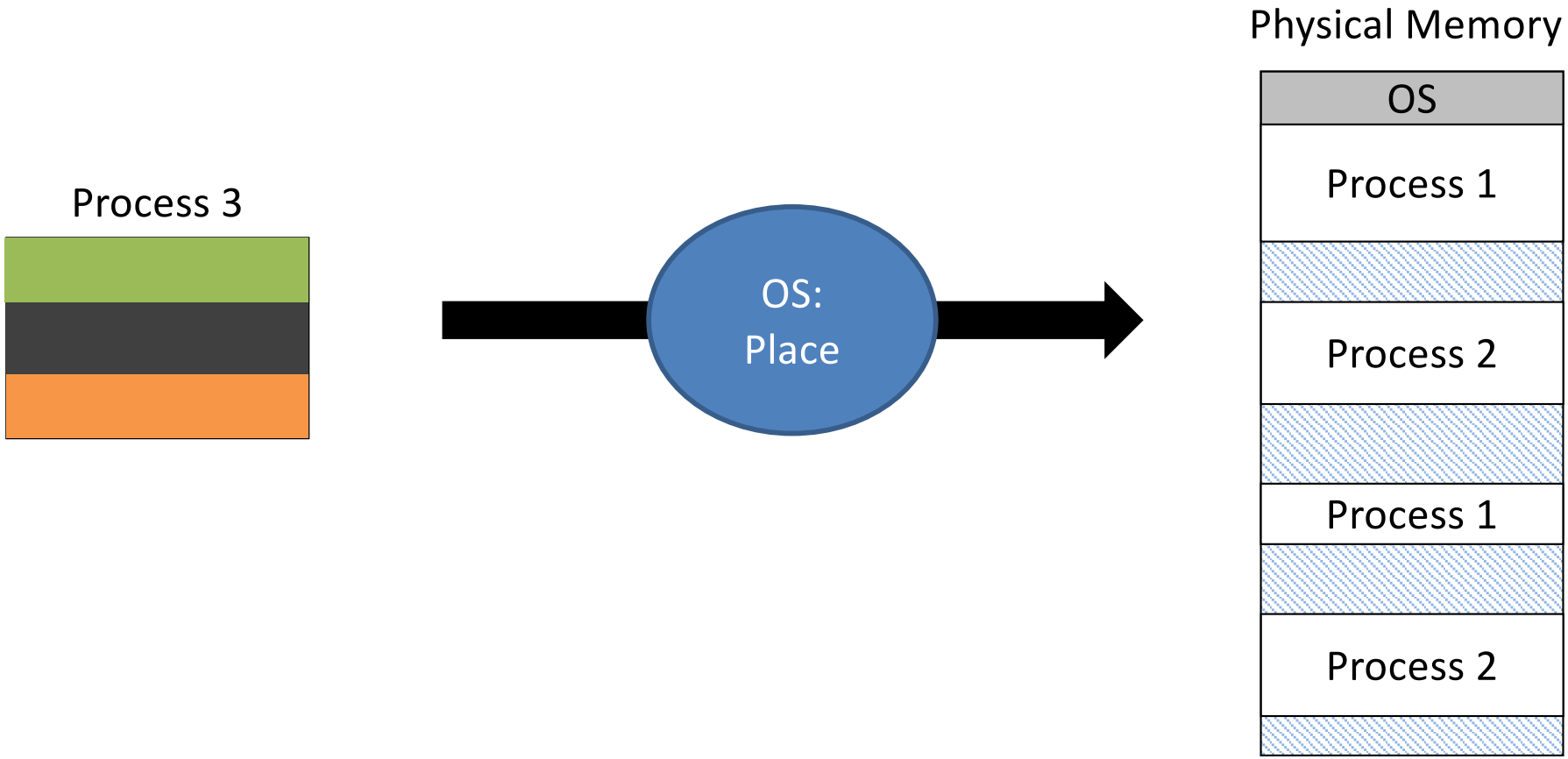
Memory Issues and Topics

- Where should process memories be placed?
  - Topic: “Classic” memory management
- How does the compiler model memory?
  - Topic: Logical memory model
- How to deal with limited physical memory?
  - Topics: Virtual memory, paging

Plan: Start with the basics (out of date) to motivate why we need the complex machinery of virtual memory and paging.

Problem Summary: Placement

- General solution: don't require all of a process's memory to be in one piece!



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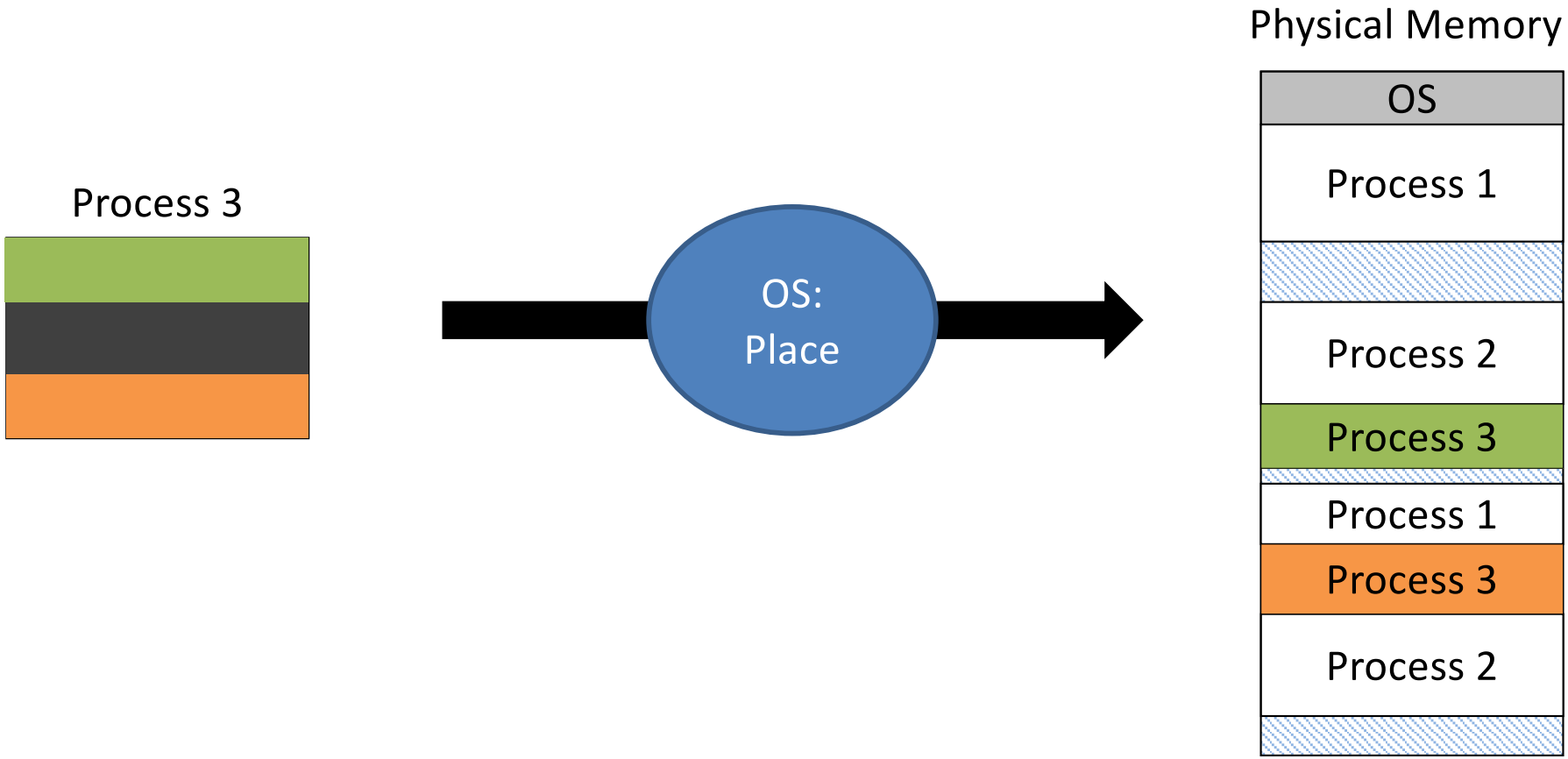

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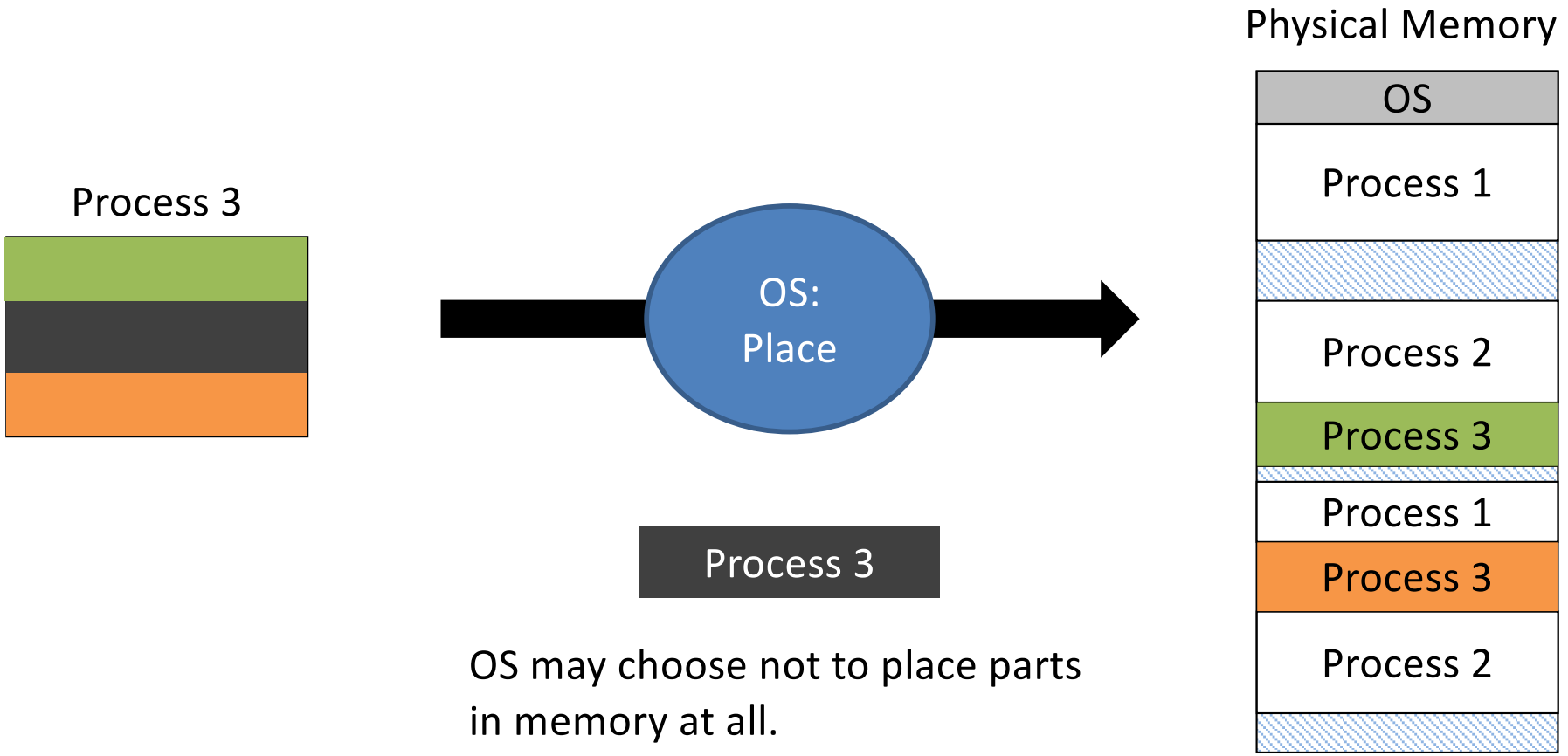
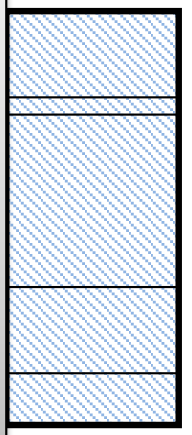


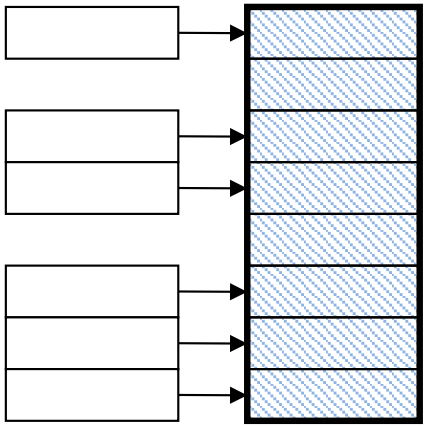
Two (Real) Approaches

- Se
- Pa
  int
- Se

In this class, we're only going to look at paging, the most common method today.



- Paged address space/memory
- Partition address space and memory into pages
- All pages are the same size



Paging Vocabulary

- For each process, the virtual address space is divided into fixed-size pages.
- For the system, the physical memory is divided into fixed-size frames.
- The size of a page is equal to that of a frame.
  - Often 4 KB in practice.

Main Idea

- ANY virtual page can be stored in any available frame.
  - Makes finding an appropriately-sized memory gap very easy – they're all the same size.

- For each process, OS keeps a table mapping each virtual page to physical frame.

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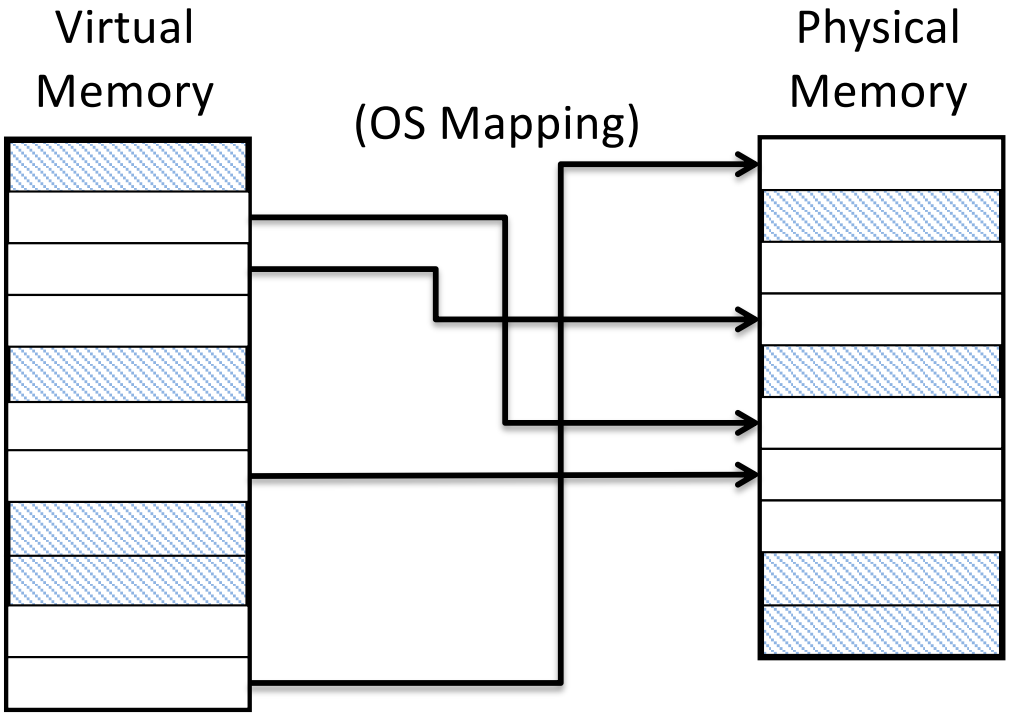

Implications for fragmentation?

External: goes away. No more awkwardly-sized, unusable gaps.

Internal: About the same. Process can always request memory and not use it.

Addressing

- Like we did with caching, we're going to chop up memory addresses into partitions.
- Virtual addresses:
  - High-order bits: page #
  - Low-order bits: offset within the page
- Physical addresses:
  - High-order bits: frame #
  - Low-order bits: offset within the frame

Example: 32-bit virtual addresses

- Suppose we have 8-KB (8192-byte) pages.
- We need enough bits to individually address each byte in the page.
  - How many bits do we need to address 8192 items?

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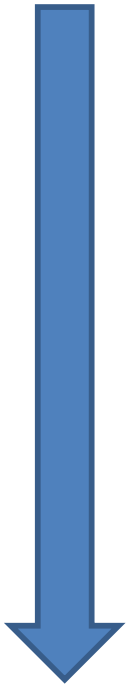
Address Partitioning

Virtual address:

We'll call these bits *p*.

We'll call these bits *i*.

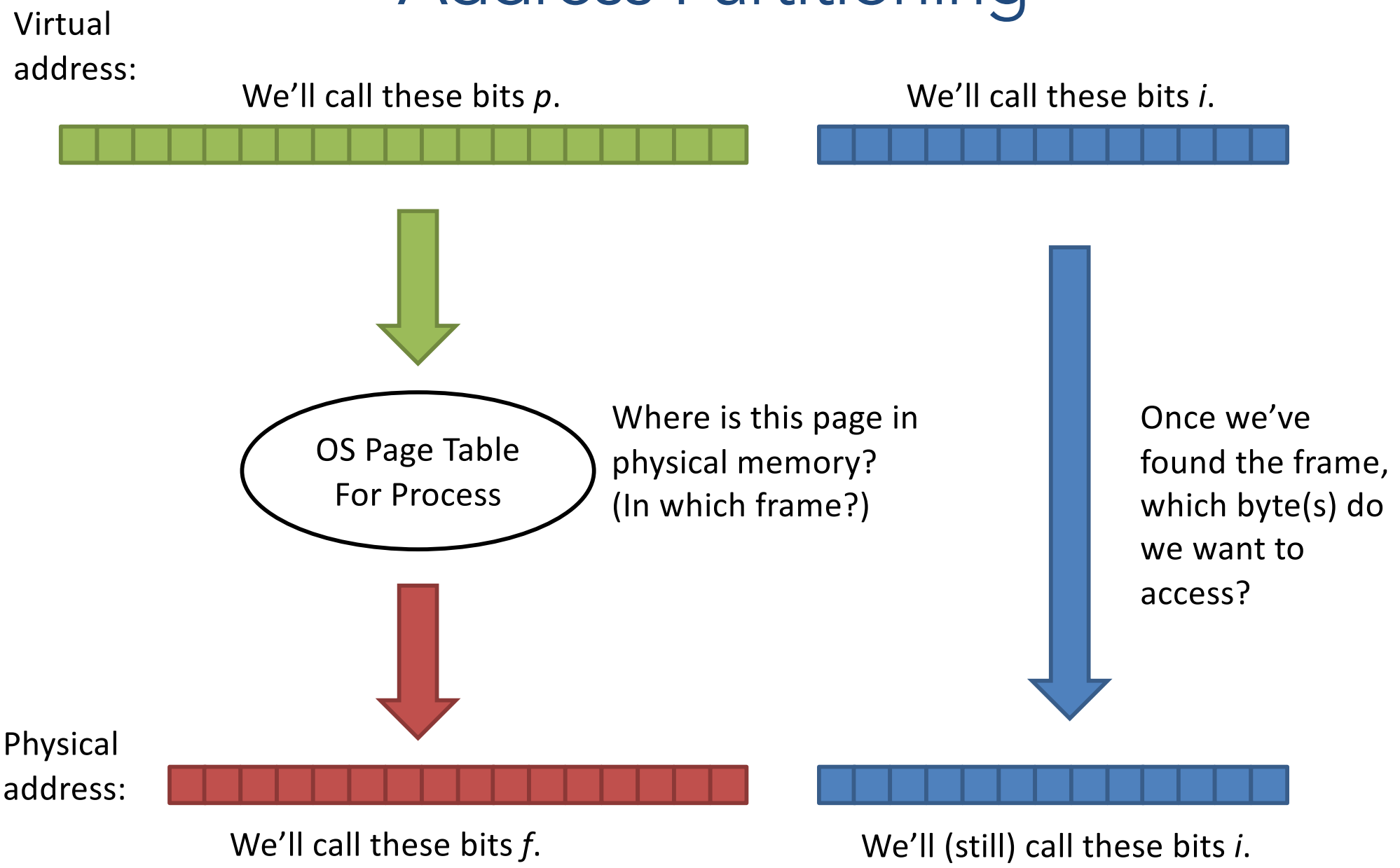


Once we've found the frame, which byte(s) do we want to access?

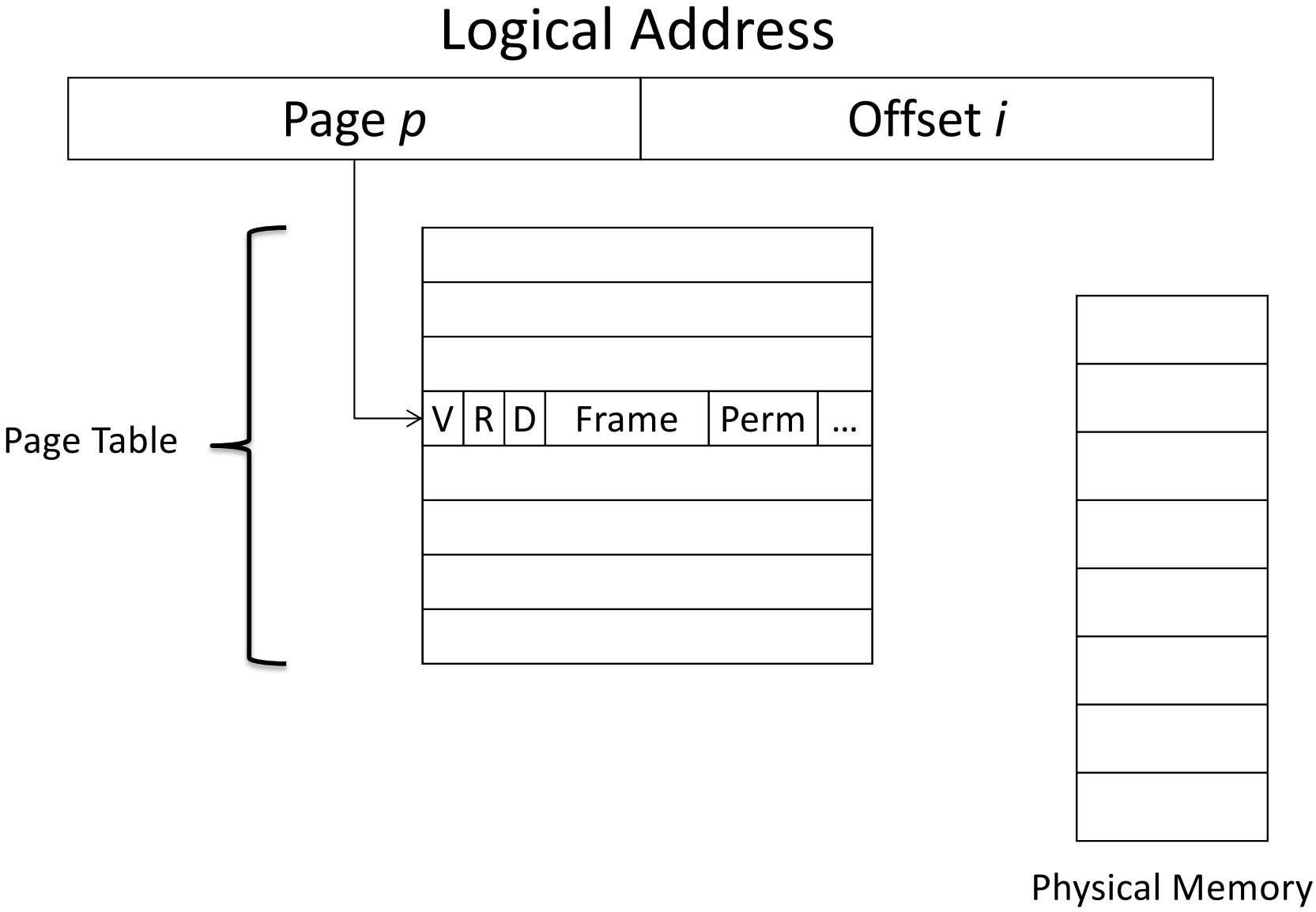
Physical address:

We'll (still) call these bits *i*.

Address Partitioning



Address Translation



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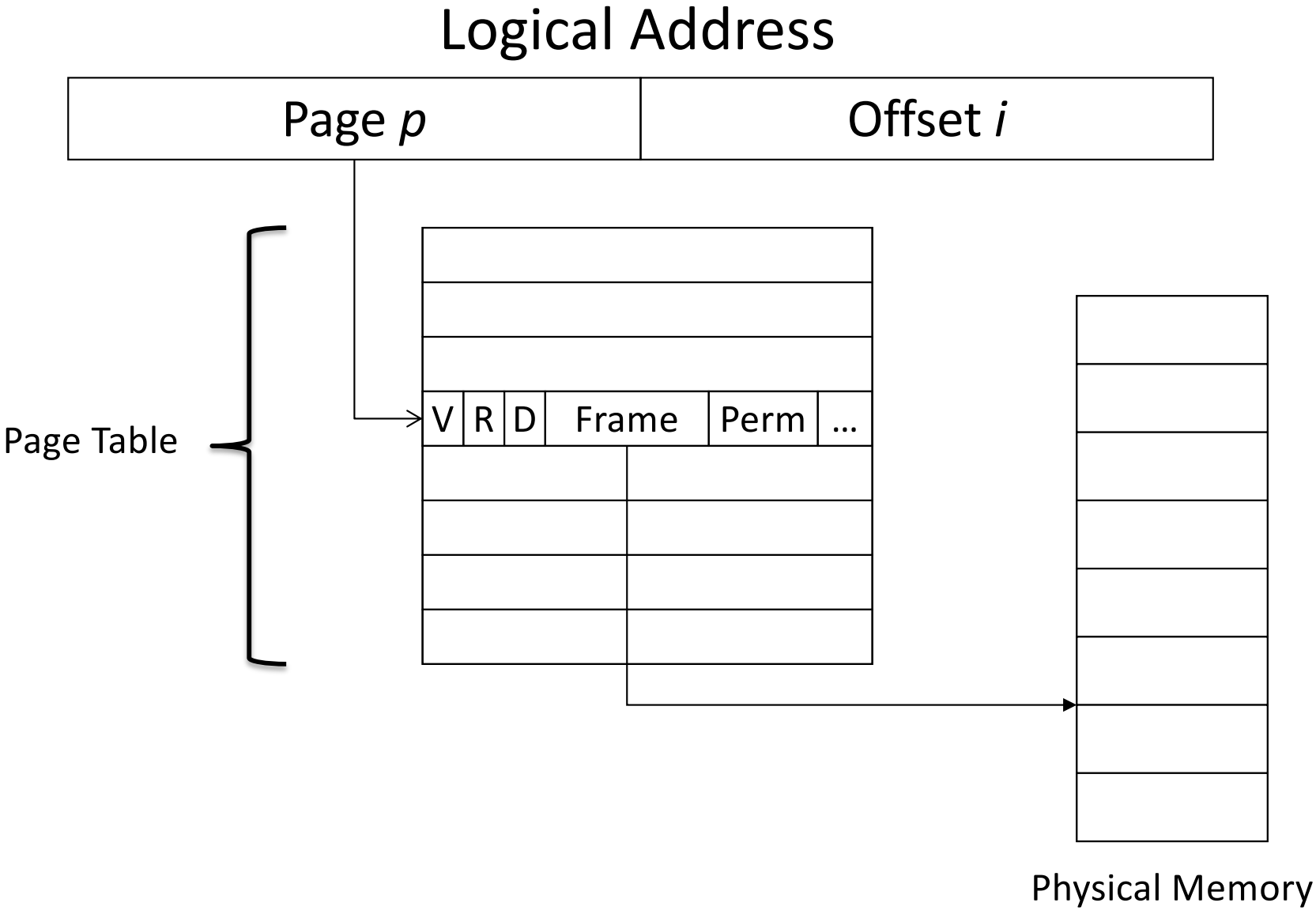

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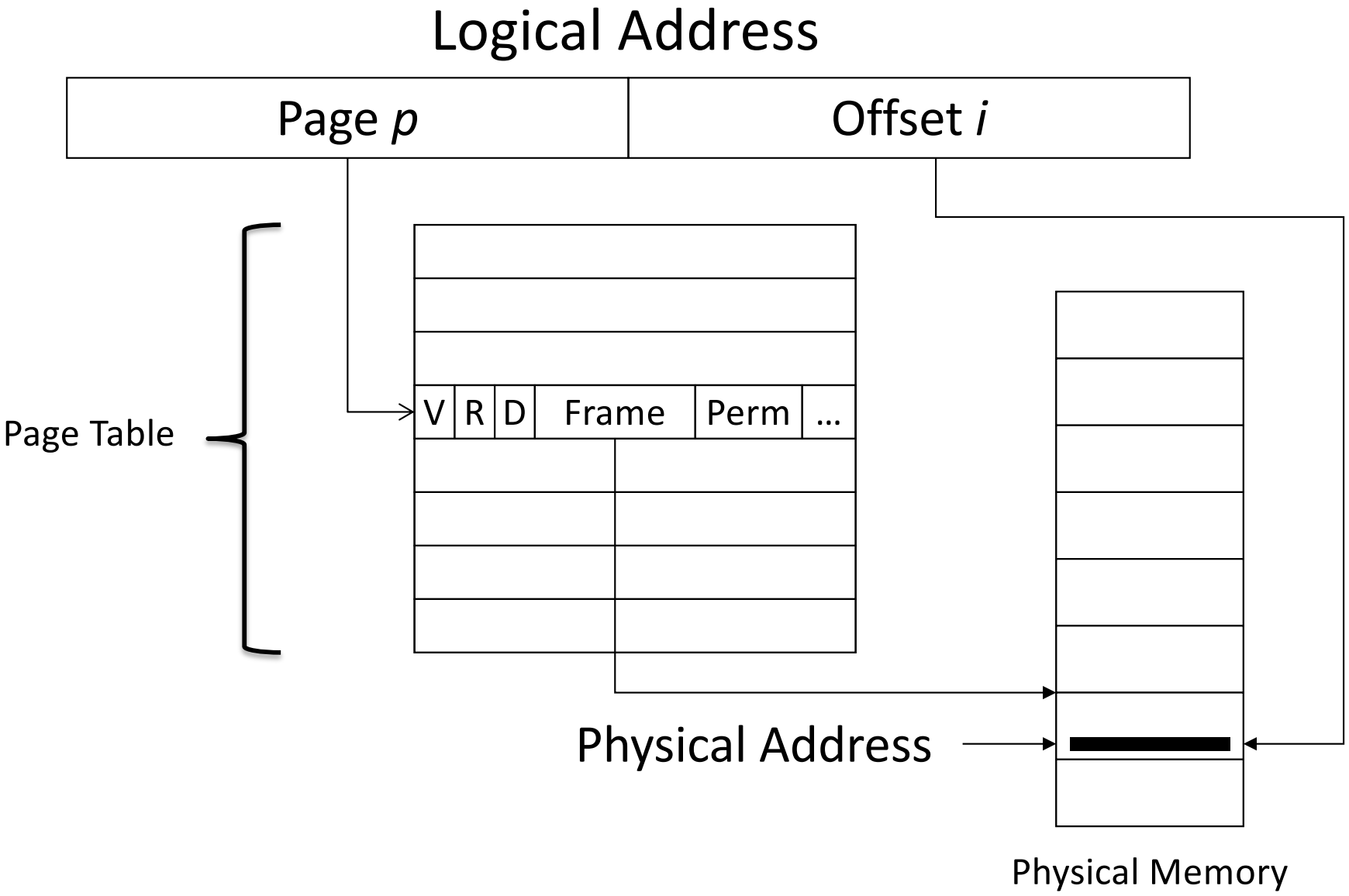
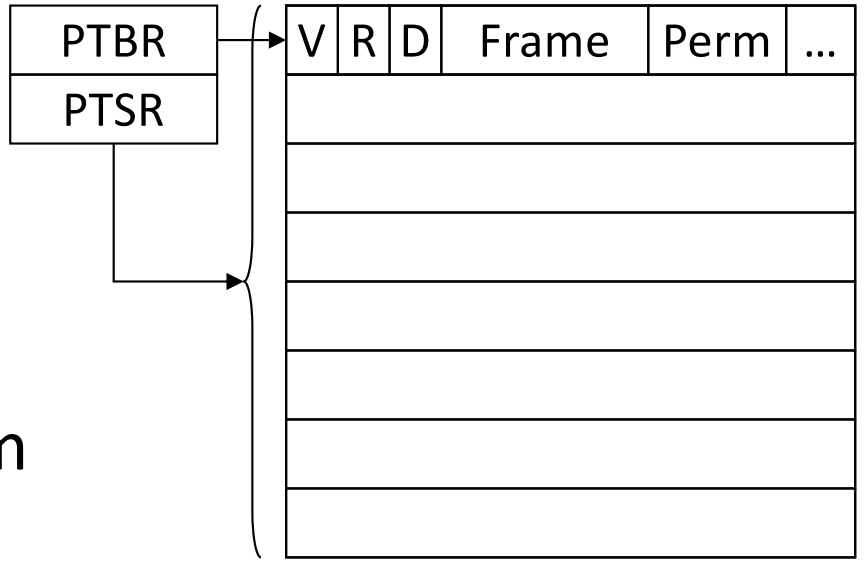


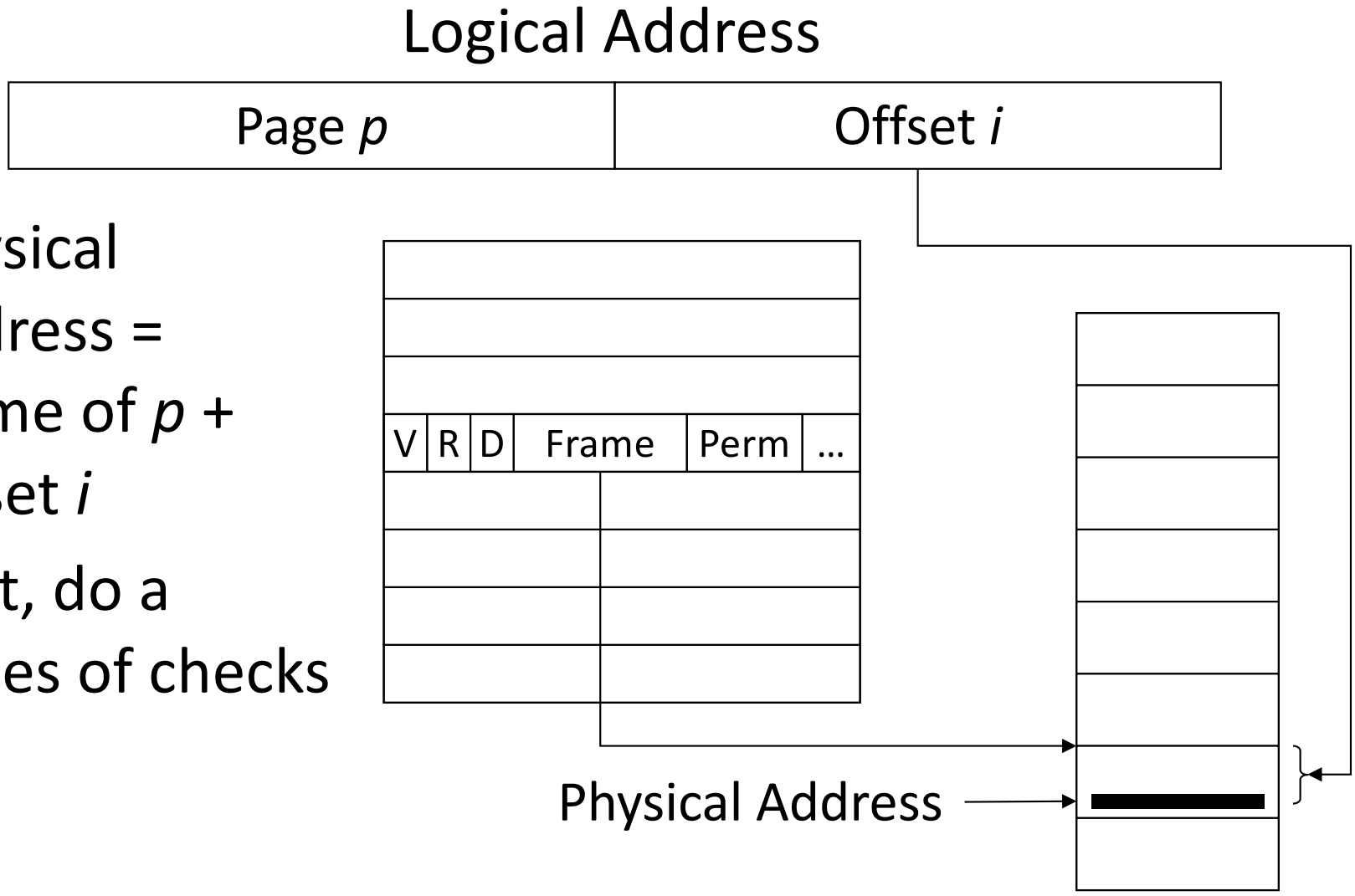
Page Table

- One table per process
- Table entry elements
  - V: valid bit
  - R: referenced bit
  - D: dirty bit
  - Frame: location in phy mem
  - Perm: access permissions
- Table parameters in memory
  - Page table base register
  - Page table size register

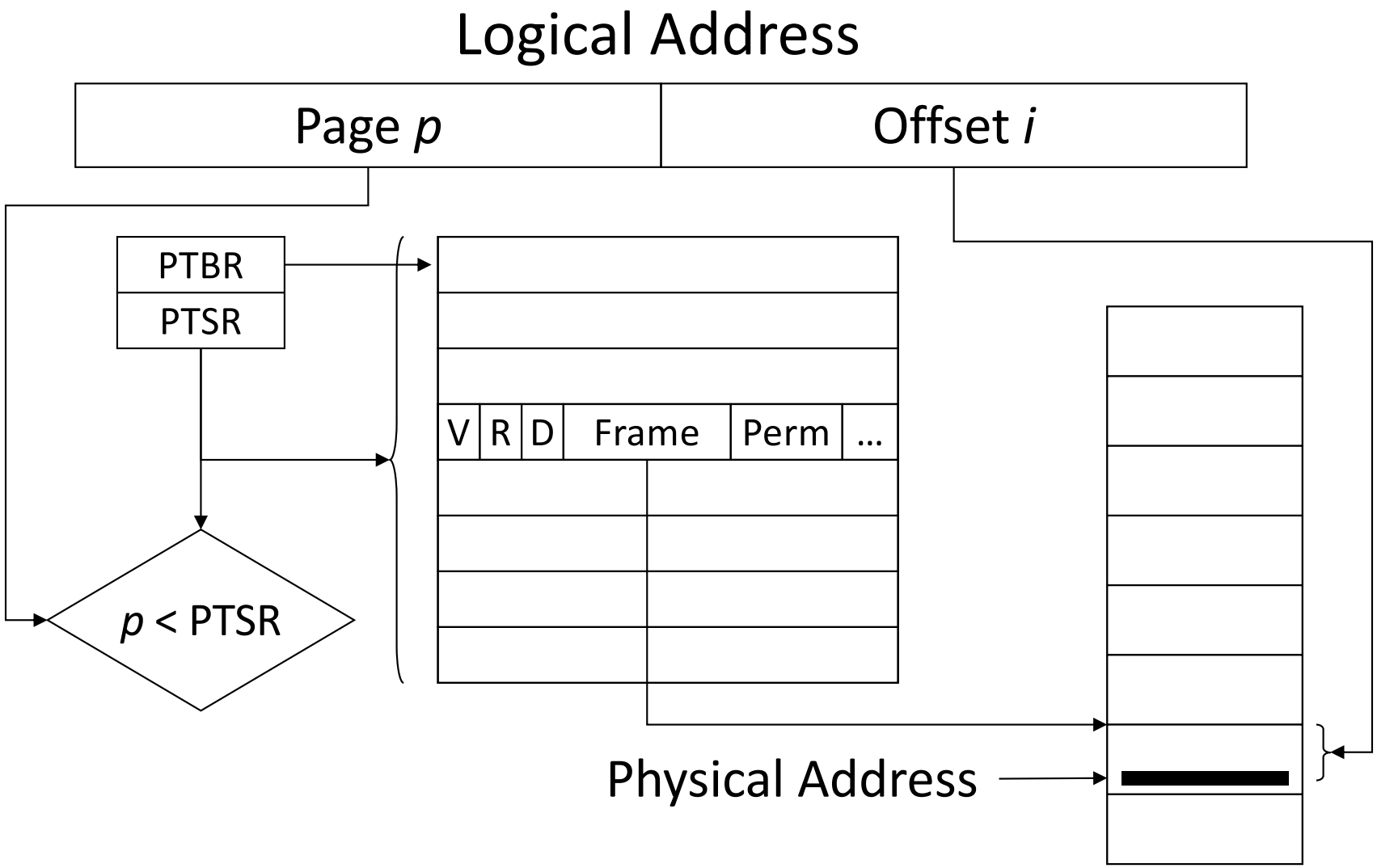


Address Translation

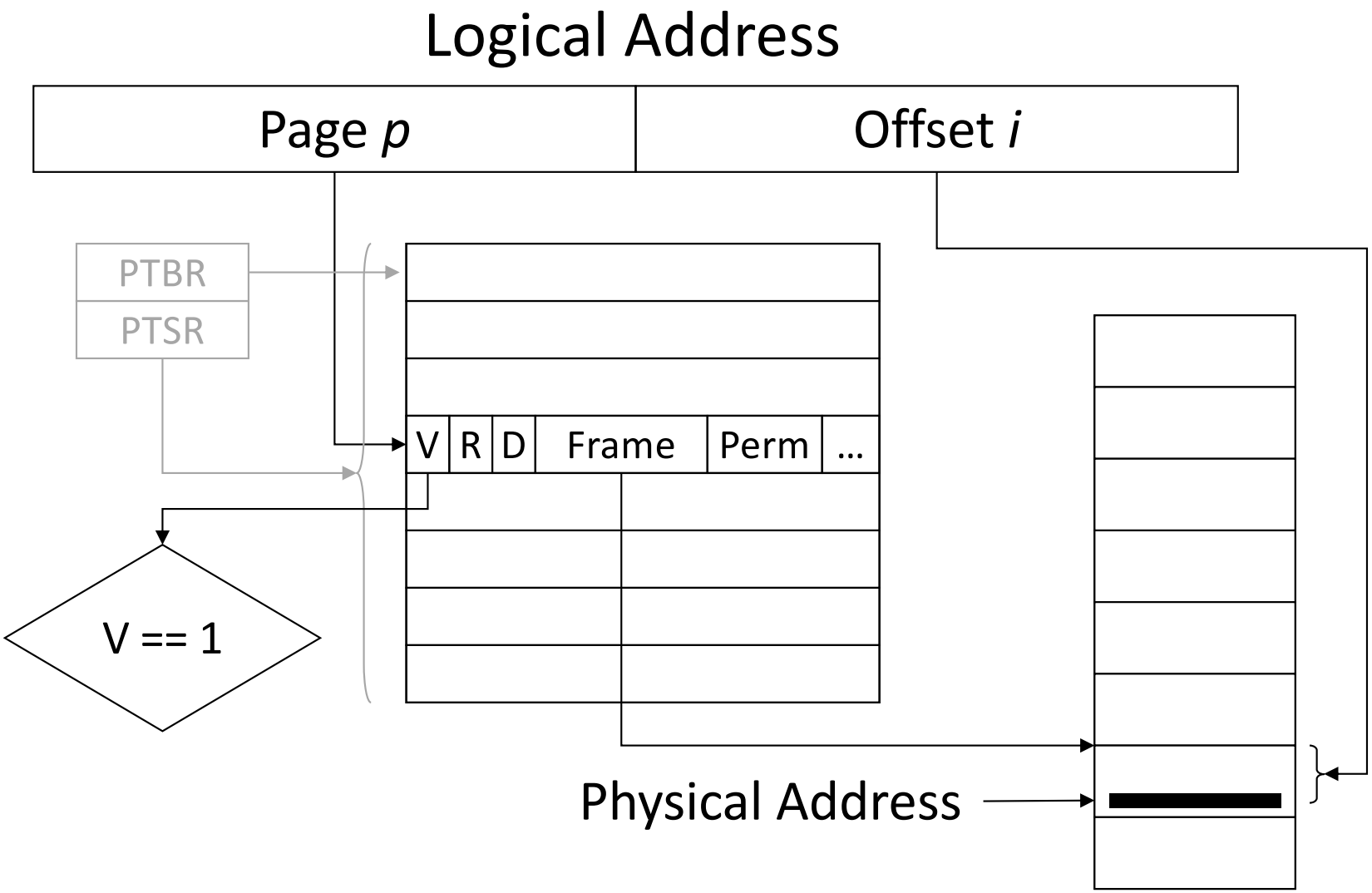
- Physical address = frame of *p* + offset *i*
- First, do a series of checks



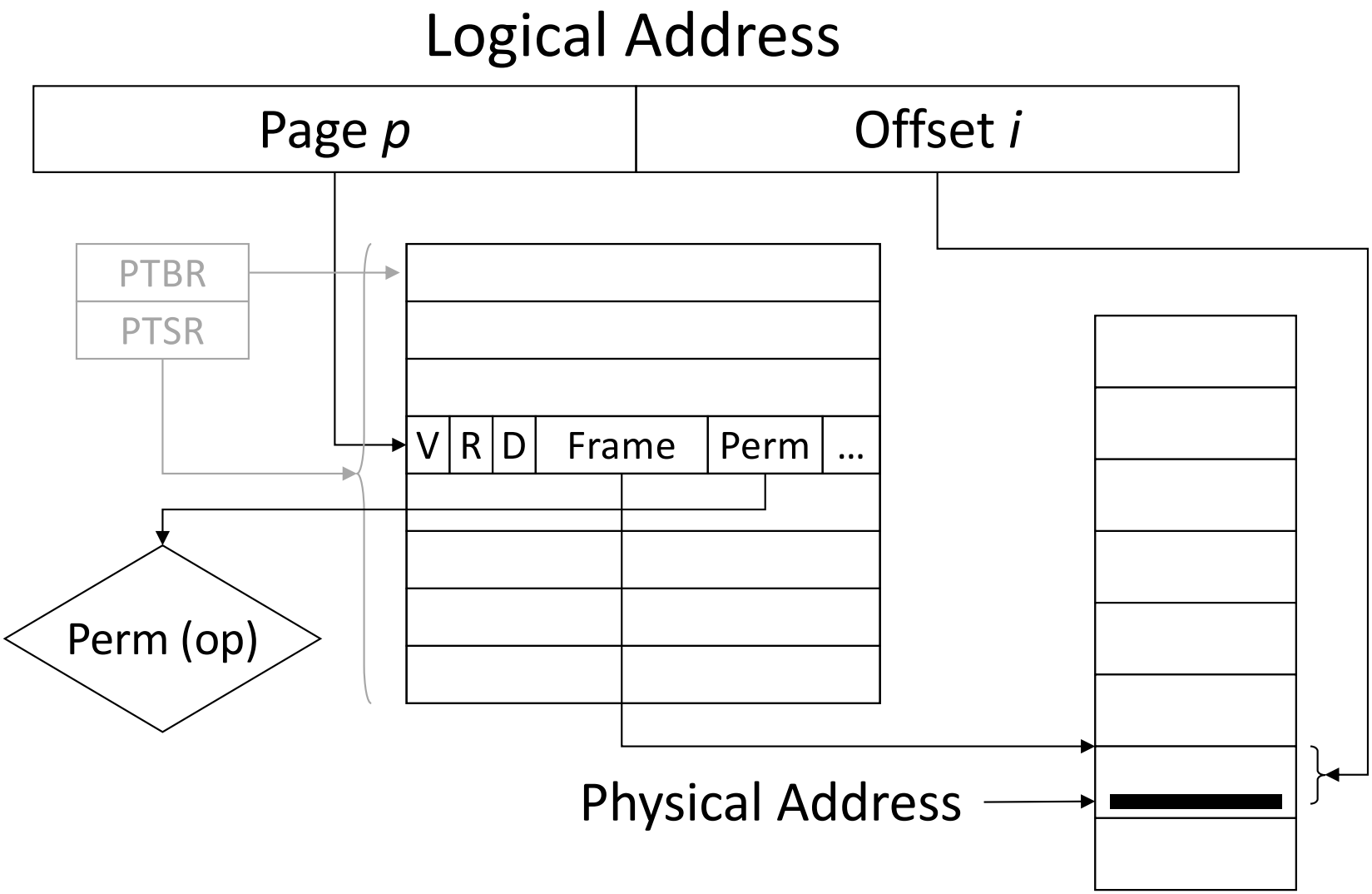
Check if Page *p* is Within Range



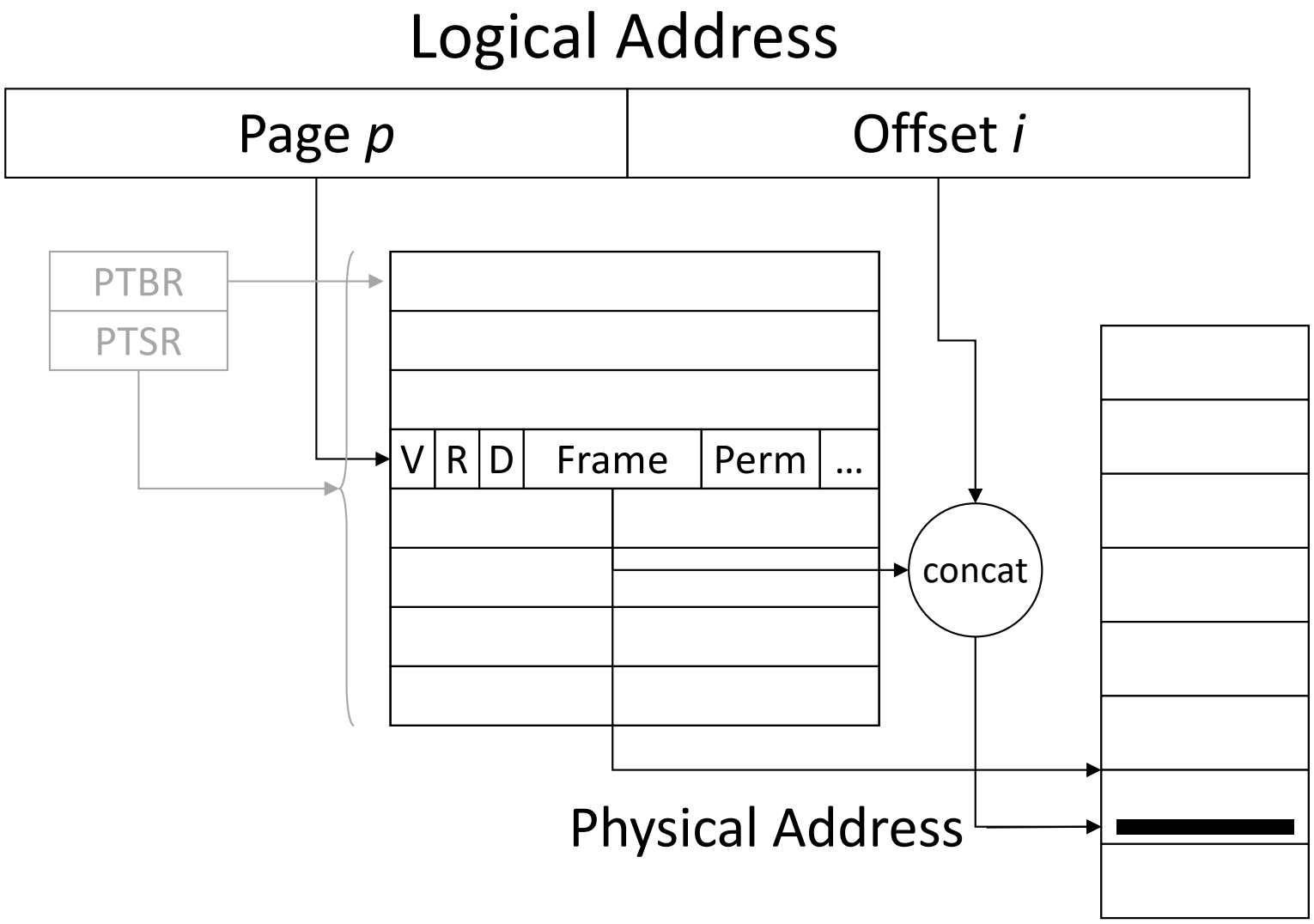
Check if Page Table Entry *p* is Valid



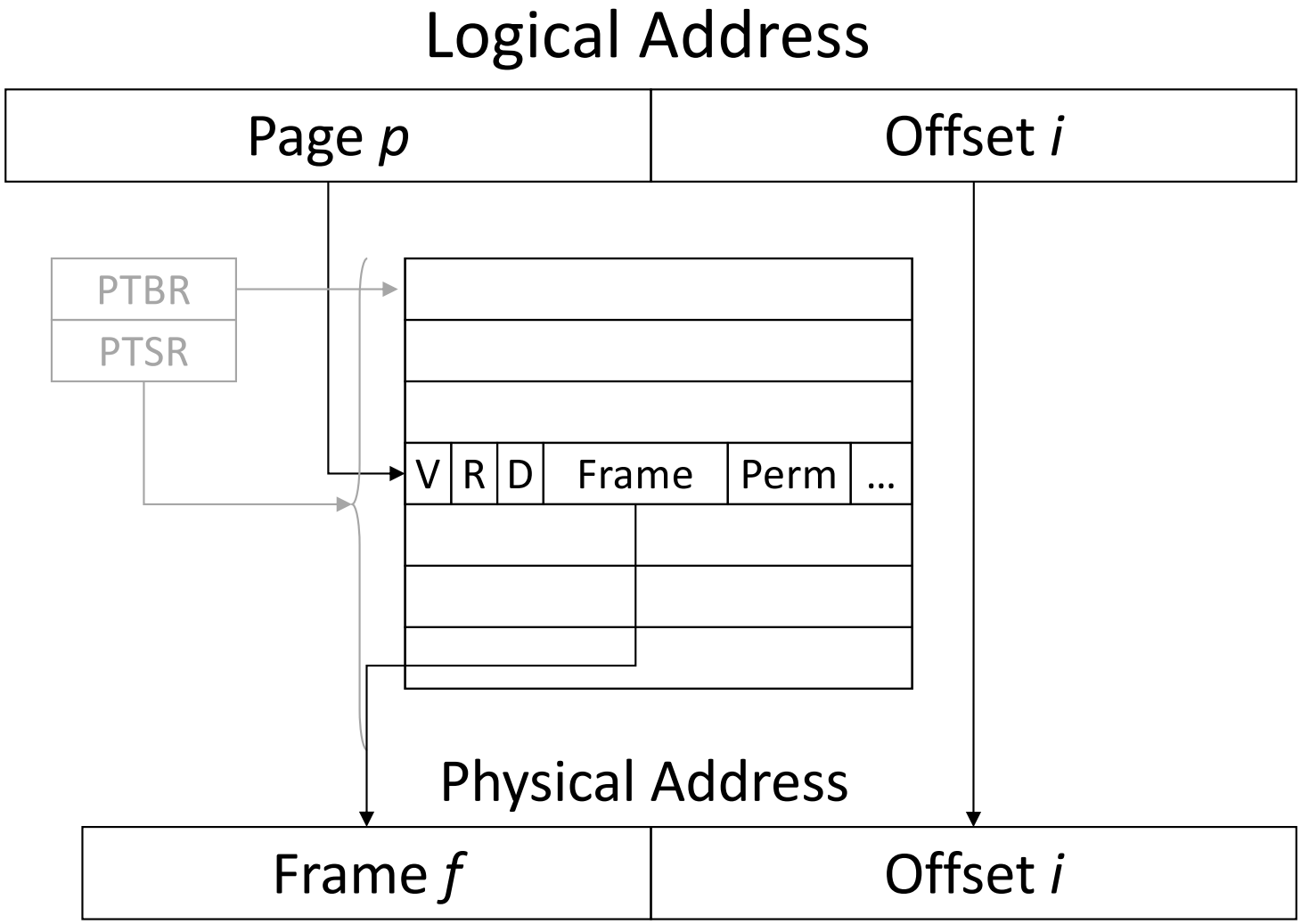
Check if Operation is Permitted



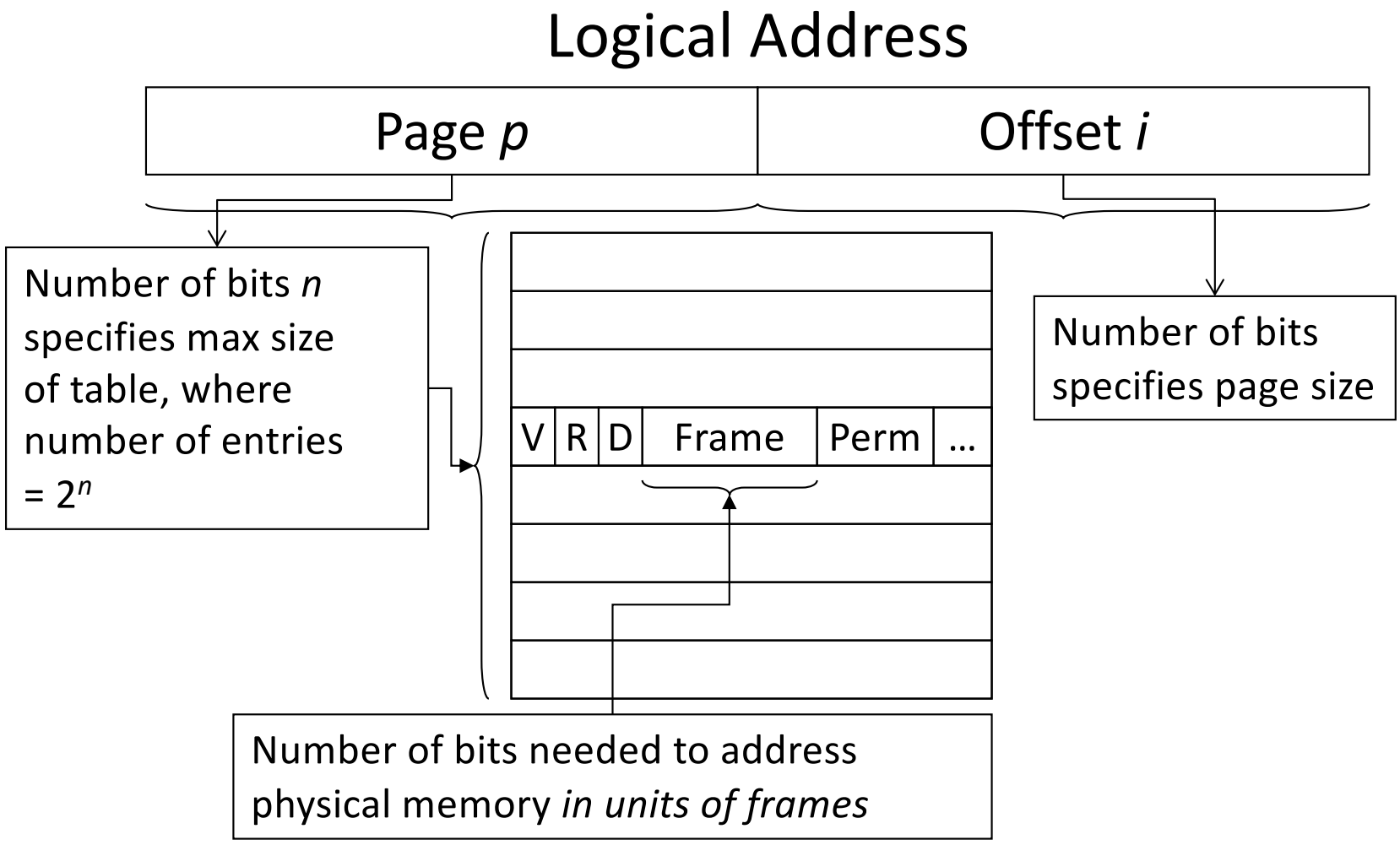
Translate Address



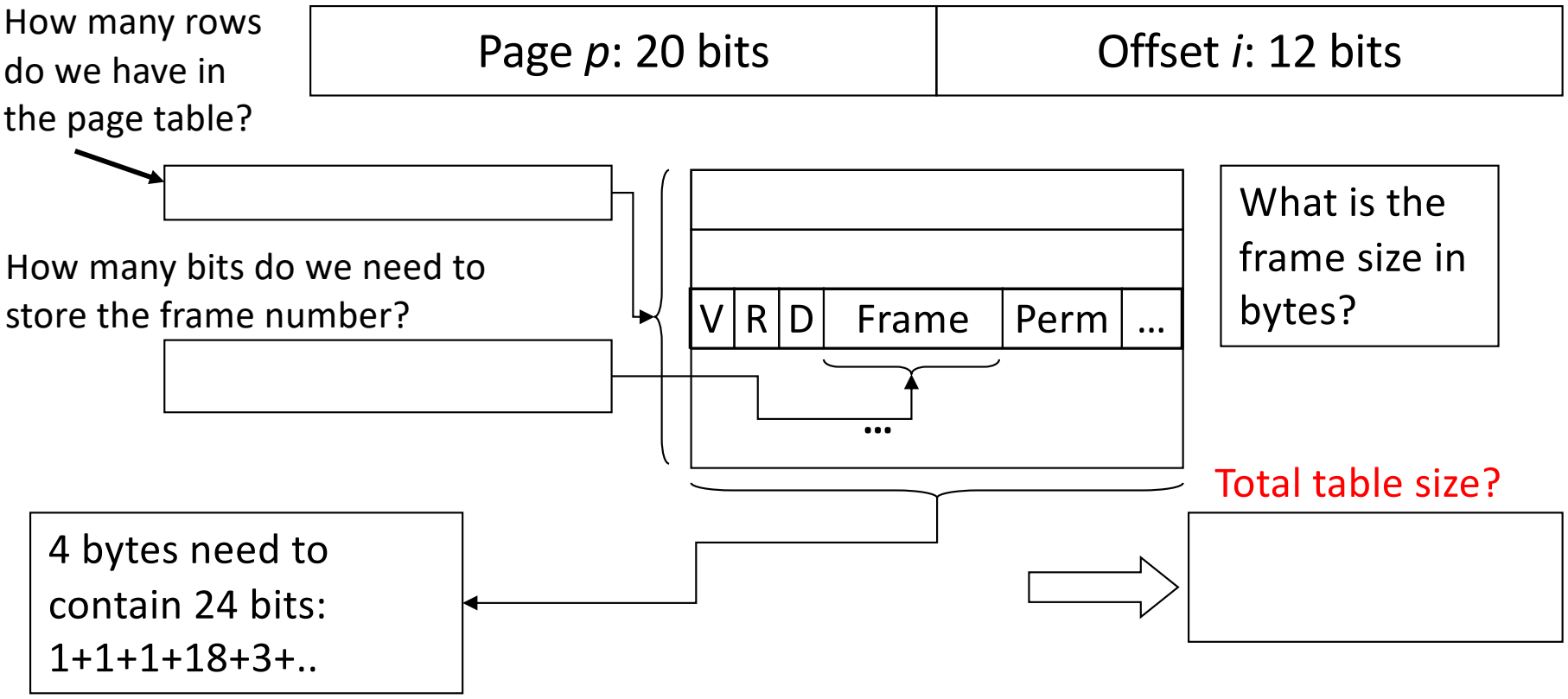
Physical Address by Concatenation



Sizing the Page Table

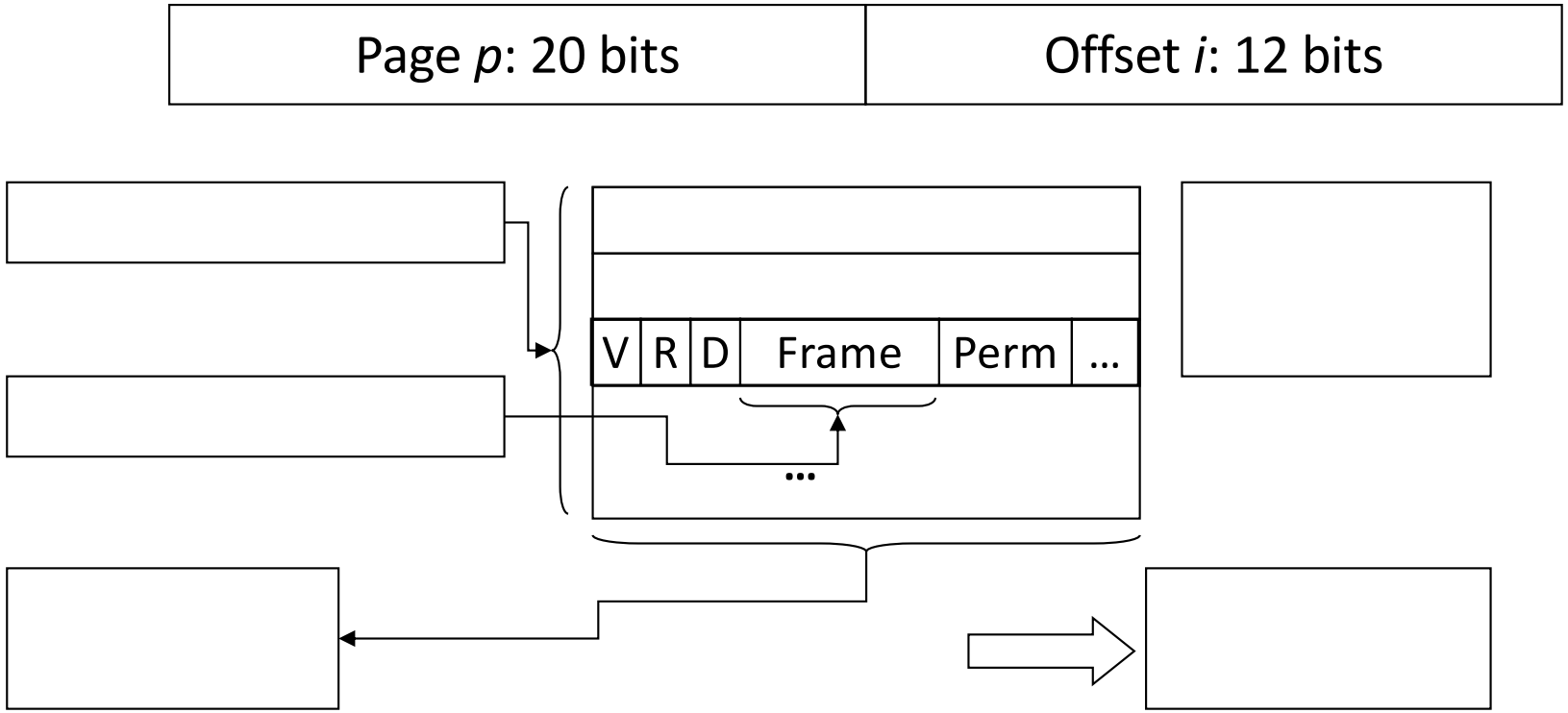


Example of Sizing the Page Table
(1K = 2^{10}, 1M = 2^{20}, 1G = 2^{30})



- Given: 32 bit virtual addresses, 1 GB physical memory
  - Address partition: 20 bit page number, 12 bit offset

Example of Sizing the Page Table



- Given: 32 bit virtual addresses, 1 GB physical memory
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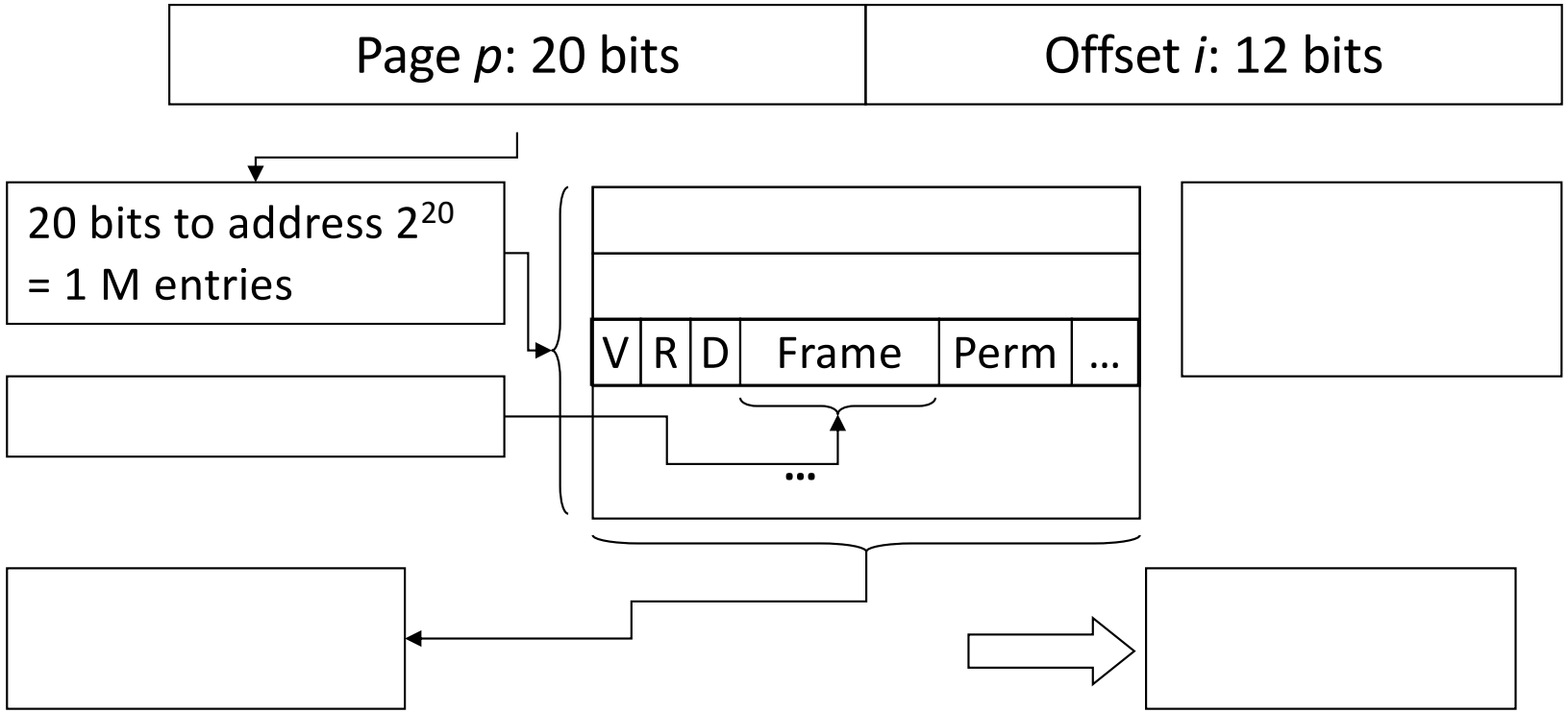
How many entries (rows) will there be in this page table?

A. 2^{12}, because that's how many the offset field can address
B. 2^{20}, because that's how many the page field can address
C. 2^{30}, because that's how many we need to address 1 GB
D. 2^{32}, because that's the size of the entire address space

Example of Sizing the Page Table



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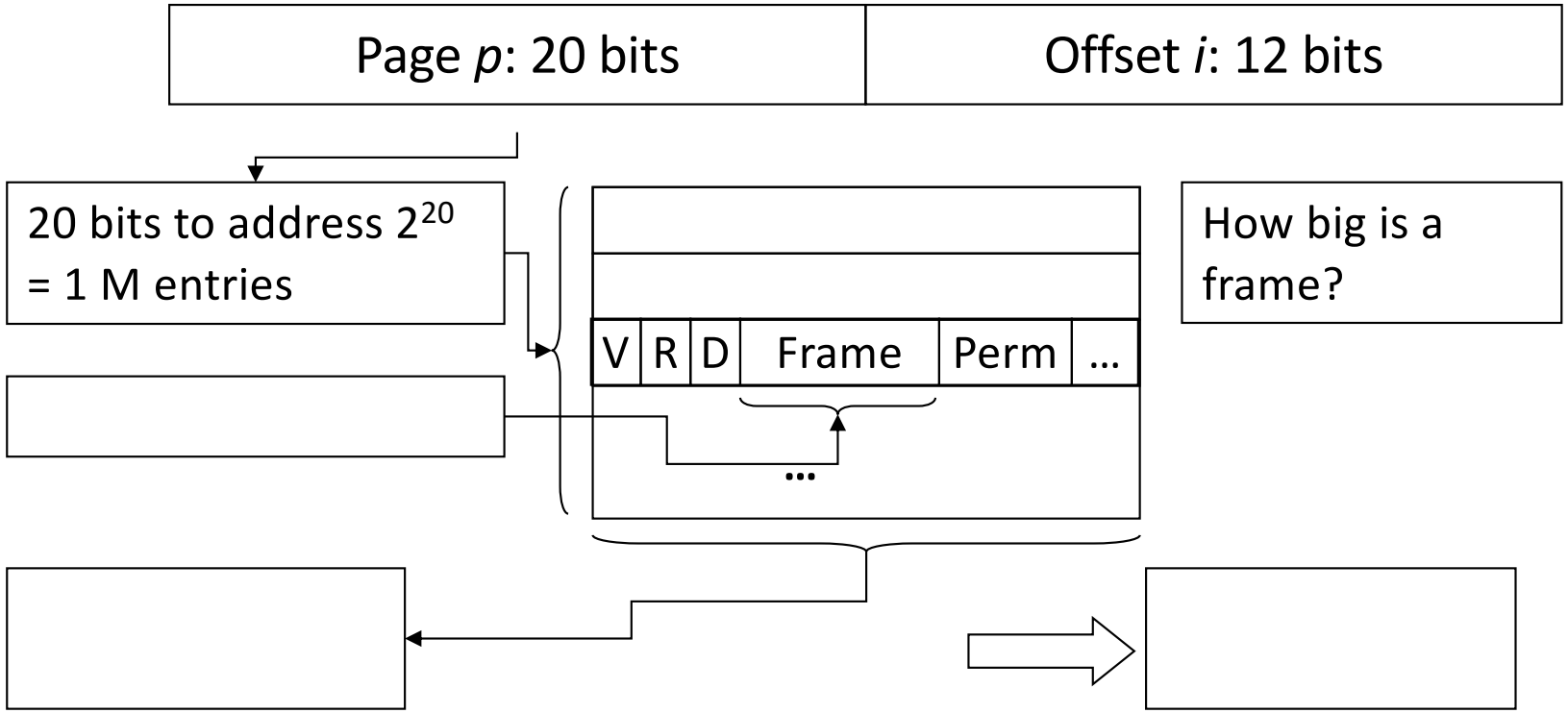

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What will be the frame size, in bytes?

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B. 2^{20}, because that's how many bytes the page field can address
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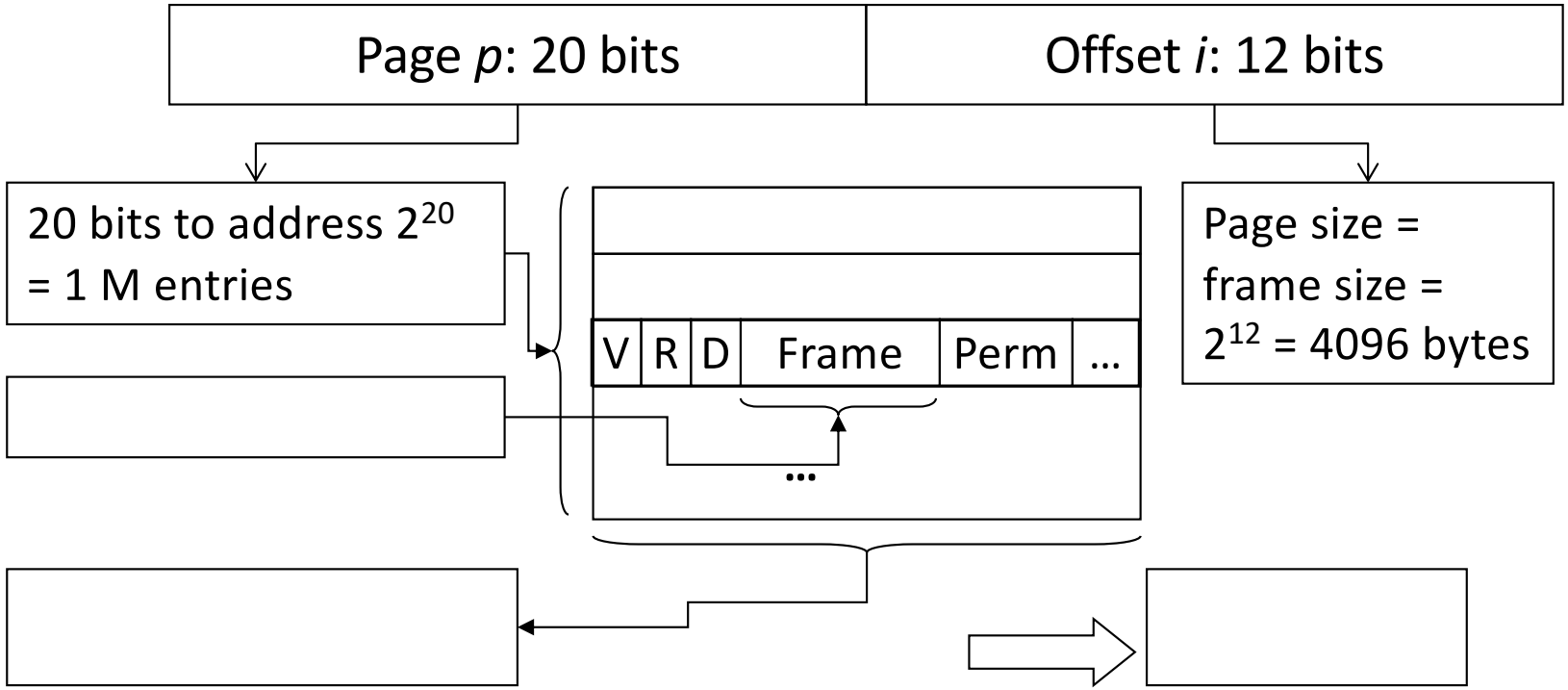

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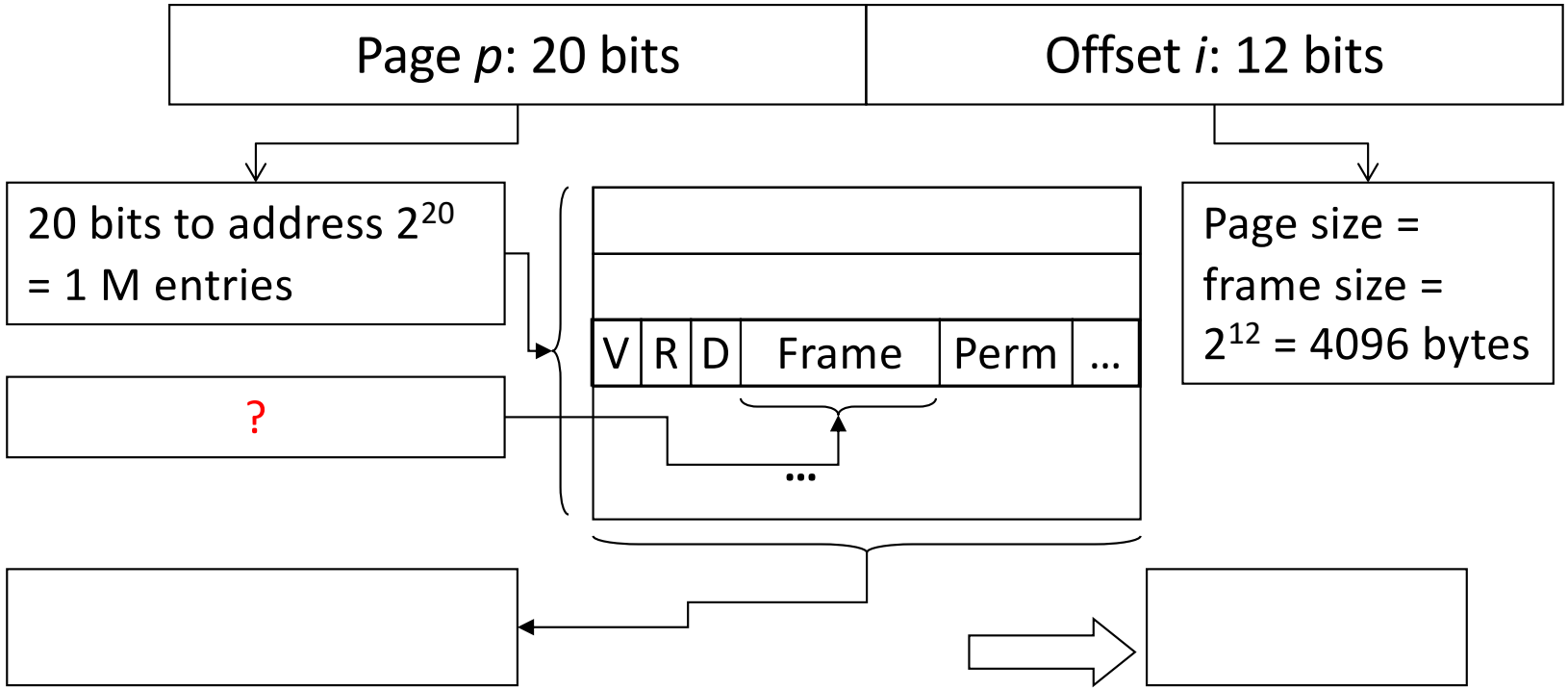
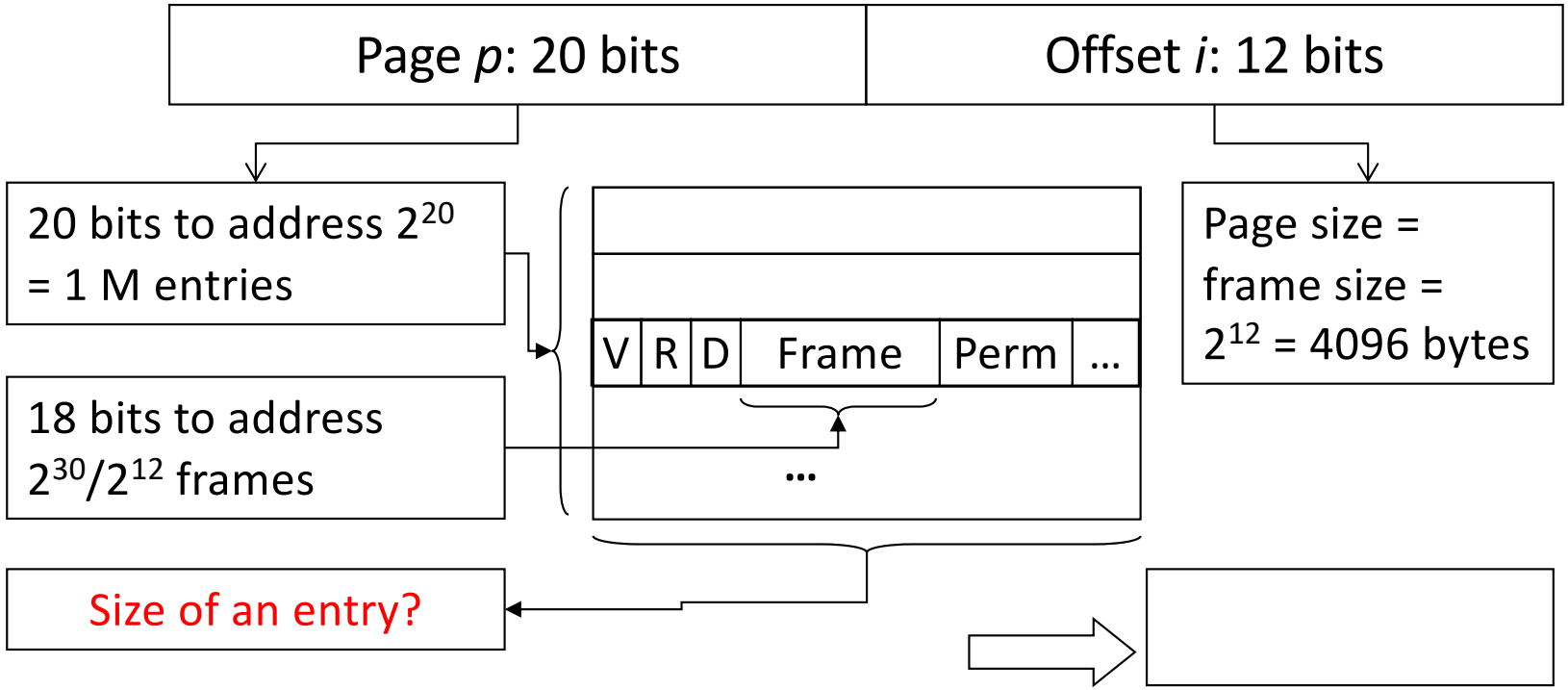
How many bits do we need to store the frame number?



- Given: 32 bit virtual addresses, 1 GB physical memory
  - Address partition: 20 bit page number, 12 bit offset
- A: 12 B: 18 C: 20 D: 30 E: 32

Example of Sizing the Page Table



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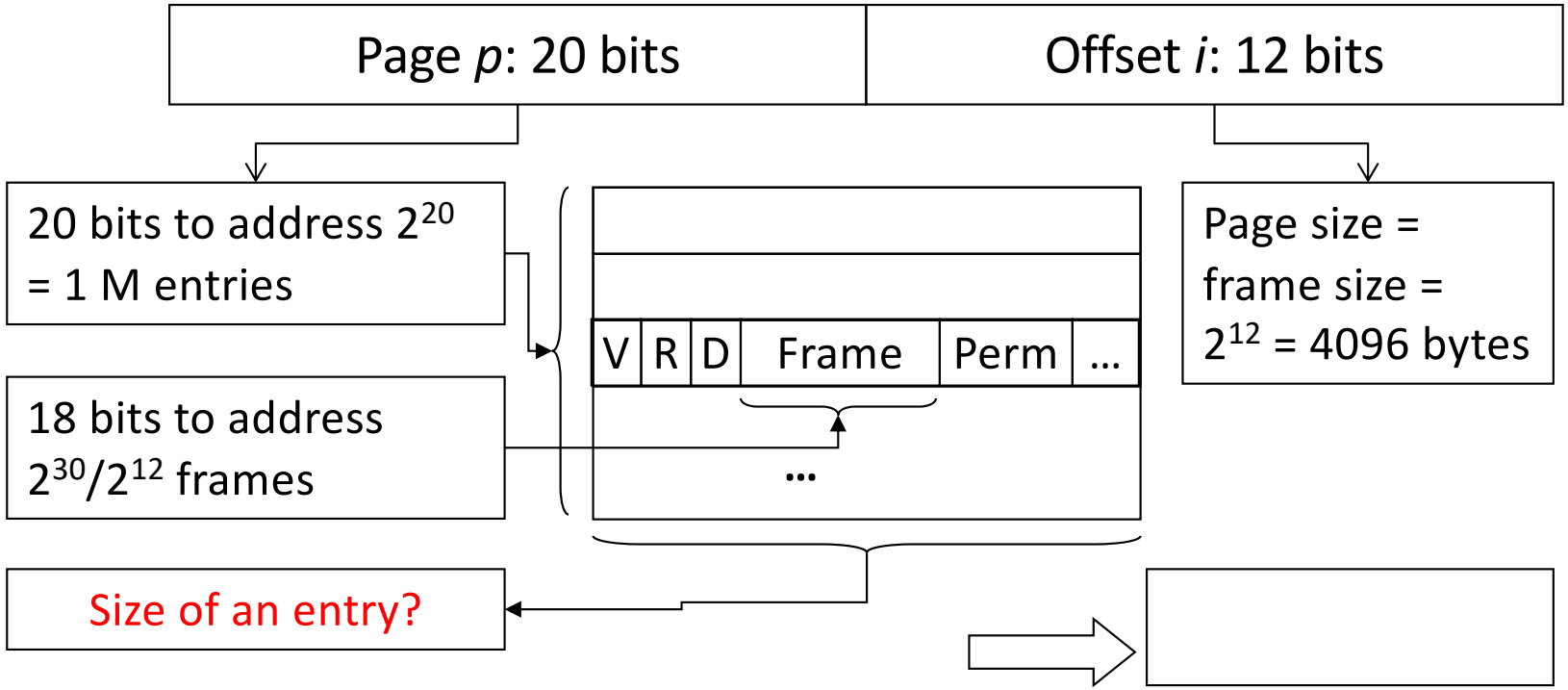
How big is an entry, in bytes? (Round to a power of two bytes.)



- Given: 32 bit virtual addresses, 1 GB physical memory
  - Address partition: 20 bit page number, 12 bit offset
- A: 1 B: 2 C: 4 D: 8

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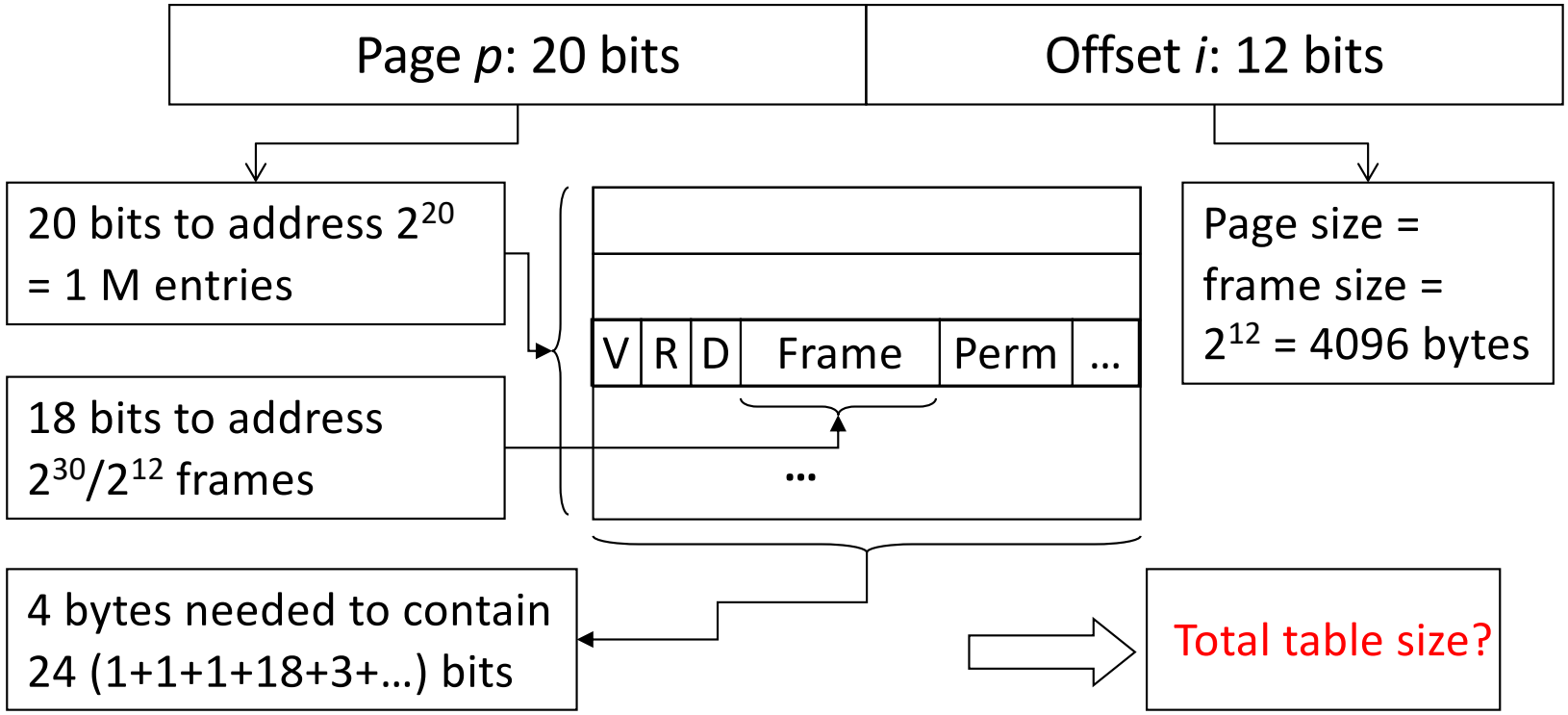

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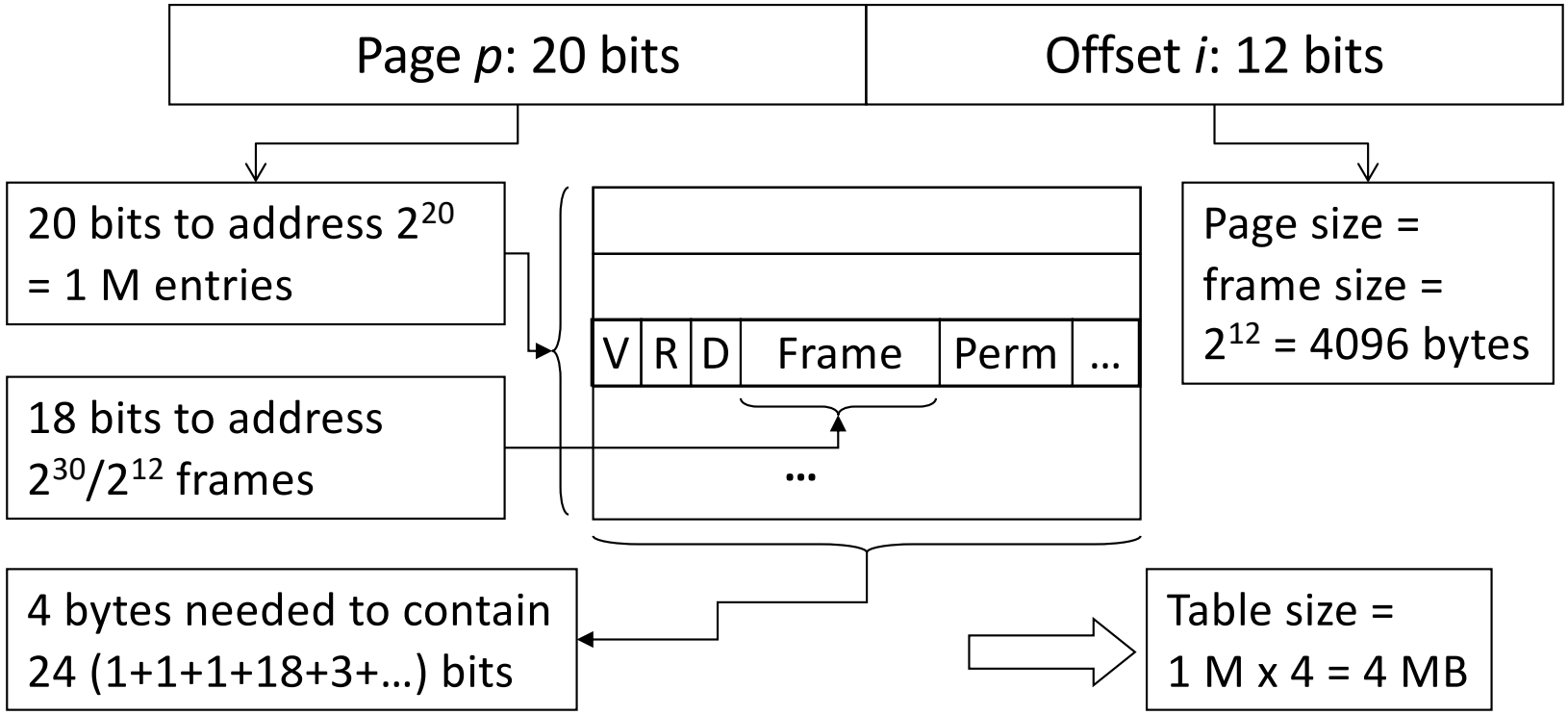


- 4 MB of bookkeeping for *every process*?
  - 200 processes -> 800 MB just to store page tables…

Concerns

- We’re going to need a ton of memory just for page tables…
- Wait, if we need to do a lookup in our page table, which is in memory, every time a process accesses memory…
  - Isn’t that slowing down memory by a factor of 2?

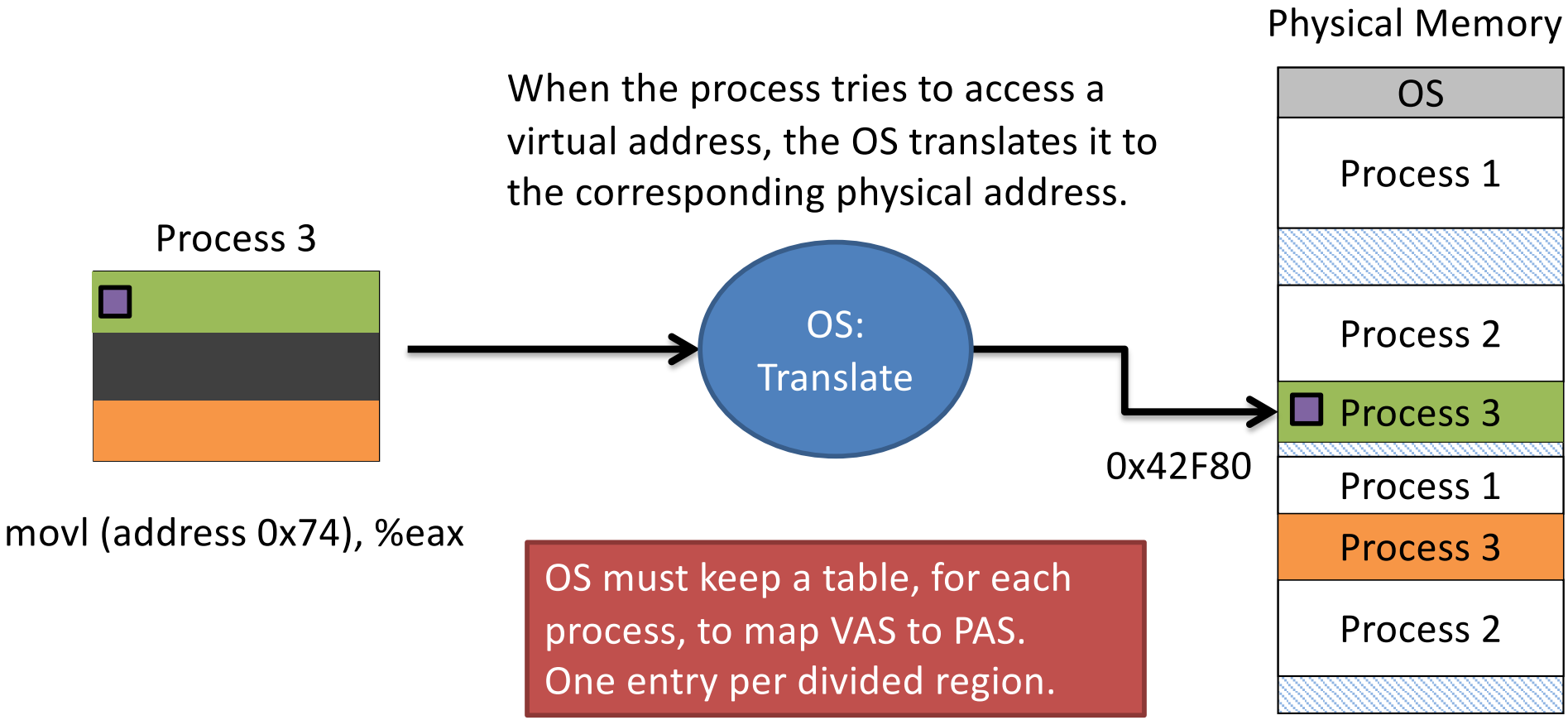
Cost of Translation

- Each lookup costs another memory reference
  - For each reference, additional references required
  - Slows machine down by factor of 2 or more

- Take advantage of locality
  - Most references are to a small number of pages
  - Keep translations of these in high-speed memory (a cache for page translation)

Problem Summary: Addressing

- General solution: OS must translate process's VAS accesses to the corresponding physical memory location.



Problem: Storage

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  - Topic: “Classic” memory management
- How does the compiler model memory?
  - Topic: Logical memory model
- How to deal with limited physical memory?
  - Topics: Virtual memory, paging

Recall "Storage Problem"

- We must keep multiple processes in memory, but how many?
  - Lots of processes: they must be small
  - Big processes: can only fit a few

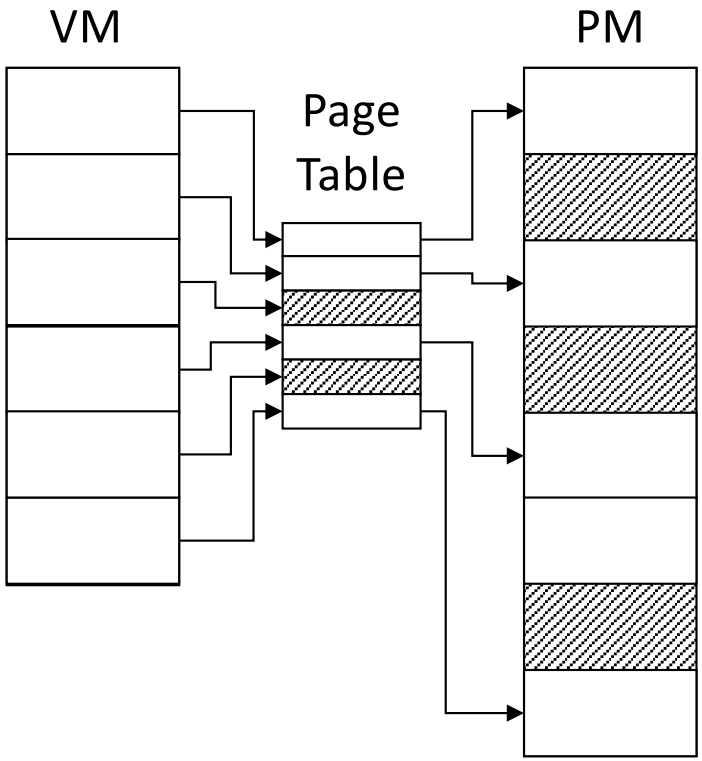
- How do we balance this tradeoff?

Locality to the rescue!

VM Implications

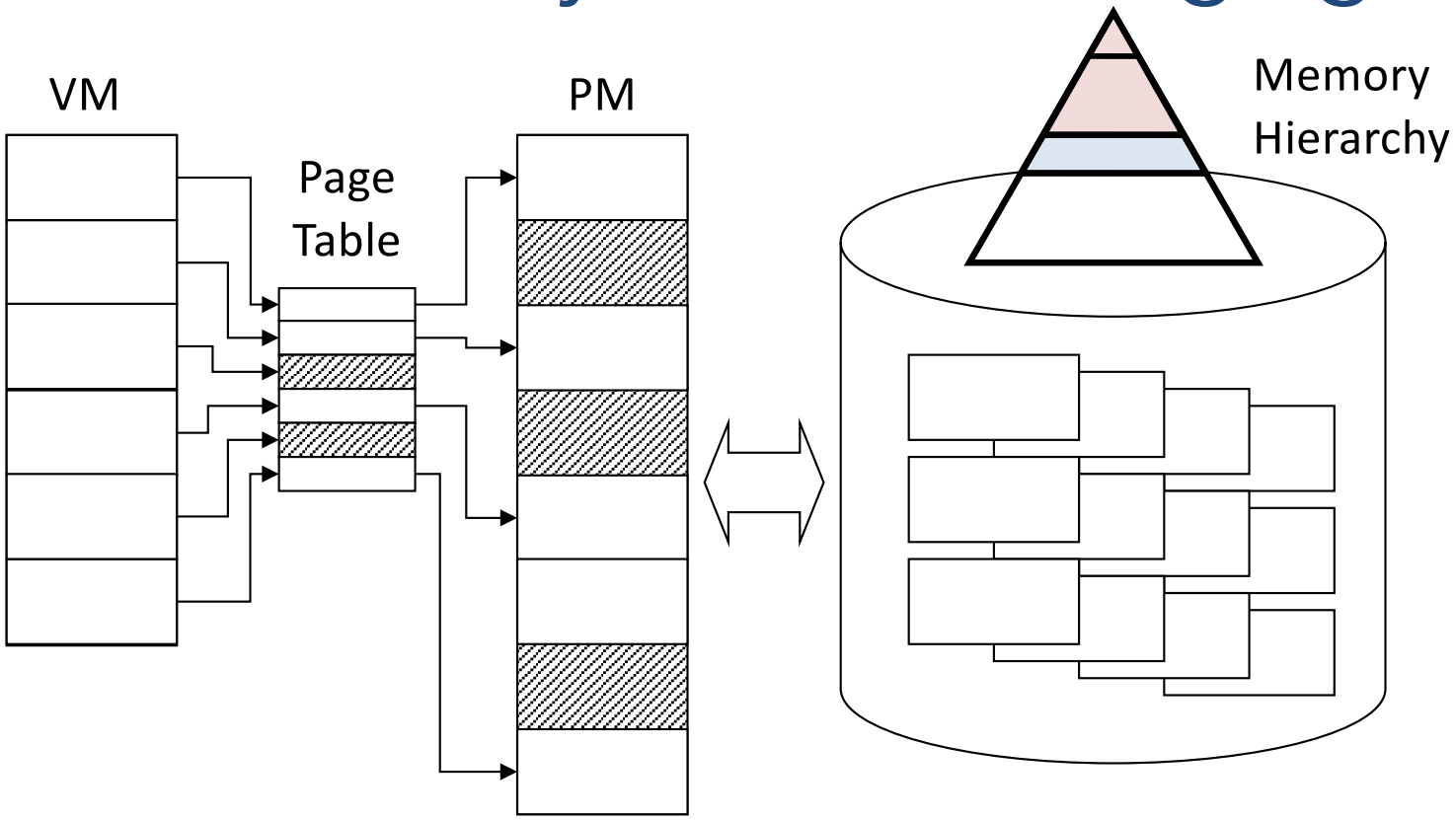
- Not all pieces need to be in memory
  - Need only piece being referenced
  - Other pieces can be on disk
  - Bring pieces in only when needed
- Illusion: there is much more memory
- What's needed to support this idea?
  - A way to identify whether a piece is in memory
  - A way to bring in pieces (from where, to where?)
  - Relocation (which we have)

Virtual Memory based on Paging



- Before
  - All virtual pages were in physical memory

Virtual Memory based on Paging



- Now
  - All virtual pages reside on disk
  - Some also reside in physical memory (which ones?)
- Ever been asked about a swap partition on Linux?

Sample Contents of Page Table Entry

Valid	Ref	Dirty	Frame number	Prot: rwx

- Valid: is entry valid (page in physical memory)?
- Ref: (LRU type policy) has this page been referenced yet?
- Dirty: has this page been modified?
- Frame: what frame is this page in?
- Protection: what are the allowable operations?
  - **r**ead/**w**rite/e**x**ecute

A page fault (valid bit = 0) occurs. What must we do in response?

A. Find the faulting page on disk.

B. Evict a page from memory and write it to disk.

C. Bring in the faulting page and retry the operation.

D. Two of the above

E. All of the above

A page fault (valid bit = 0) occurs. What must we do in response? – a lot like caching!

A. Find the faulting page on disk.

B. Evict a page from memory and write it to disk (if physical mem. is full, and write it to disk if evicting page is dirty)

C. Bring in the faulting page and retry the operation.

D. Two of the above

E. All of the above

Address Translation and Page Faults

- Get entry: index page table with page number
- If valid bit is zero, page fault
  - Trap into operating system
  - Find page on disk (kept in kernel data structure)
  - Read it into a free frame
    - may need to make room: page replacement
  - Record frame number in page table entry, set valid
  - Retry instruction (return from page-fault trap)

Adv: The process does not know that this is happening

Disadv: Execution slows down

Page Faults are Expensive

- Disk: 5-6 orders magnitude slower than RAM
  - Very expensive; but if very rare, tolerable
- Example
  - RAM access time: 100 nsec
  - Disk access time: 10 msec
  - p = page fault probability
  - Effective access time: 100 + p × 10,000,000 nsec
  - If p = 0.1%, effective access time = 10,100 nsec !

Handing faults from disk seems very expensive. How can we get away with this in practice?

A. We have lots of memory, and it isn't usually full.

B. We use special hardware to speed things up.

C. We tend to use the same pages over and over.

D. This is too expensive to do in practice!

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Principle of Locality

- Not all pieces referenced uniformly over time
  - Make sure most referenced pieces in memory
  - If not, thrashing: constant fetching of pieces
- References cluster in time/space
  - Will be to same or neighboring areas
  - Allows prediction based on past

Page Replacement

- Goal: remove page(s) not exhibiting locality
- Page replacement policy is about
  - which page(s) to remove
  - when to remove them
- How to do it in the cheapest way possible
  - Least amount of additional hardware
  - Least amount of software overhead

Basic Page Replacement Algorithms

- FIFO: select page that is oldest
  - Simple: use frame ordering
  - Doesn't perform very well (oldest may be popular)
- OPT: select page to be used furthest in future
  - Optimal, but requires future knowledge
  - Establishes best case, good for comparisons
- LRU: select page that was least recently used
  - Predict future based on past; works given locality
  - Costly: time-stamp pages each access, find least
- Goal: minimize replacements (maximize locality)

Summary

- We give each process a virtual address space to simplify process execution.
- OS maintains mapping of virtual address to physical memory location (e.g., in page table).
  - One page table for every process
  - TLB hardware helps to speed up translation
- Provides the abstraction of very large memory: not all pages need be resident in memory
  - Bring pages in from disk on demand