Virtual Memory: Just an Illusion

Hung-Wei Tseng

Let’s dig into this code

```
int main(int argc, char *argv[])
{
    int i,j;
    double **a;
    double sum=0, average;
    int dim=32768;
    if(argc < 2)
    {
        fprintf(stderr, "Usage: %s dimension\n",argv[0]);
        exit(1);
    }
    dim = atoi(argv[1]);
    a = (double **)malloc(sizeof(double *)*dim);
    for(i = 0 ; i < dim; i++)
        a[i] = (double *)malloc(sizeof(double)*dim);
    for(i = 0 ; i < dim; i++)
        for(j = 0 ; j < dim; j++)
            a[i][j] = rand();
    for(i = 0 ; i < dim; i++)
        for(j = 0 ; j < dim; j++)
            sum+=a[i][j];
    average = sum/(dim*dim);
    fprintf(stderr,"average: %lf\n",average);
    for(i = 0 ; i < dim; i++)
        free(a[i]);
    free(a);
    return 0;
}
```

https://www.pollev.com/hungweitseng close in 1:30

What will happen?

- If we execute the code on the right-hand side code on a machine with only 16 GB of physical memory installed and the dim is "48000" (requires 48000*48000*8 bytes ~ 18 GB memory at least), What will happen?
  A. The program will crash in one of the malloc function call
  B. The program will crash due to a "segmentation fault" that caused by accessing NULL pointer
  C. The program will be killed automatically by the OS as it uses more than installed physical main memory
  D. The program will finish without any issue

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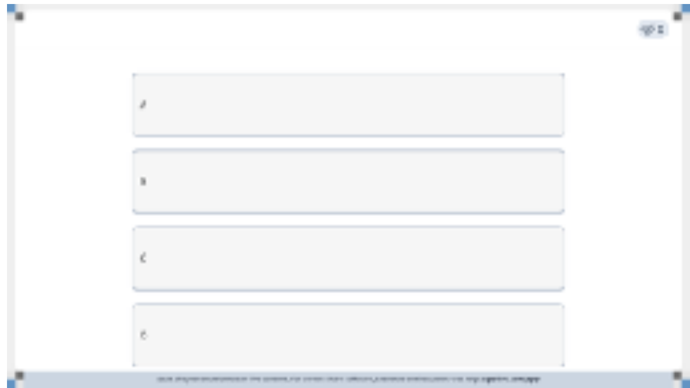

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Let’s dig into this code

```
#define _GNU_SOURCE
#include <unistd.h>
#include <stdio.h>
#include <stdlib.h>
#include <assert.h>
#include <sched.h>
#include <sys/syscall.h>
#include <time.h>

double a;

int main(int argc, char *argv[])
{
    int i, number_of_total_processes=4;
    number_of_total_processes = atoi(argv[1]);
    // Create processes
    for(i = 0; i< number_of_total_processes-1 && fork(); i++);
    // Generate rand seed
    srand((int)time(NULL)+(int)getpid());
    a = rand();
    fprintf(stderr, "\nProcess %d. Value of a is %lf and address of a is %p\n",getpid(), a, &a);
    sleep(10);
    fprintf(stderr, "\nProcess %d. Value of a is %lf and address of a is %p\n",getpid(), a, &a);
    return 0;
}
```

Consider the following code …

- Consider the case when we run 4 instances of the given program at the same time on modern machines, which pair of statements is correct?
  1. The printed "address of a" is the same for every running instances
  2. The printed "address of a" is different for each instance
  3. All running instances will print the same value of a
  4. Some instances will print the same value of a
  5. Each instance will print a different value of a

  A. (1) & (3)
  B. (1) & (4)
  C. (1) & (5)
  D. (2) & (3)
  E. (2) & (4)

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double a;

int main(int argc, char *argv[])
{
    int i, number_of_total_processes=4;
    number_of_total_processes = atoi(argv[1]);
    for(i = 0; i< number_of_total_processes-1 && fork(); i++);
    srand((int)time(NULL)+(int)getpid());
    fprintf(stderr, "\nProcess %d. Value of a is %lf and address of a is %p\n",getpid(), a, &a);
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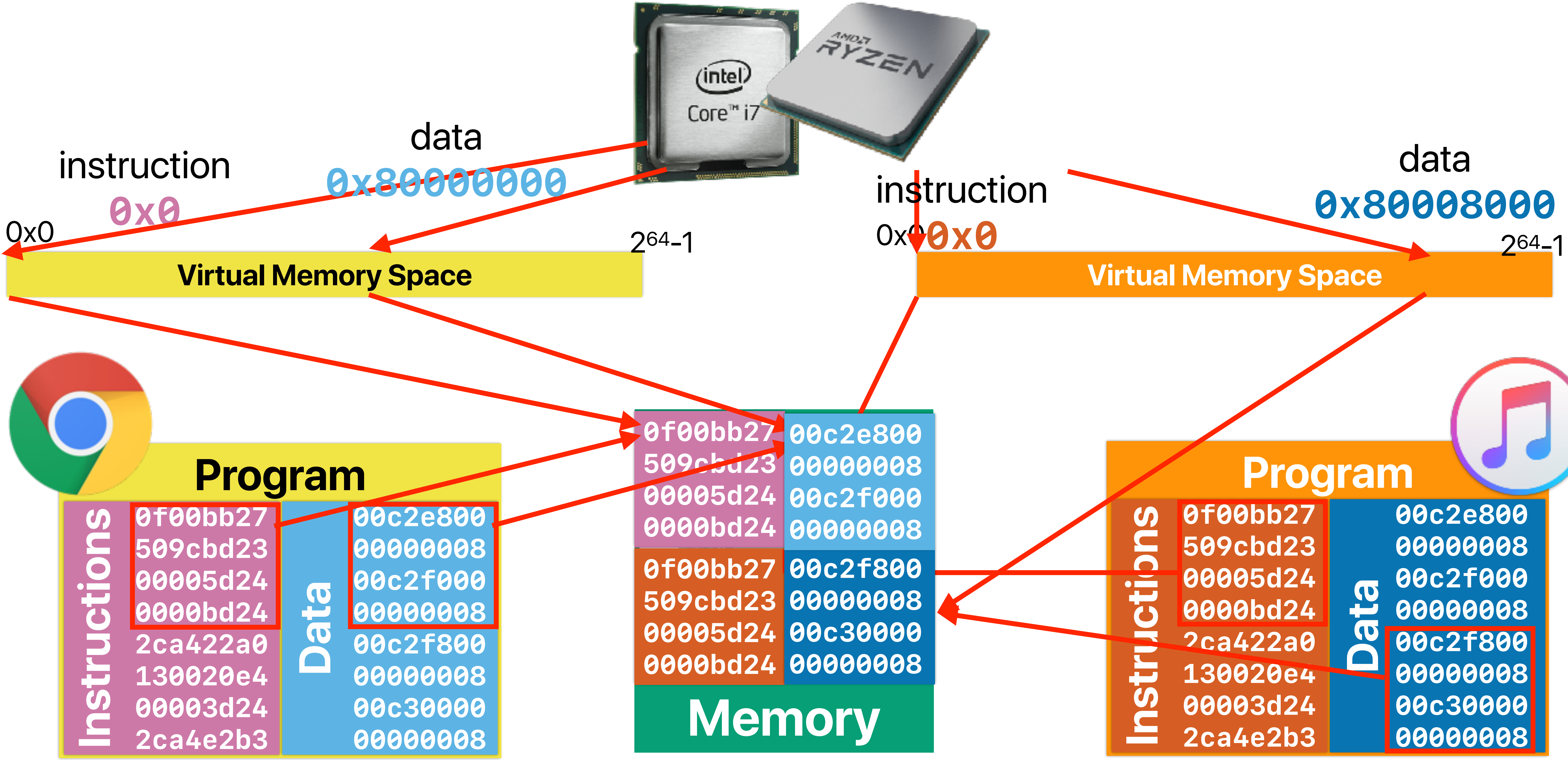
Outline

- Virtual memory
- Architectural support for virtual memory

Virtual Memory

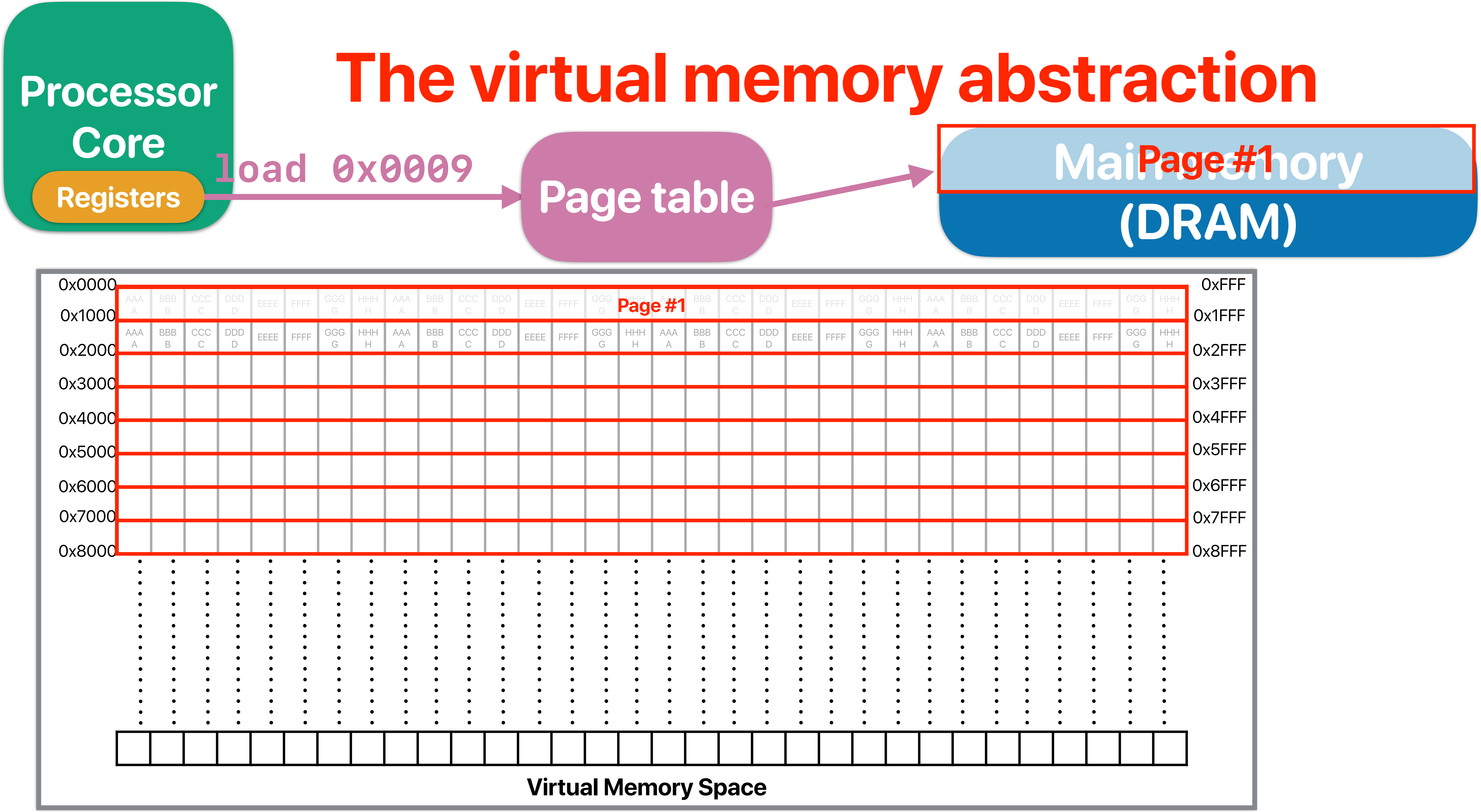
Virtual memory



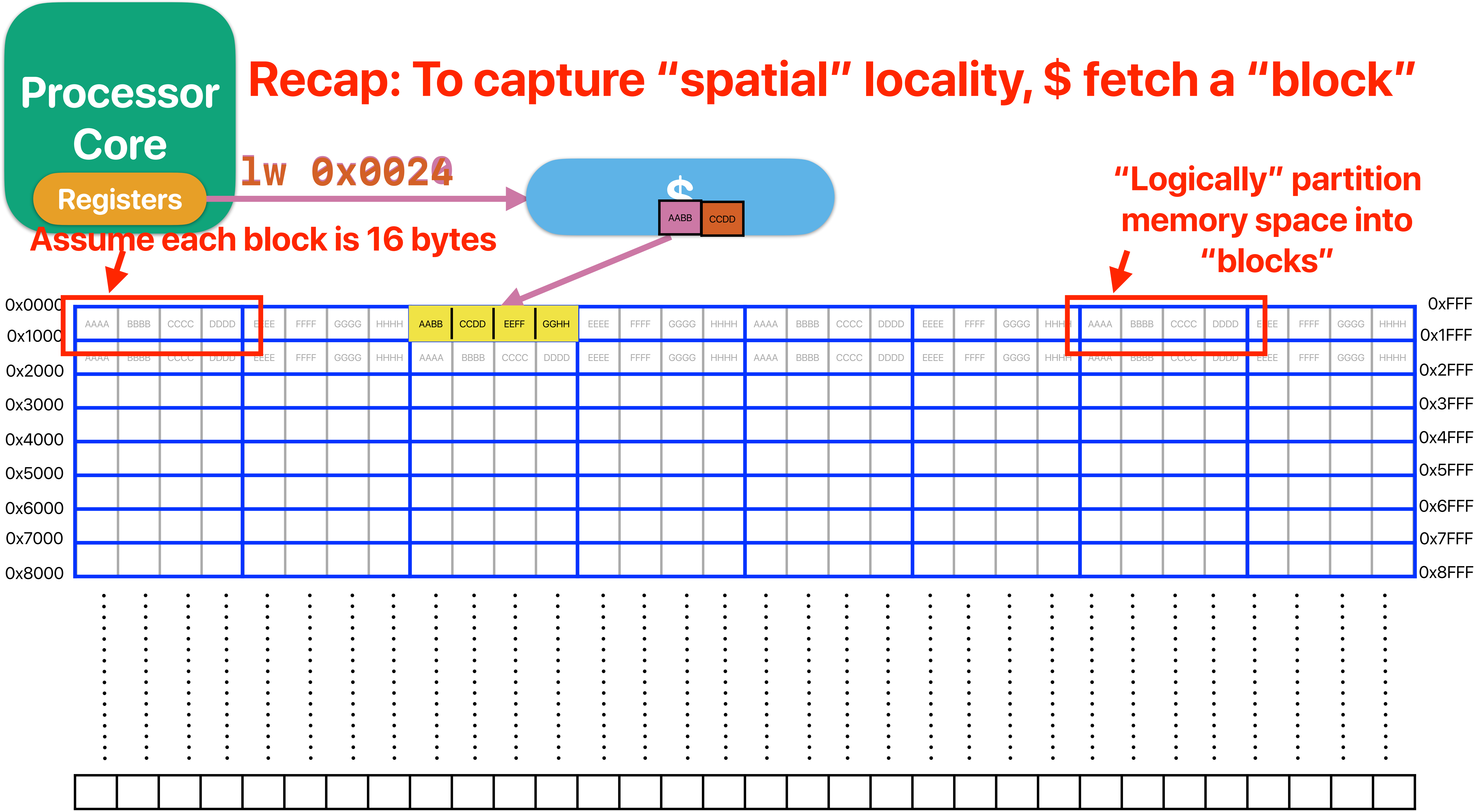
Virtual memory

- An **abstraction** of memory space available for programs/software/programmer
- Programs execute using virtual memory address
- The operating system and hardware work together to handle the mapping between virtual memory addresses and real/physical memory addresses
- Virtual memory organizes memory locations into "**pages**"

The virtual memory abstraction



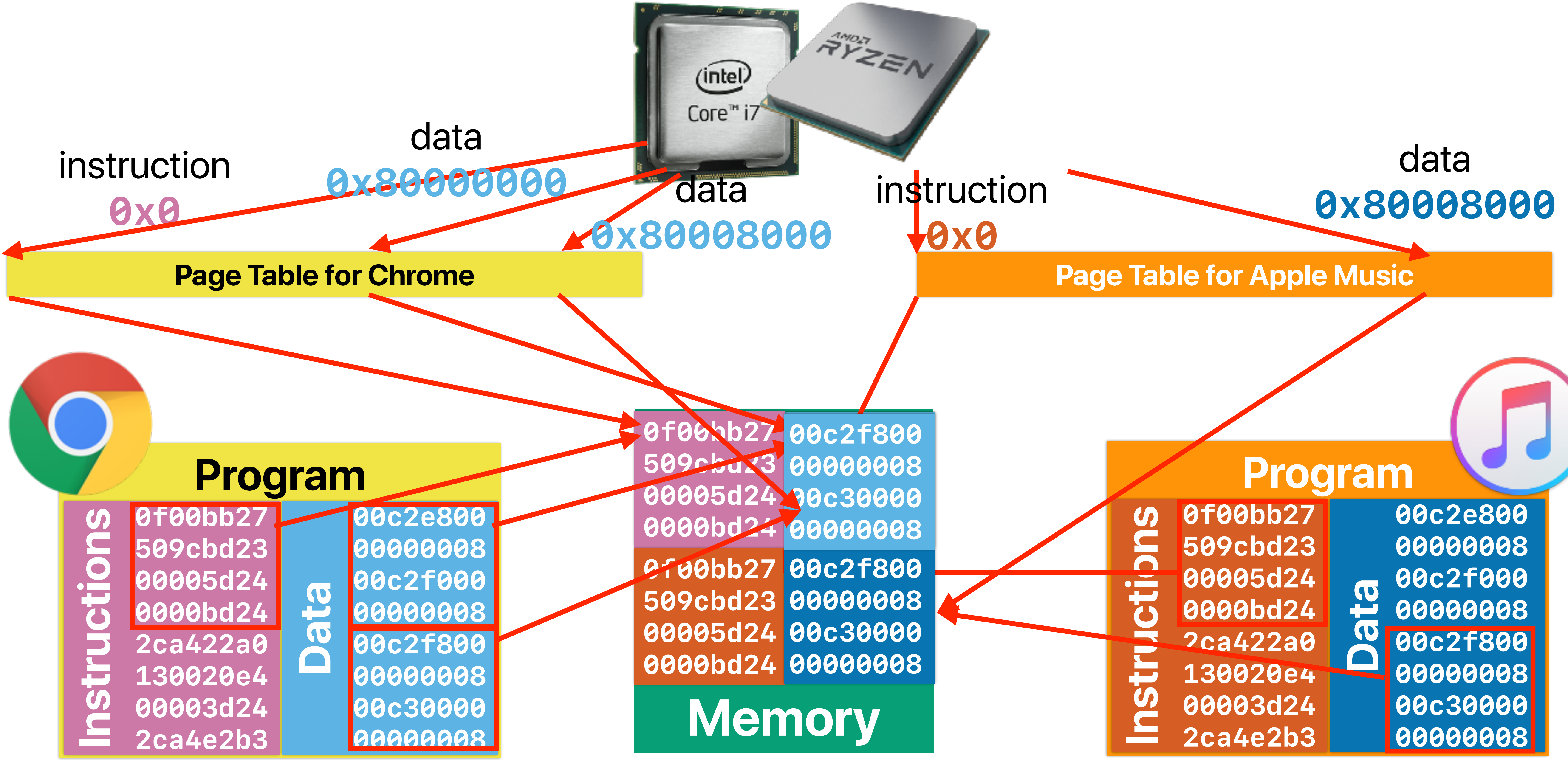
Recap: To capture “spatial” locality, $ fetch a “block”



Why Virtual memory?

- Allowing multiple applications to share physical main memory
  - Memory protection/isolation among programs/processes is automatically achieved
- Allowing applications to work even the installed physical memory or available physical memory is smaller than the working set of the application
  - Programmer does not need to worry about the physical memory capacity of different machines — make compiled program compatible
  - Multiple programs can work concurrently even through their total memory demand is larger than the installed physical memory

Demand paging

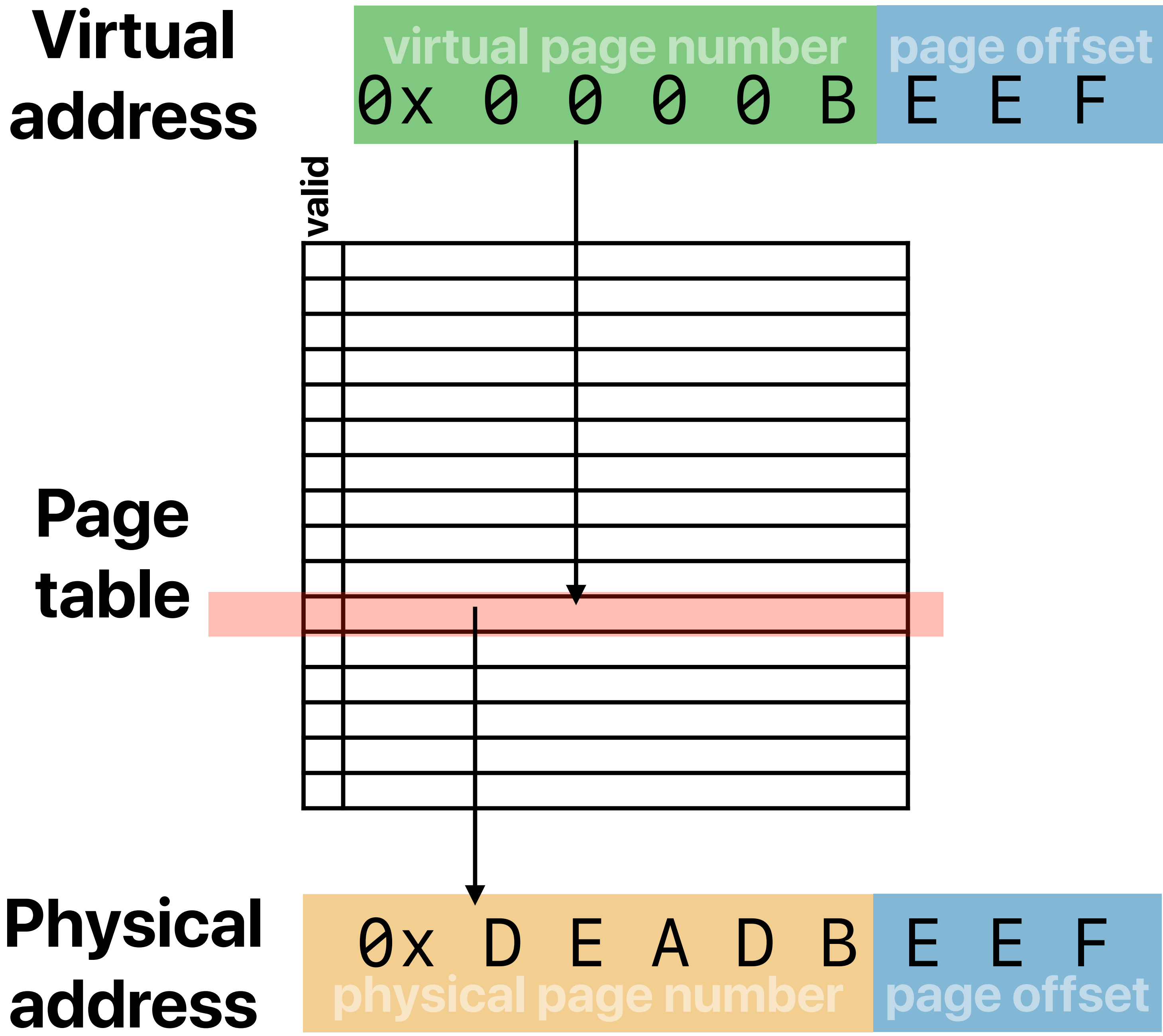


Demand paging

- Treating physical main memory as a “cache” of virtual memory
- The block size is the “page size”
- The page table is the “tag array”
- It’s a “fully-associate” cache — a virtual page can go anywhere in the physical main memory

Address translation

- Processor receives virtual addresses from the running code, main memory uses physical memory addresses
- Virtual address space is organized into "pages"
- The system references the **page table** to translate addresses
  - Each process has its own page table
  - The page table content is maintained by OS



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Size of page table

- Assume that we have **64-bit** virtual address space, each page is 4KB, each page table entry is 8 Bytes, what magnitude in size is the page table for a process?
  A. MB — 2^{20} Bytes
  B. GB — 2^{30} Bytes
  C. TB — 2^{40} Bytes
  D. PB — 2^{50} Bytes
  E. EB — 2^{60} Bytes

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  D. $\boxed{\text{PB — } 2^{50} \text{ Bytes}}$
  E. EB — 2^{60} Bytes

$$\frac{2^{64}\ Bytes}{4\ KB} \times 8\ Bytes = 2^{55}\ Bytes = 32\ PB$$

If you still don't know why — you need to take CS202

Conventional page table

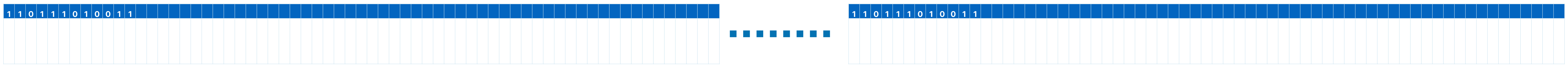
0x0 0xFFFFFFFFFFFFFFFF

— must be consecutive in the physical memory

— need a big segment! — difficult to find a spot

— simply too big to fit in memory if address space is large!

$\frac{2^{64}\ B}{2^{12}\ B}$ page table entries/leaf nodes

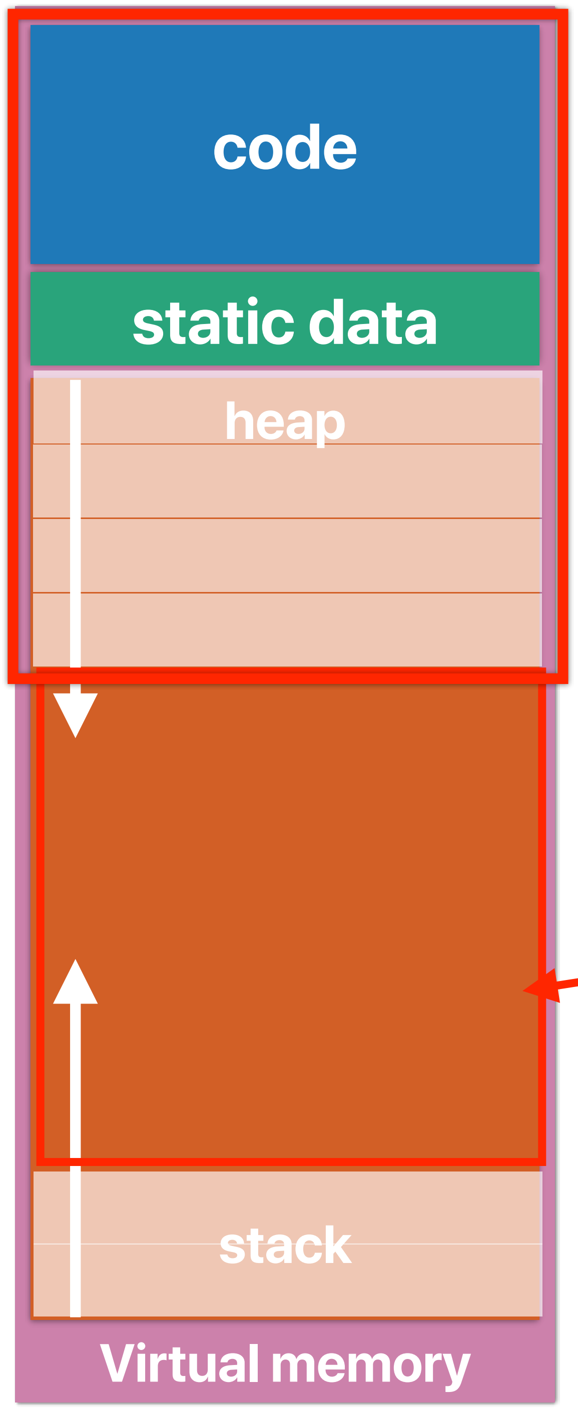


Do we really need a large table?

0x0000000000000000

1TB — only 0.000006% of 2^{64} Bytes

Dynamic allocated data: `malloc()`



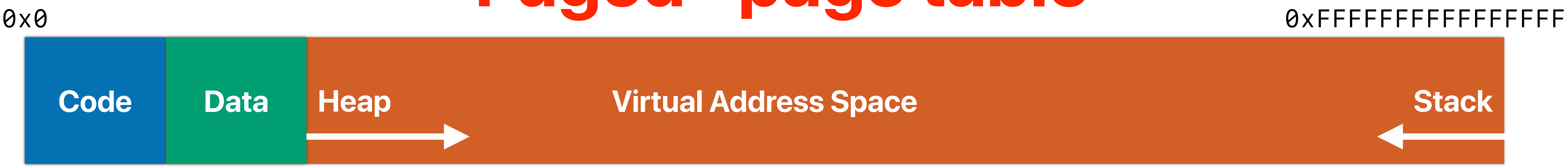
Your program probably never uses this huge area!

Local variables, arguments

If you still don't know why — you need to take CS202

0xFFFFFFFFFFFFFFFF

“Paged” page table

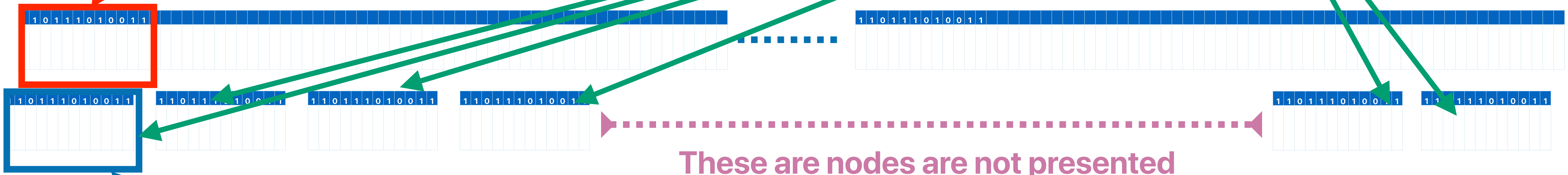


Break up entries into pages!
Each of these occupies exactly a page

— $\frac{2^{12}\ B}{2^{3}\ B} = 2^{9}$ **PTEs per node**

Otherwise, you always need to find more than one consecutive pages — difficult!

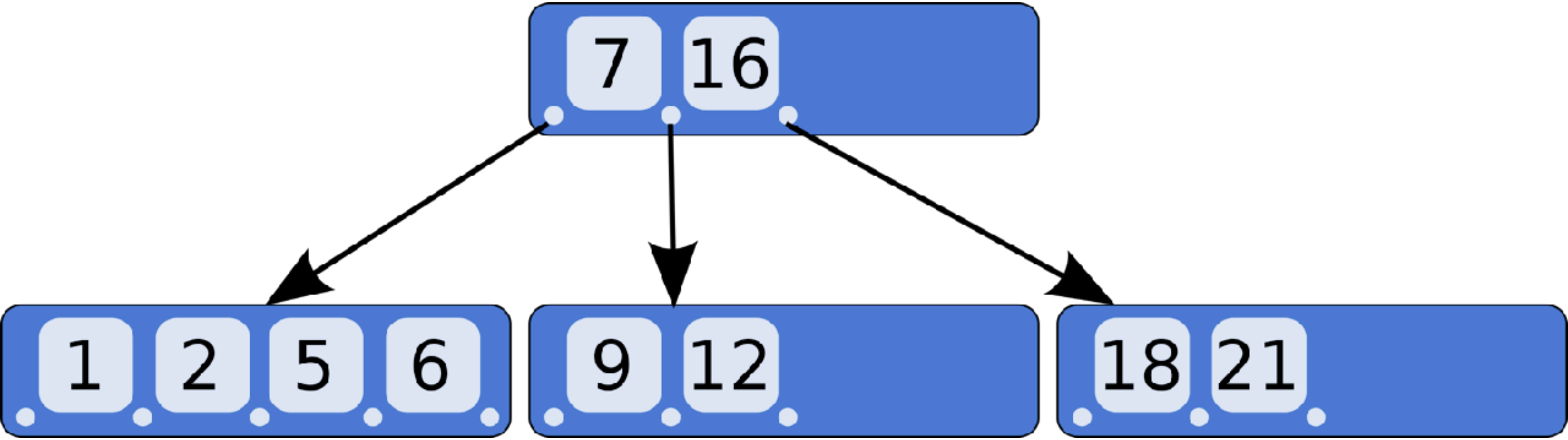
Question:
These nodes are spread out, how to locate them in the memory?



These are nodes are not presented if they are not referenced at all — save space

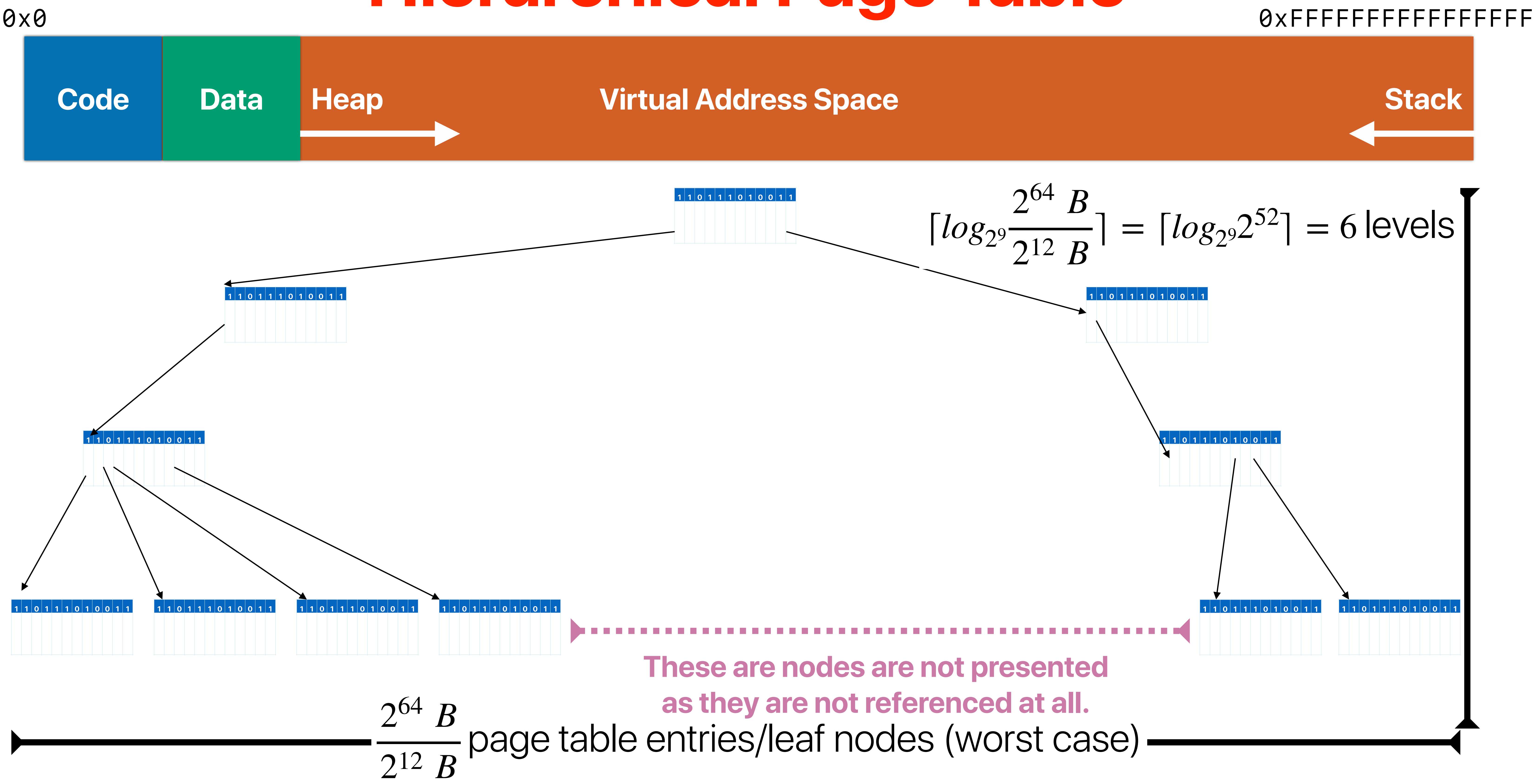
Allocate page table entry nodes “on demand”

B-tree



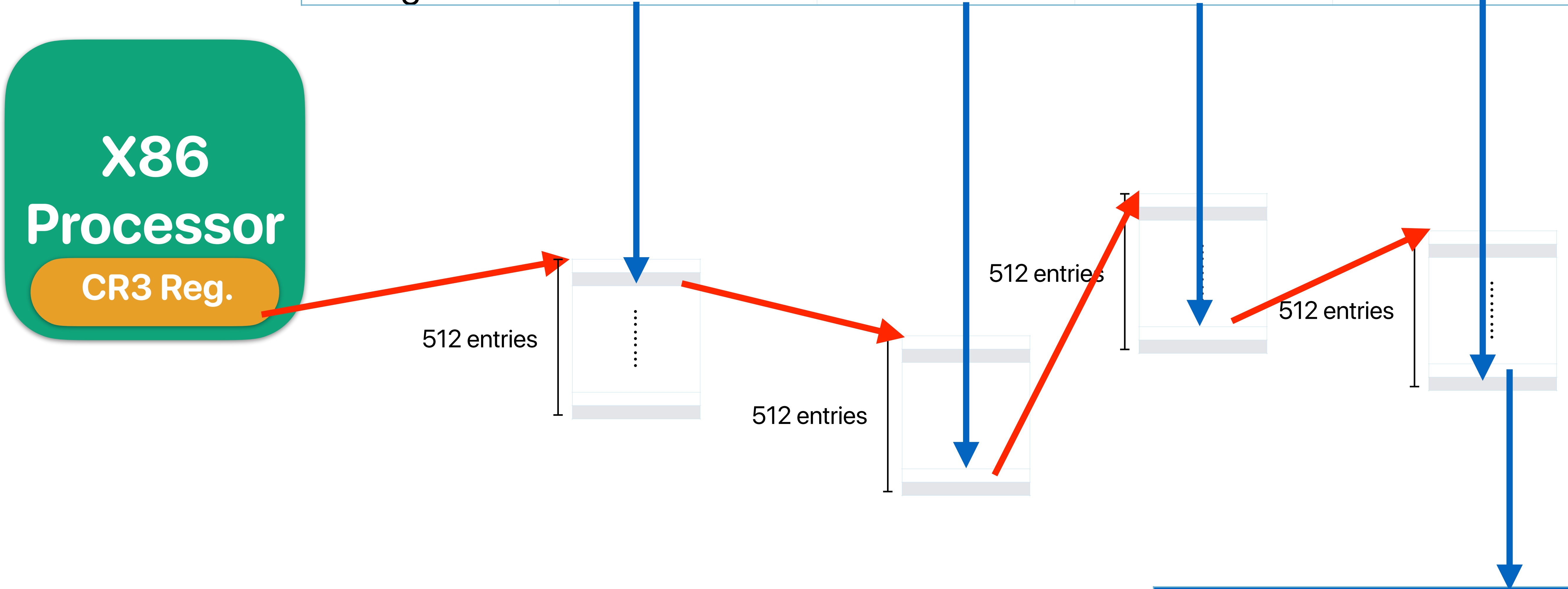
https://en.wikipedia.org/wiki/B-tree#/media/File:B-tree.svg

Hierarchical Page Table



Address translation in x86-64

63:48 (16	47:39 (9 bits)	38:30 (9 bits)	29:21 (9 bits)	20:12 (9 bits)	11:0 (12 bits)
SignExt	L4 index	L3 index	L2 index	L1 index	page offset



	11:0 (12 bits)
physical page #	page offset

Translation Caching: Skip, Don't Walk (the Page Table)
Thomas W. Barr, Alan L. Cox, Scott Rixner

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When we have virtual memory...

- If an x86 processor supports virtual memory through the basic format of the page table as shown in the previous slide, how many memory accesses can a **mov** instruction that access data memory once incur?
  A. 2
  B. 4
  C. 6
  D. 8
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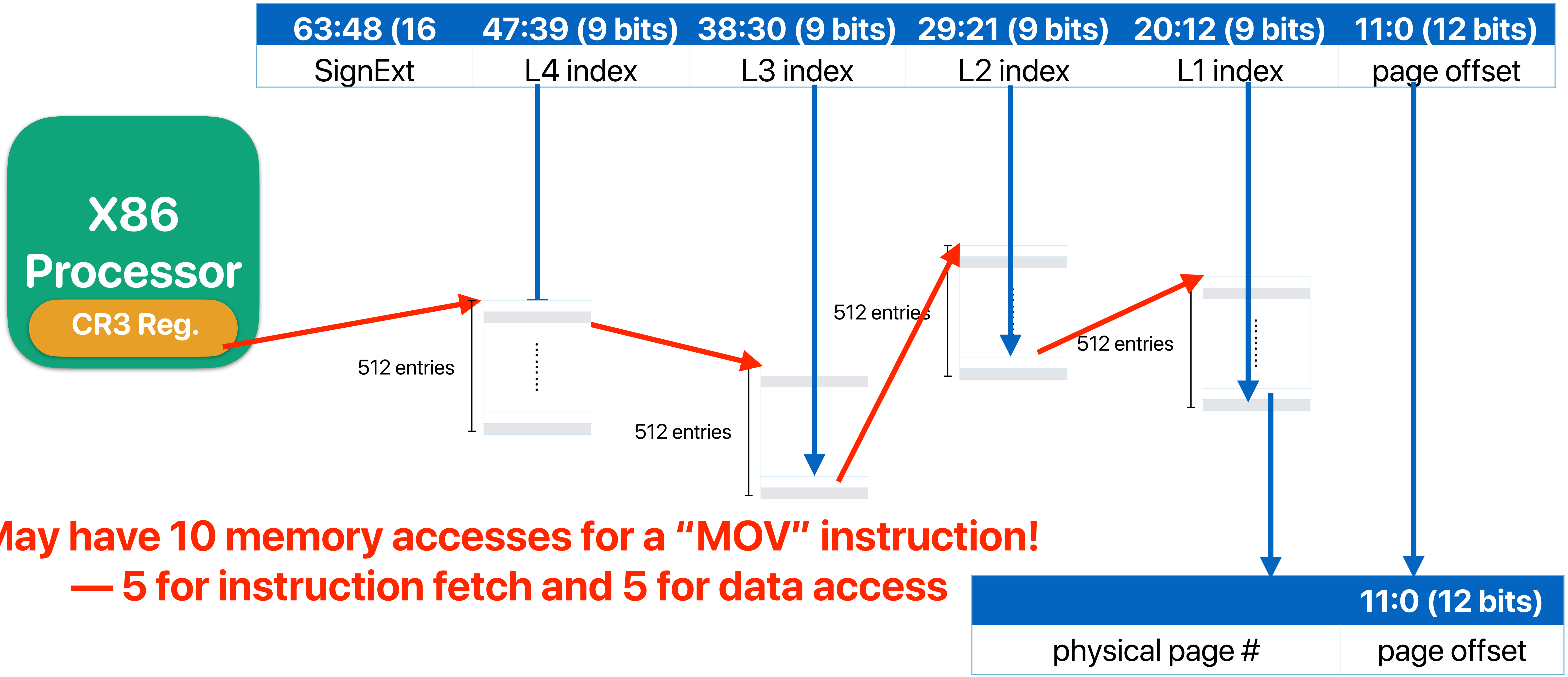
Address translation in x86-64



May have 10 memory accesses for a "MOV" instruction!
— 5 for instruction fetch and 5 for data access

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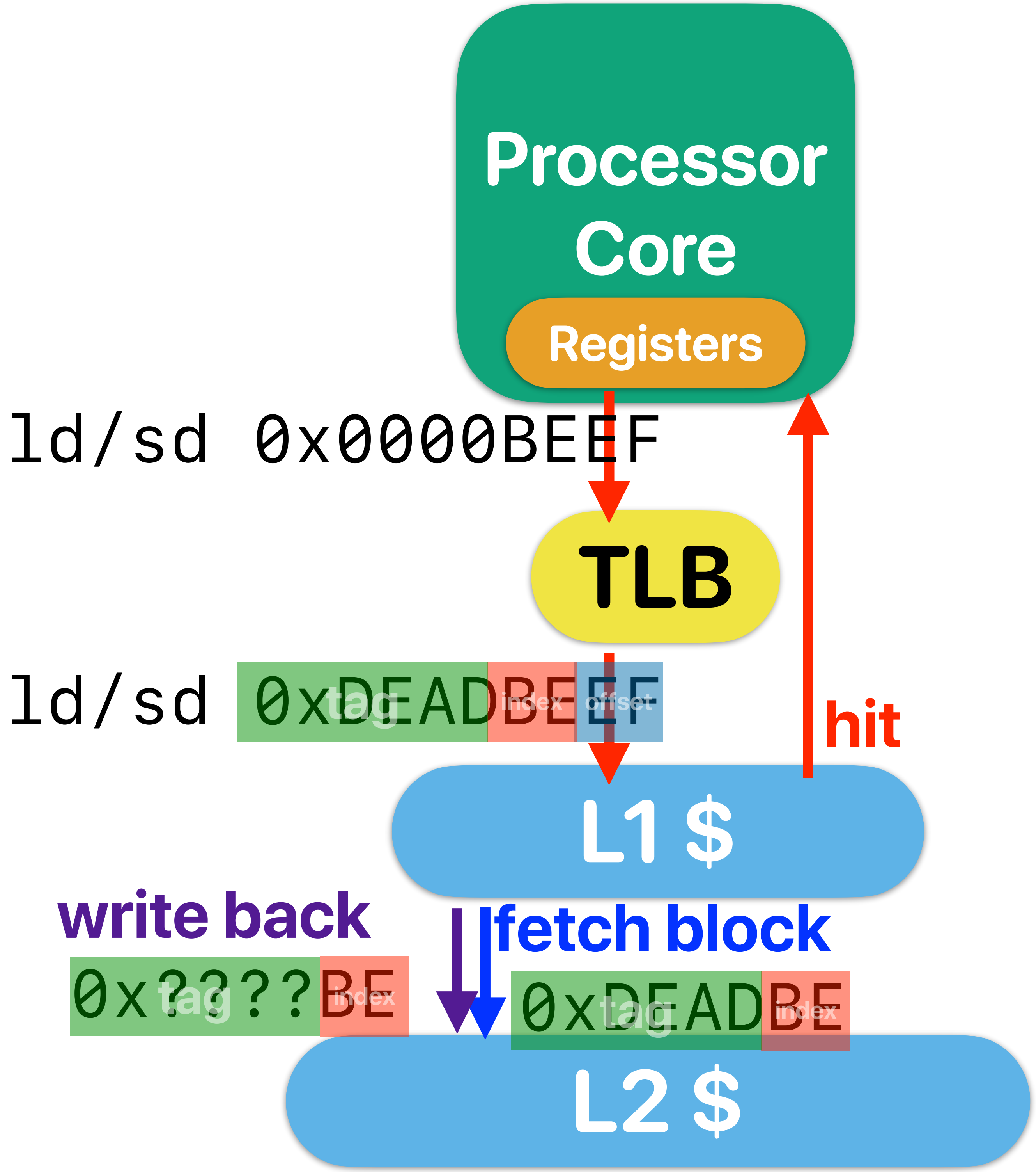
Avoiding the address translation overhead

TLB: Translation Look-aside Buffer



- TLB — a small SRAM stores frequently used page table entries
- Good — A lot faster than having everything going to the DRAM
- Bad — Still on the critical path

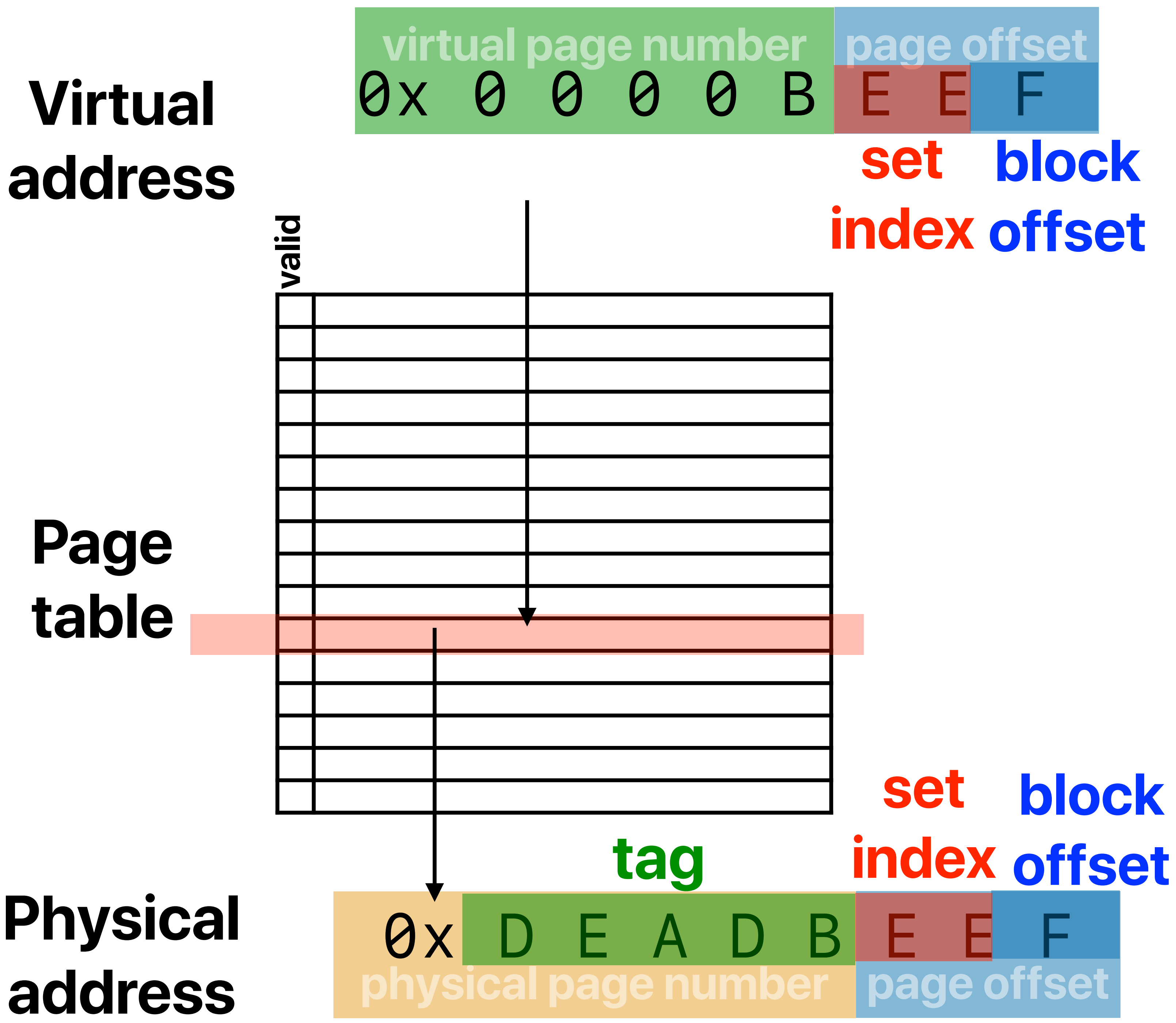
TLB + Virtual cache

- L1 $ accepts virtual address — you don't need to translate
- Good — you can access both TLB and L1-$ at the same time and physical address is only needed if L1-$ misses
- Bad — it doesn't work in practice
  - Many applications have the same virtual address but should be pointing different **physical addresses**
  - An application can have "aliasing virtual addresses" pointing to the same **physical address**

You really need "physical address" to judge if that's what you want

Virtually indexed, physically tagged cache

- Can we find physical address directly in the virtual address
  — Not everything — but the page offset isn't changing!
- Can we indexing the cache using the "partial physical address"?
  — Yes — Just make set index + block set to be exactly the page offset



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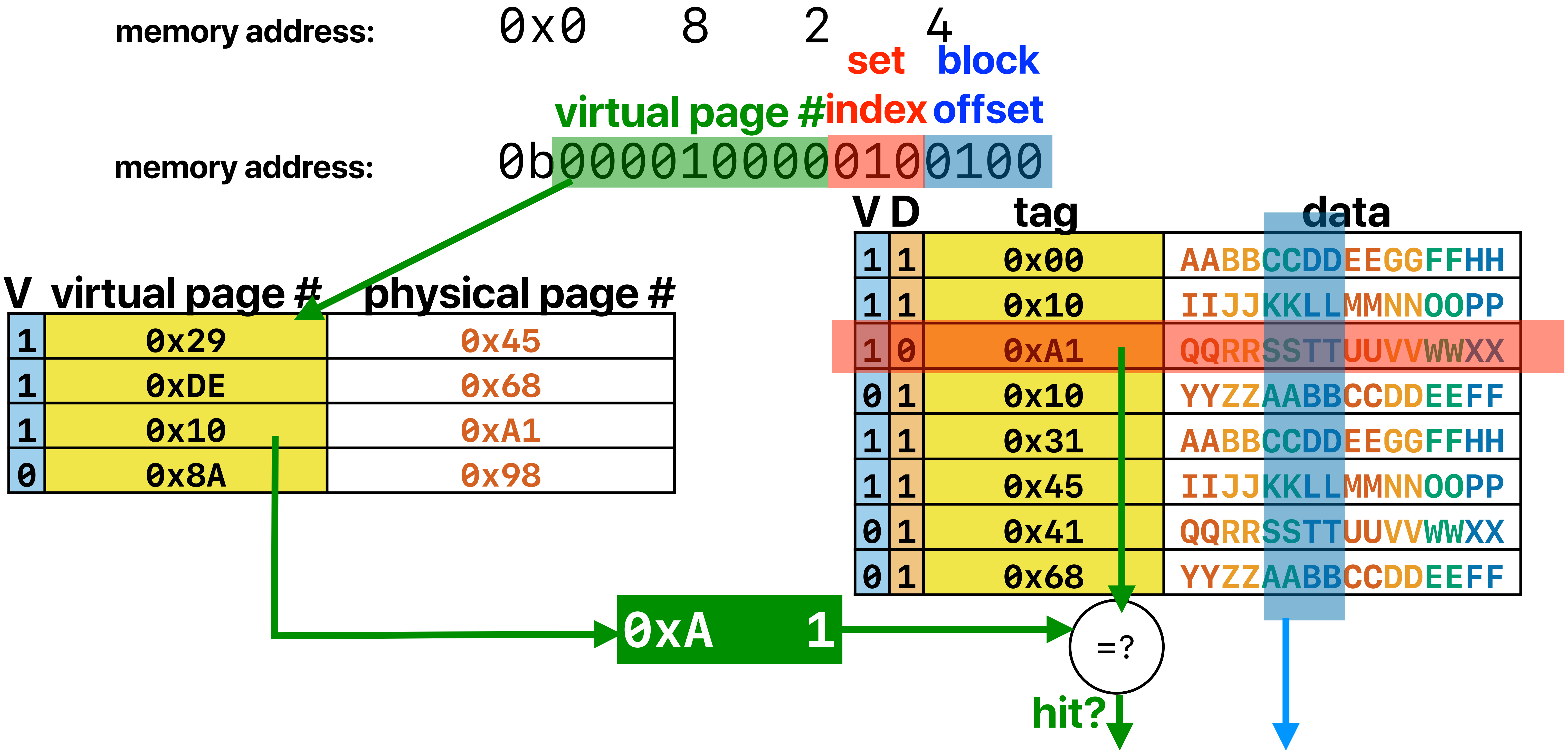


V	virtual page #	physical page #
1	0x29	0x45
1	0xDE	0x68
1	0x10	0xA1
0	0x8A	0x98

V	D	tag	data
1	1	0x00	AABBCCDDEEGGFFHH
1	1	0x10	IIJJKKLLMMNNOOPP
1	0	0xA1	QQRRSSTTUUVVWWXX
0	1	0x10	YYZZAABBCCDDEEFF
1	1	0x31	AABBCCDDEEGGFFHH
1	1	0x45	IIJJKKLLMMNNOOPP
0	1	0x41	QQRRSSTTUUVVWWXX
0	1	0x68	YYZZAABBCCDDEEFF

Virtually indexed, physically tagged cache

- If page size is 4KB —

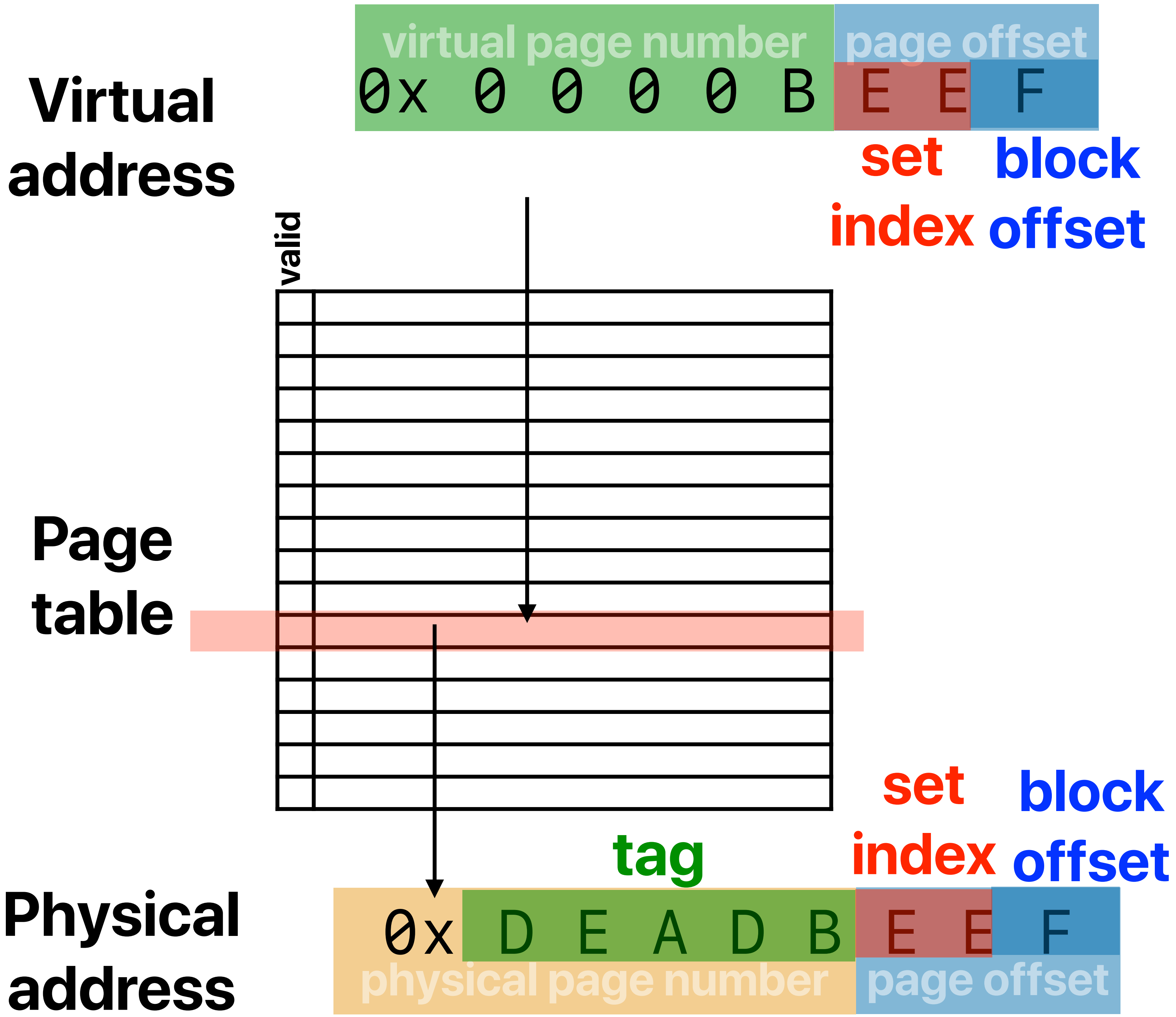
$$lg(B) + lg(S) = lg(4096) = 12$$

$$C = ABS$$

$$C = A \times 2^{12}$$

$$if\ A = 1$$

$$C = 4KB$$



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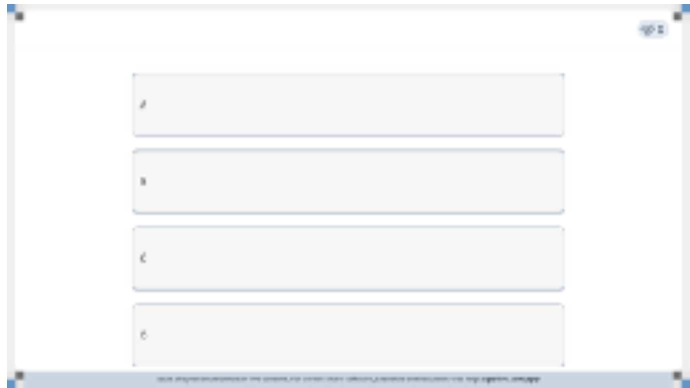
Virtual indexed, physical tagged cache limits the cache size

- If you want to build a virtual indexed, physical tagged cache with 32KB capacity, which of the following configuration is possible? Assume the operating system use 4K pages.
   A. 32B blocks, 2-way
   B. 32B blocks, 4-way
   C. 64B blocks, 4-way
   D. 64B blocks, 8-way



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Exactly how Core i7 9th generation configures its own cache

$$lg(B) + lg(S) = lg(4096) = 12$$

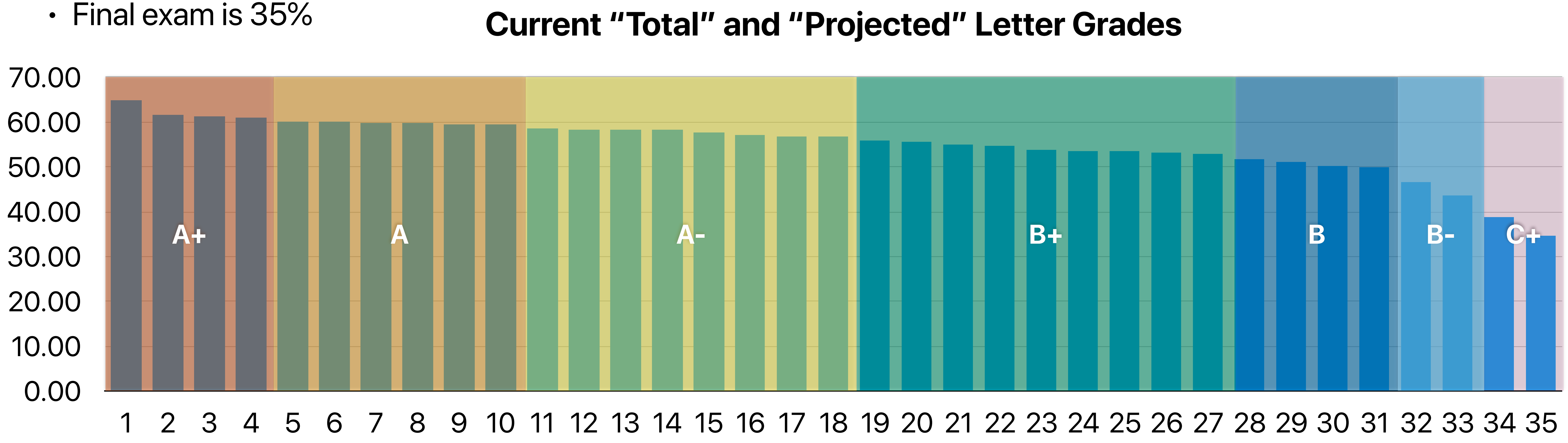
$$C = ABS$$

$$32KB = A \times 2^{12}$$

$$A = 8$$

Announcements

- Reading quiz due tomorrow
- Assignment 3 released
- Your overall grade and your ranking in the class decides your final letter grade, not just the midterm.
  - The bar chart below shows the current "total" and the "projected" letter grades
  - The curve is flexible — we don't mind to give more As, but depending on how good is the class overall
  - Midterm is only 25% — max 100, mean 74.
  - Final exam is 35%



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