6.1800 Spring 2025

Lecture #3: Virtual Memory

how does it work, but more importantly, why does an OS use it?

Katrina LaCurts | lacurts@mit.edu | 6.1800 2025

6.1800 in the news

caveat: this does not appear to be a large-scale measurement study, we should not draw huge conclusions about the performance of Tubi vs. YouTube TV from these results alone

We measured latency against the over-the-air (OTA) broadcast the local San Francisco Fox affiliate KTVU delivered. Although our TV supports NextGen TV and KTVU broadcasts a NextGen signal we stuck with the regular ATSC 1.0 broadcast.[i] Note that the TV broadcast is delayed behind the actual live game.

The Tubi stream was consistently at or slightly ahead of the OTA. The Tubi browser was three or more seconds ahead, while the connected TV app was about a second behind. Even T-Mobile's network delivered slightly ahead of the OTA broadcast. These delays are very small, and stream viewers had no reason to worry about social media posts calling a play before they had seen it.

	Tubi	Tubi Mobile	YouTube TV	Tubi Browser	Tubi CTV
1st Quarter					
Delay	-3.2	4.4	35.3	-5.5	
Start Time	2	9.9	1.9	1.7	
2nd Quarter					
Delay	0	1	30.1	-7	
Start Time	7.3	27.9	2	1.5	
3rd Quarter					
Delay	-2.5	-4.5	29.9	-5.5	2
Start Time	7.4	25	2.2	1.7	5.5
4th Quarter					
Delay	-0.5	-2.3	31.4	5	0.5
Start Time	3	17.5	3	7	3

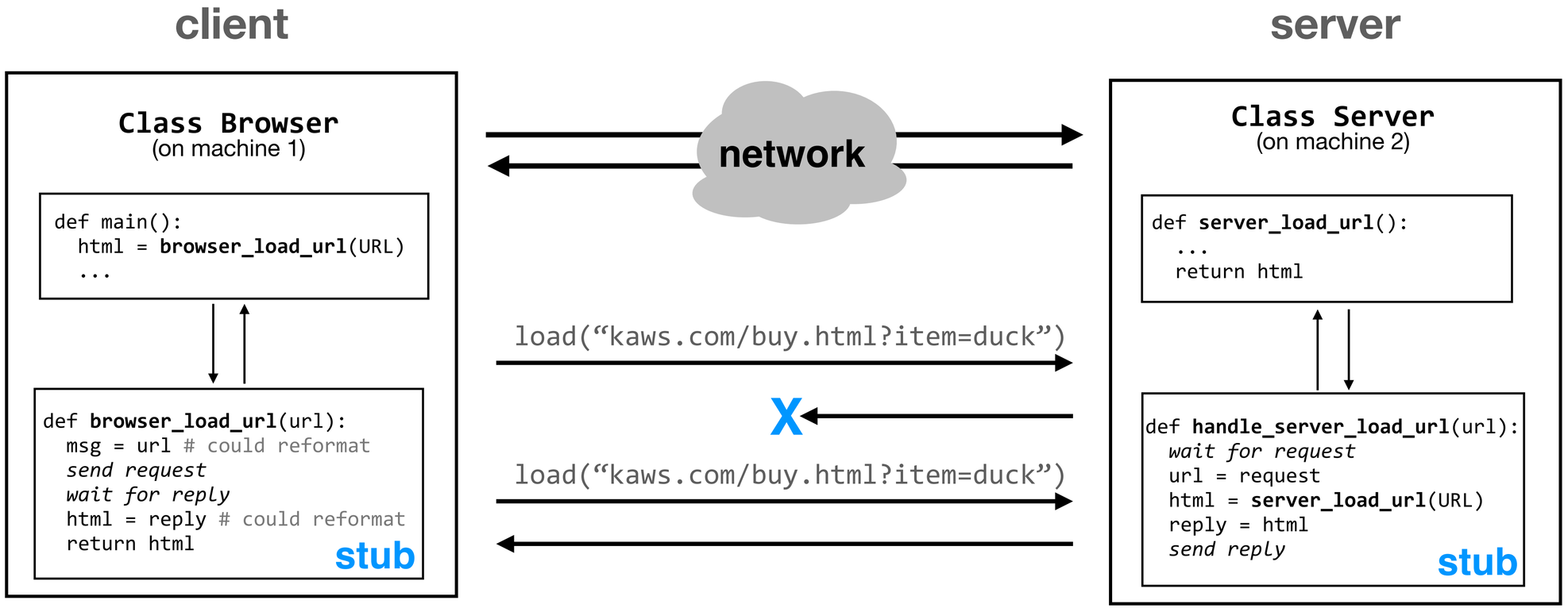
All times are seconds. Delay is relative to local TV over-the-air broadcast

Source: nScreenMedia

On the other hand, YouTube TV viewers needed to be very careful about monitoring their social accounts during the game. The vMVPD consistently delivered almost a full down behind the action on the OTA broadcast. When the Chiefs went into hurry-up offense in the fourth quarter, the YouTube TV stream was almost two downs behind at one point!

https://nscreenmedia.com/tubi-super-bowl-lix-quality-better-than-broadcast-experience/

last time: enforced modularity via client/server + naming



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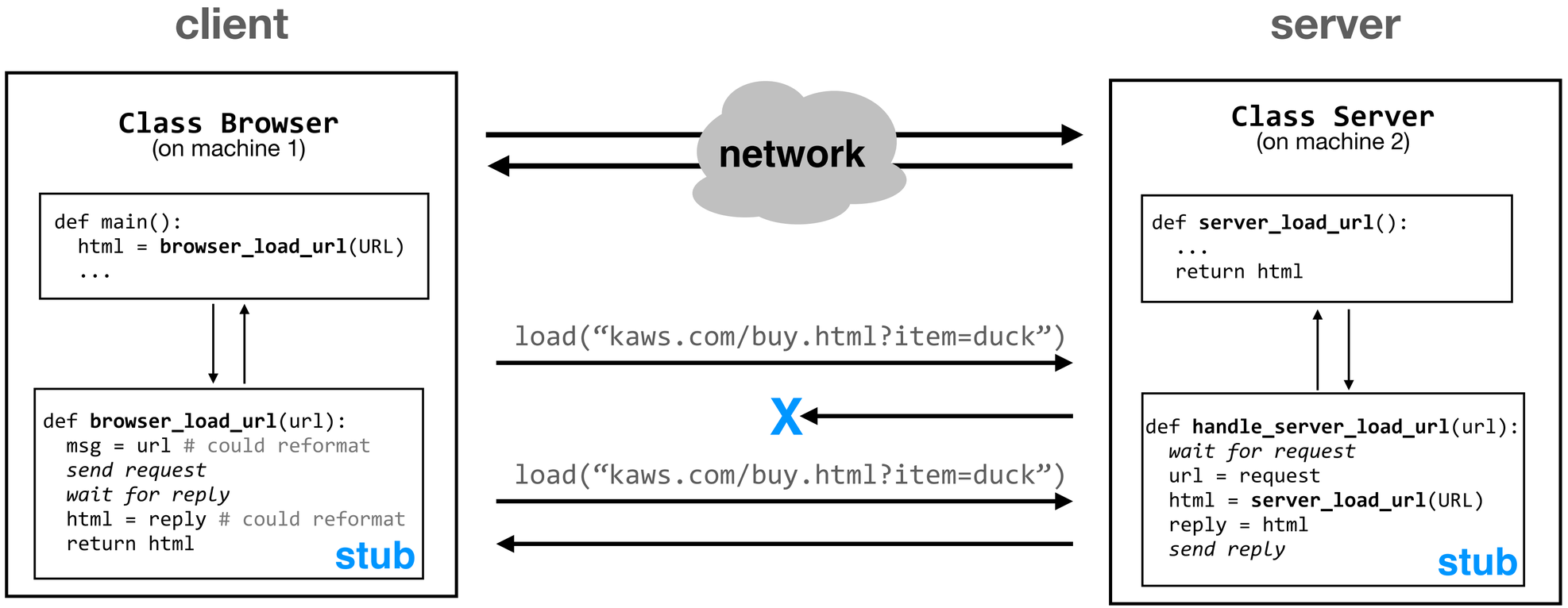

today: what if we *don't* want to put each module on a separate machine?

operating systems enforce modularity on a single machine

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in order to enforce modularity + have an effective operating system, a few things need to happen

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in some sense, we want every program to *think* that it has access to the full physical hardware, when of course they don't; the OS *virtualizes* different components of hardware

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in order to enforce modularity + have an effective operating system, a few things need to happen

1. programs shouldn't be able to refer to (and corrupt) each others' **memory** → virtualize **memory**
2. programs should be able to **communicate** with each other → assume they don't need to (for today)
3. programs should be able to **share a CPU** without one program halting the progress of the others → assume one program per CPU (for today)

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CPU_2 (used by $program_2$)

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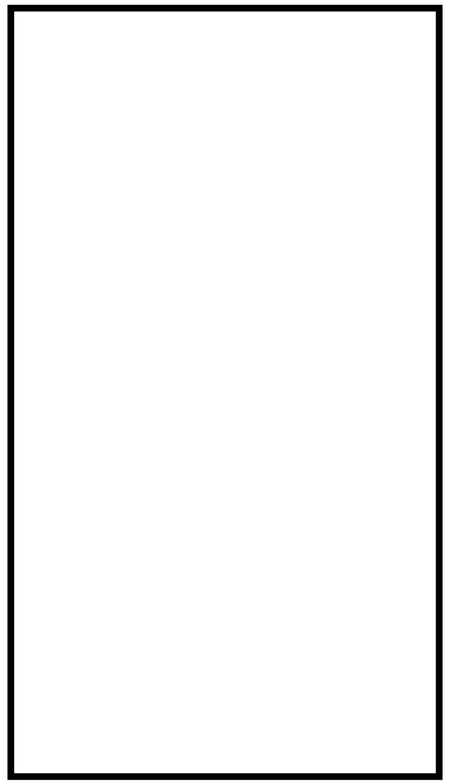
CPU$_2$ (used by program$_2$)

main memory



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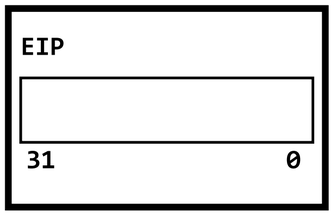
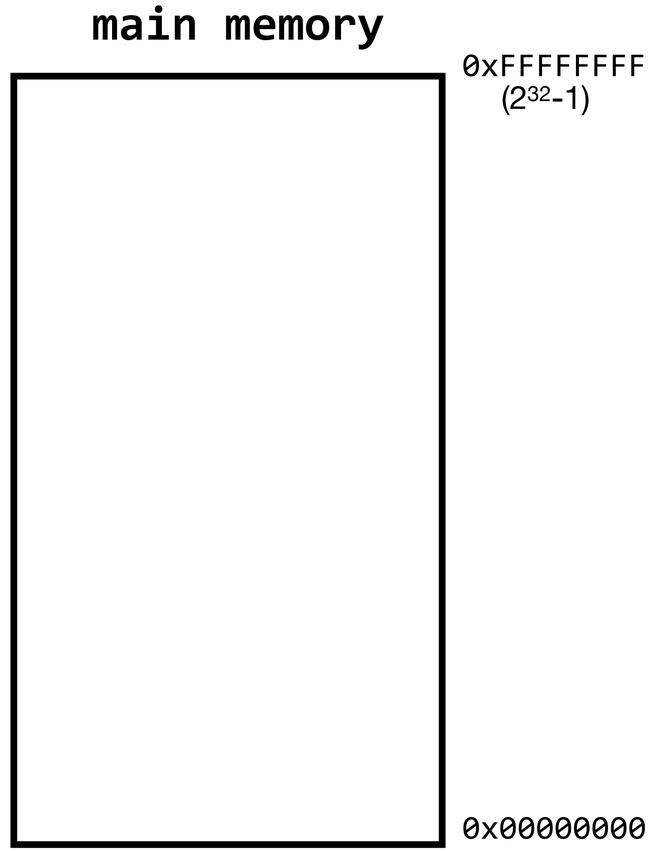


CPU$_2$ (used by program$_2$)



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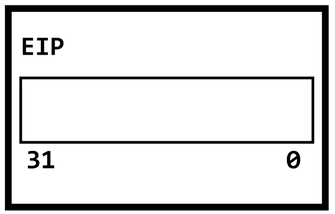

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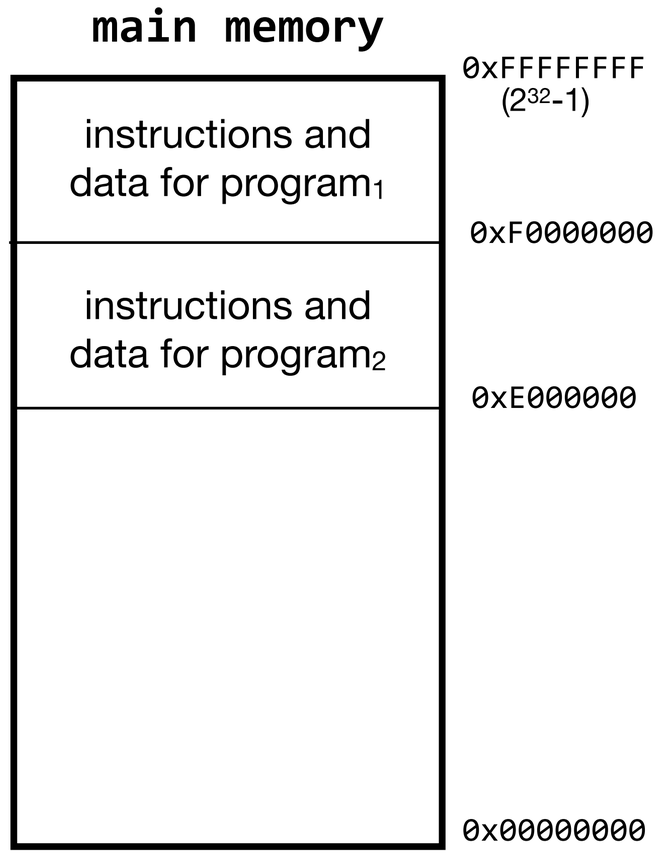

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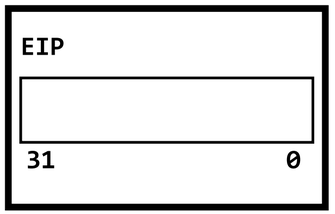

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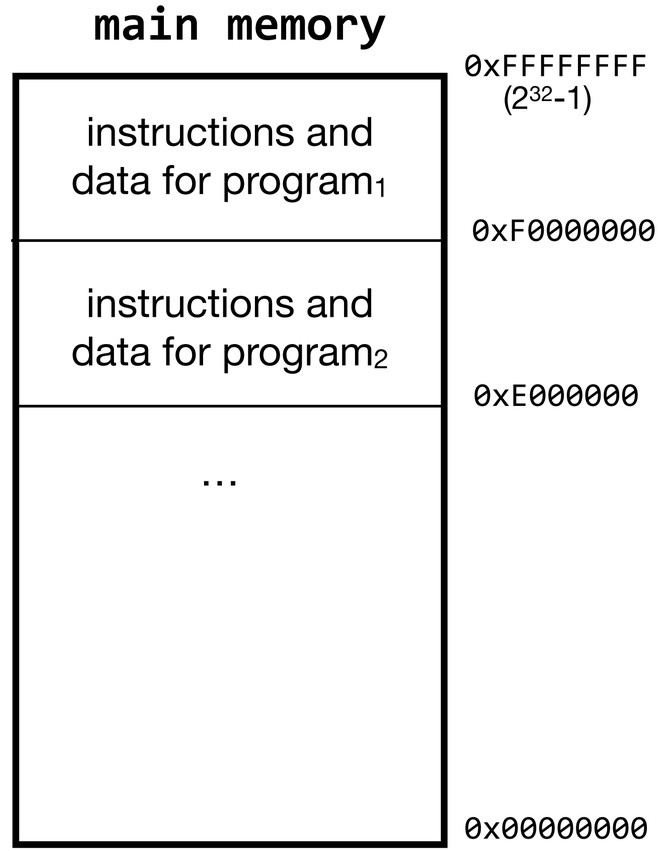

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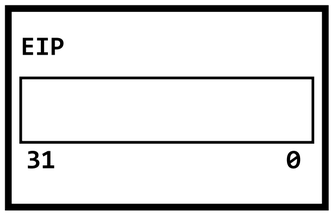

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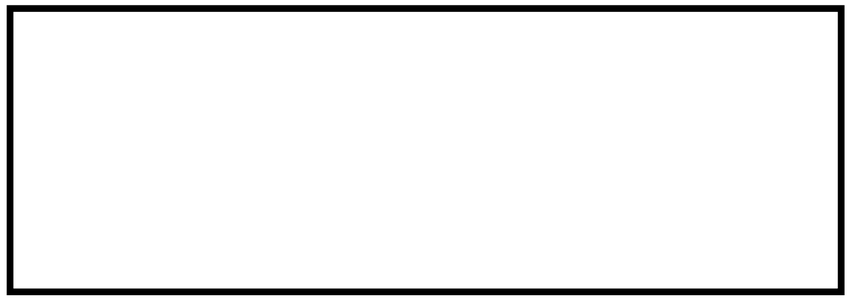

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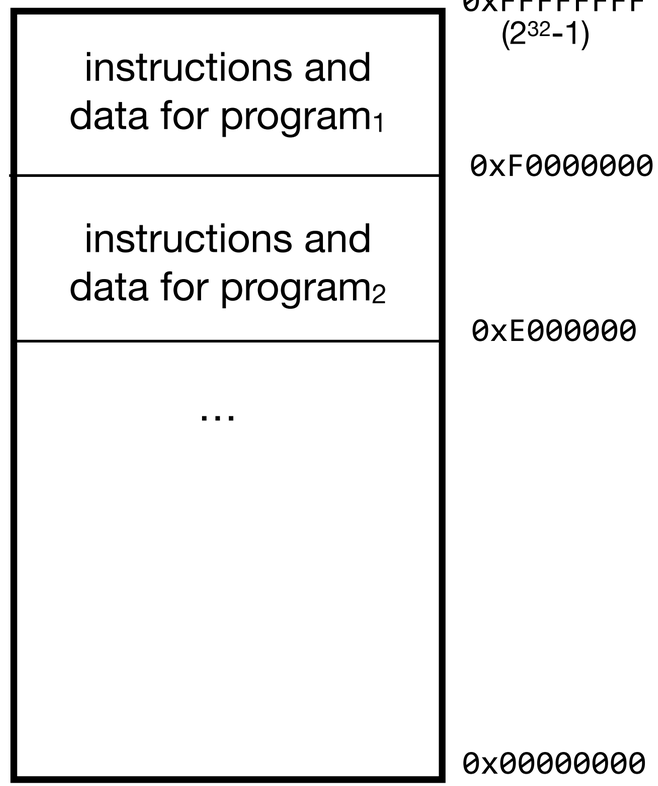

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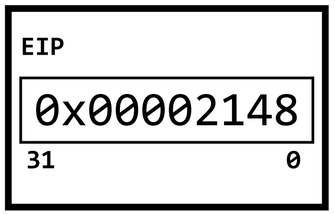

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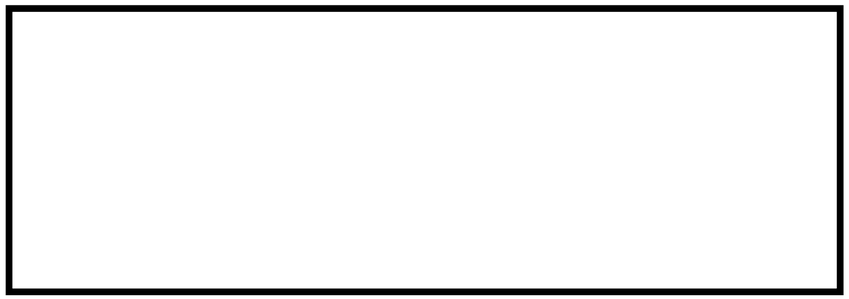

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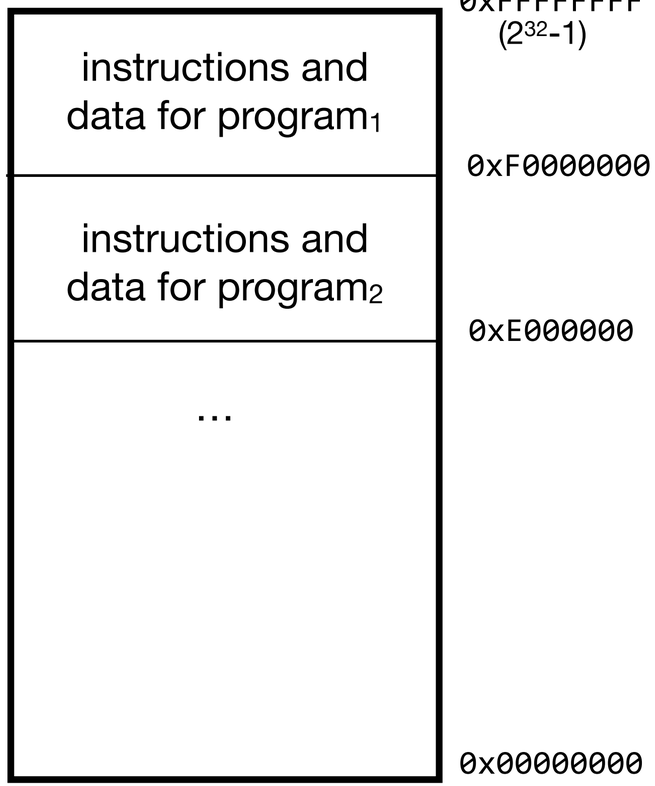

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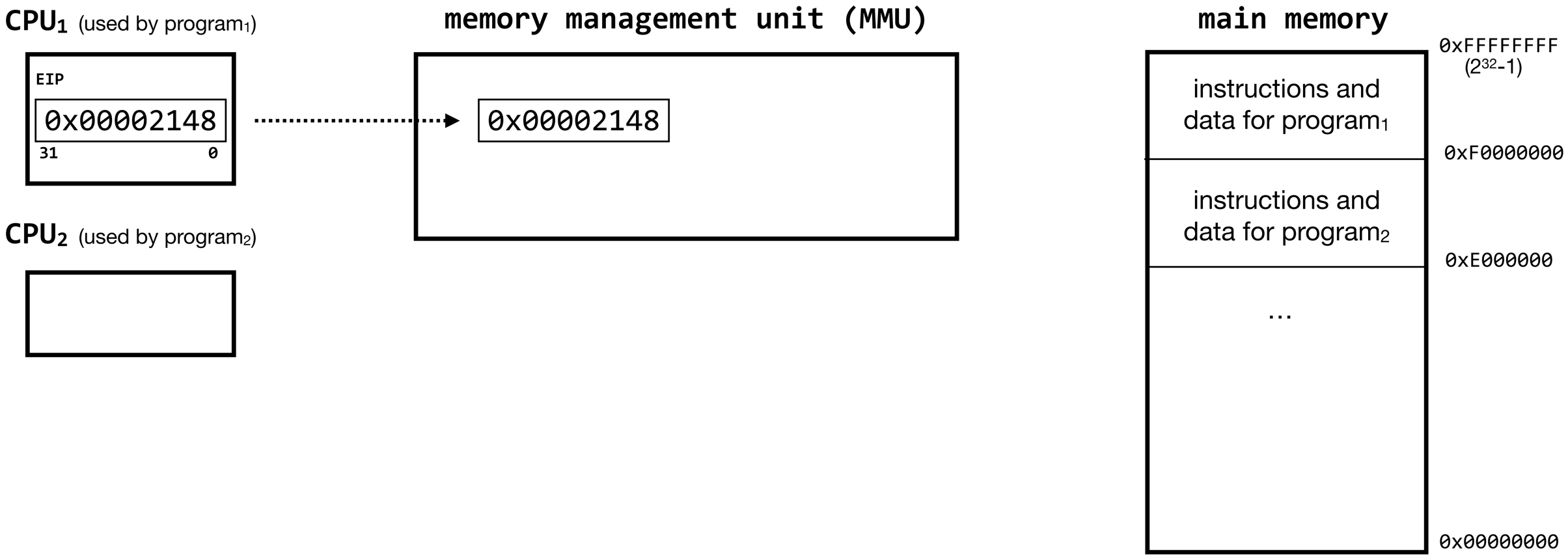

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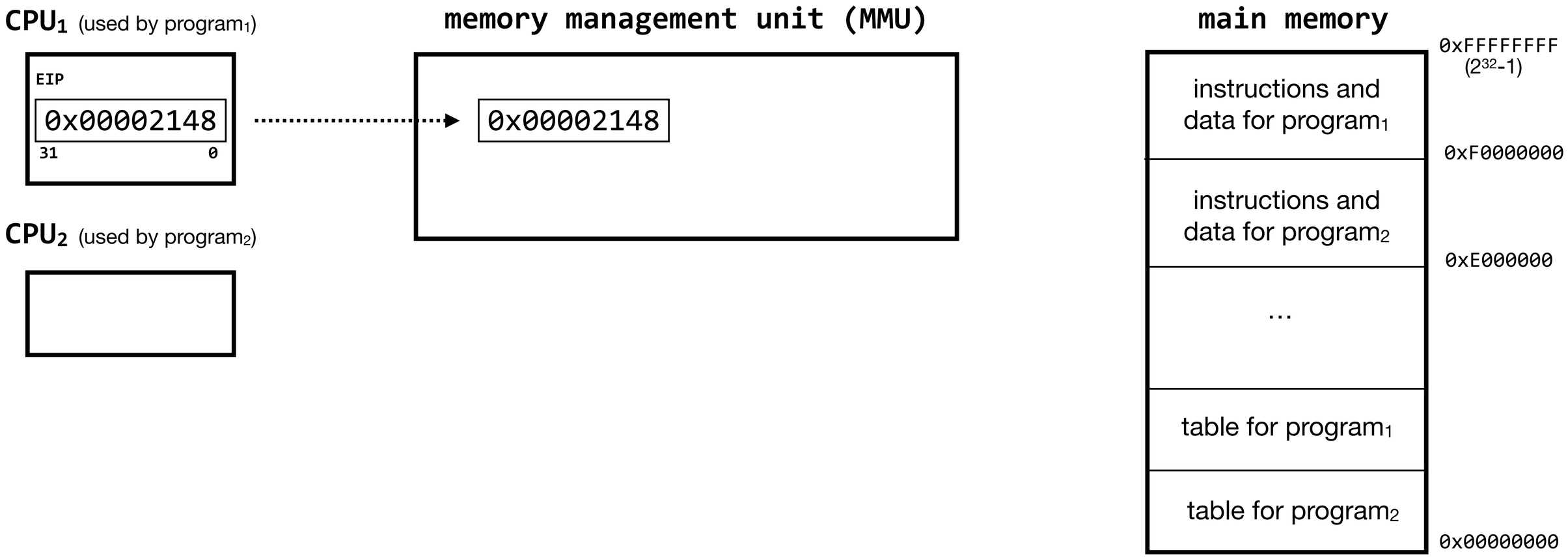

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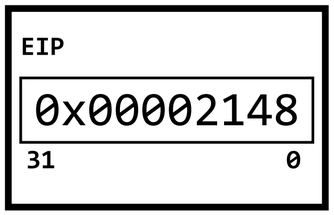

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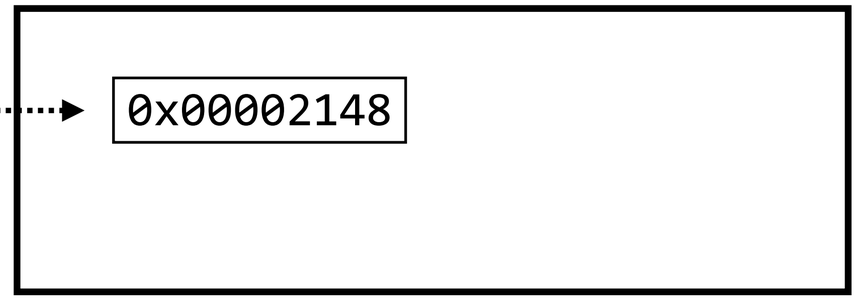

the MMU is going to use program$_1$'s table to *translate* a virtual address from program$_1$ into a physical address

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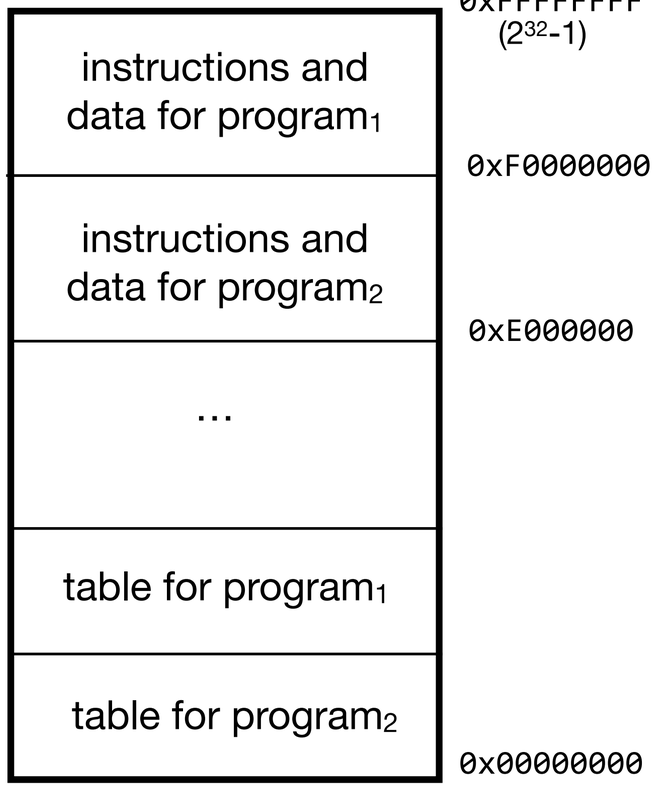

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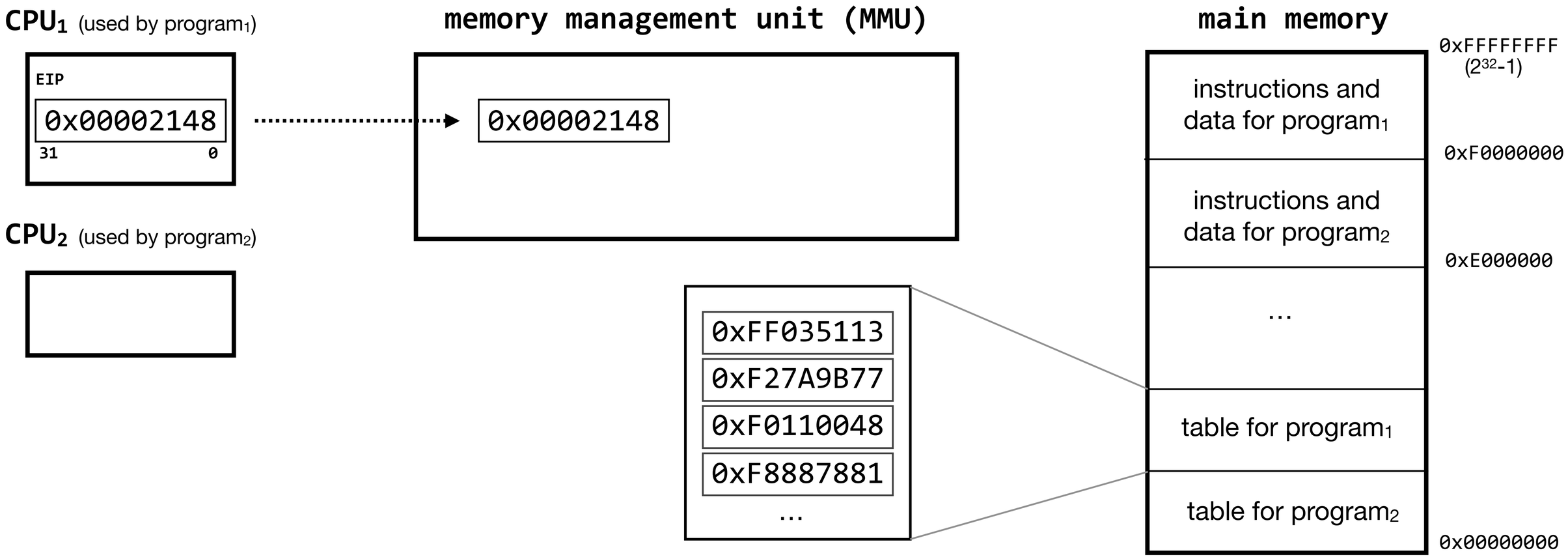

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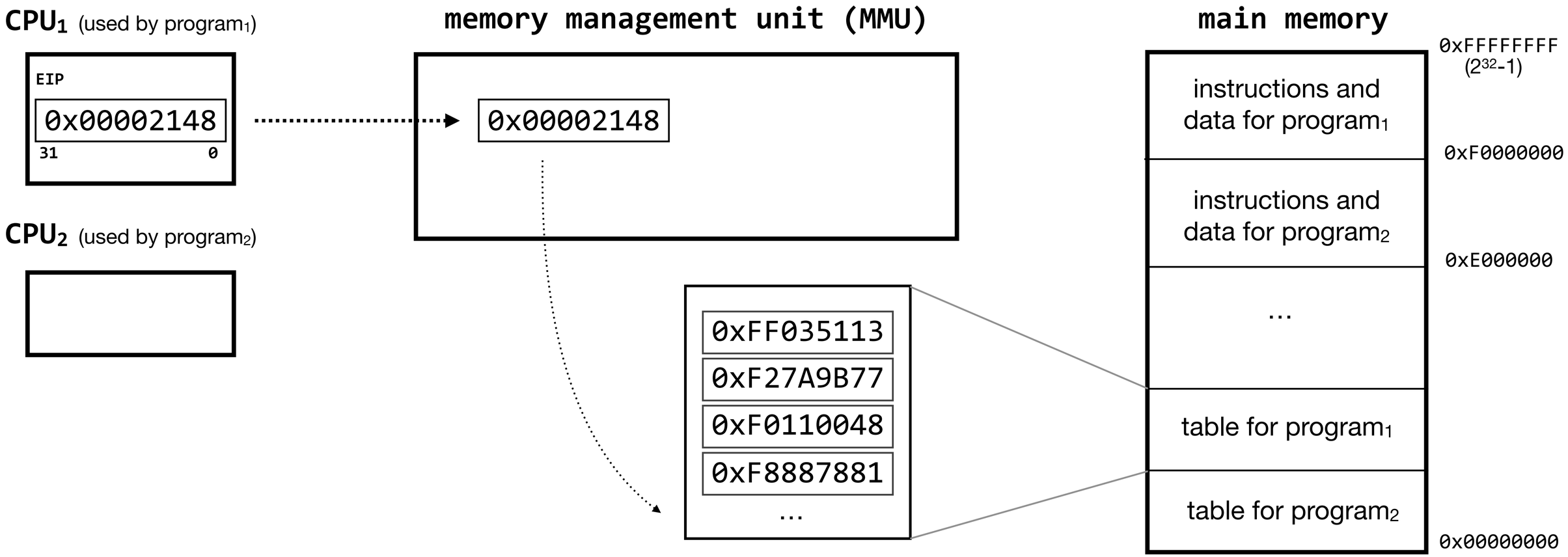

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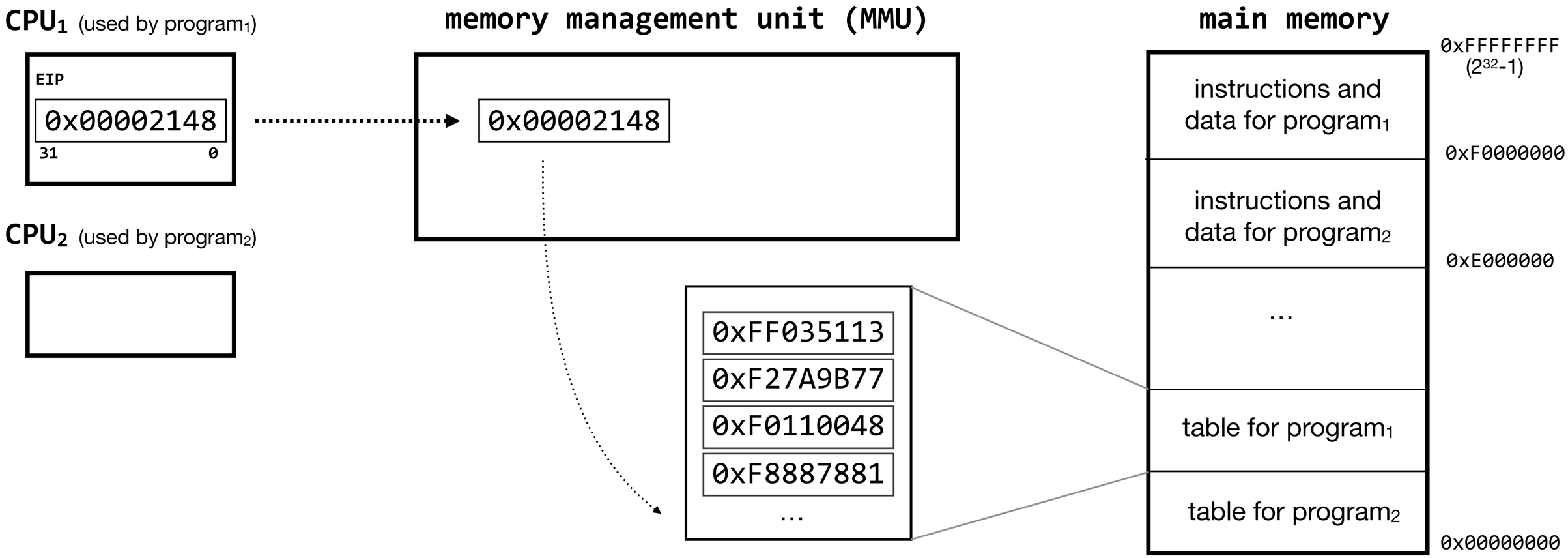

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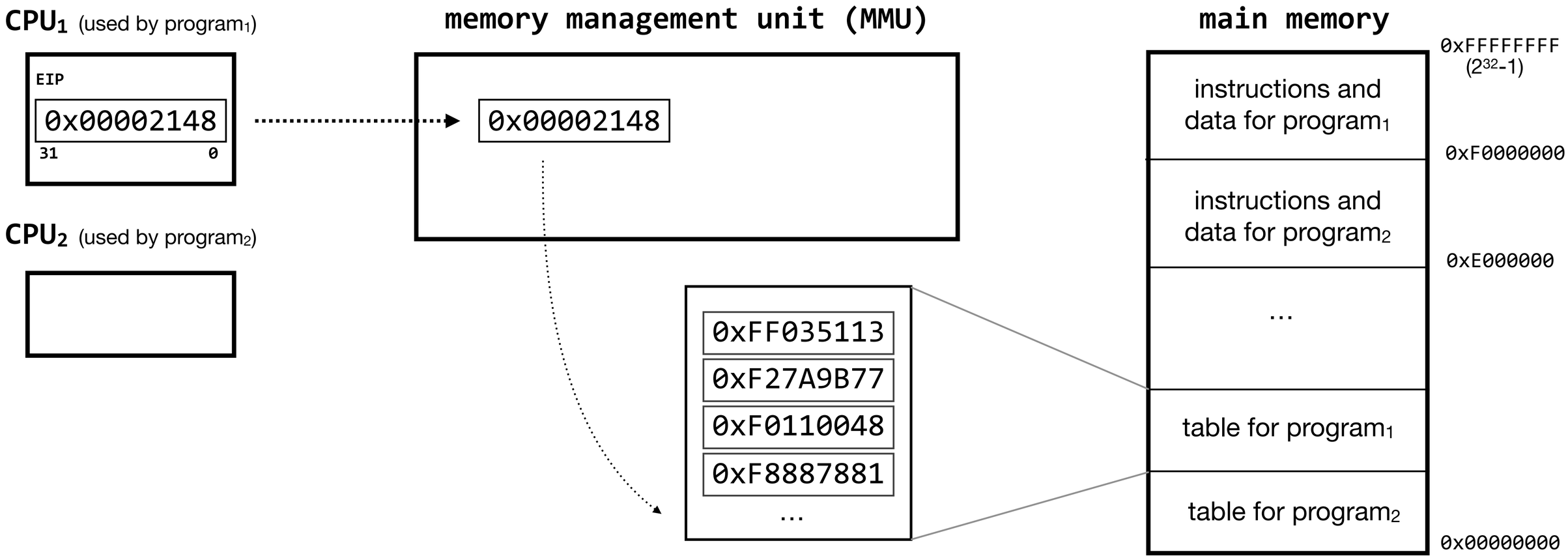

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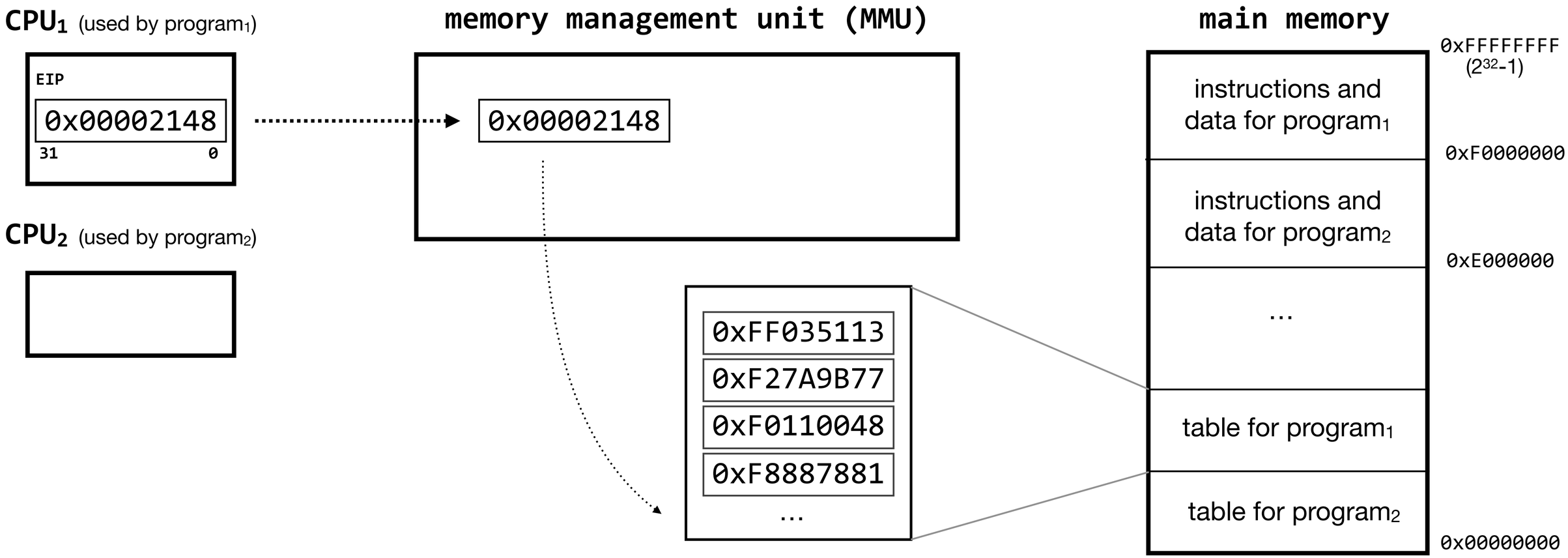

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16GB is *quite a lot* of memory

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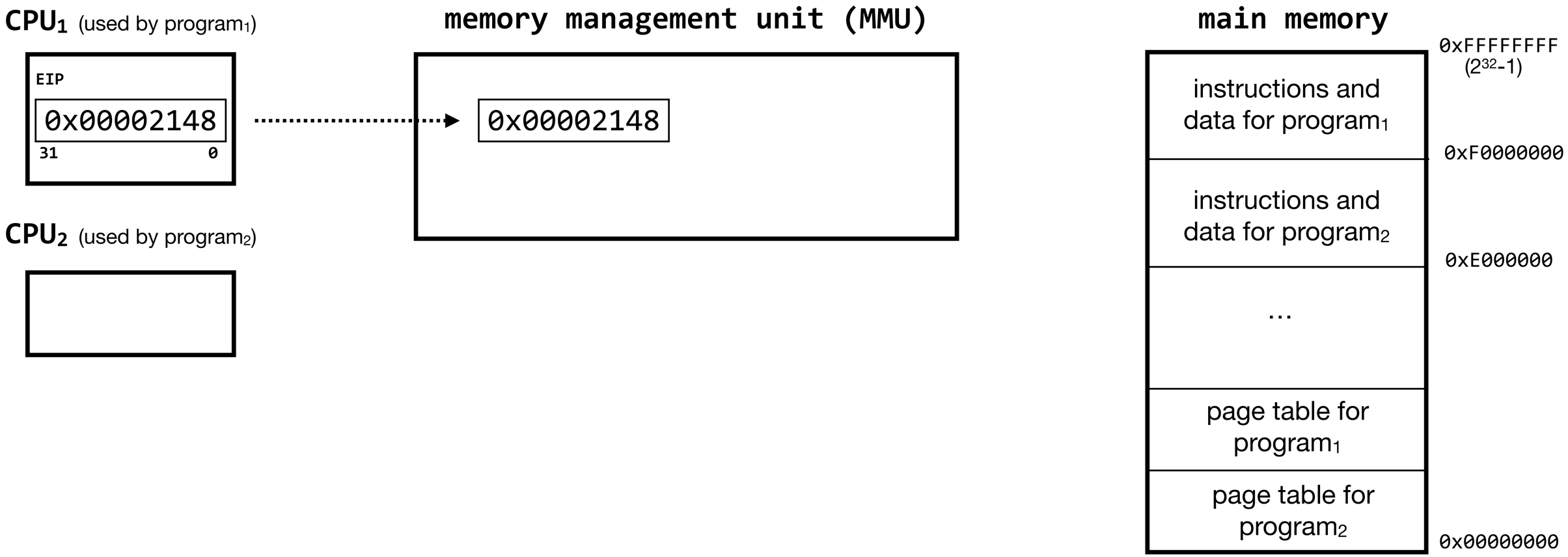

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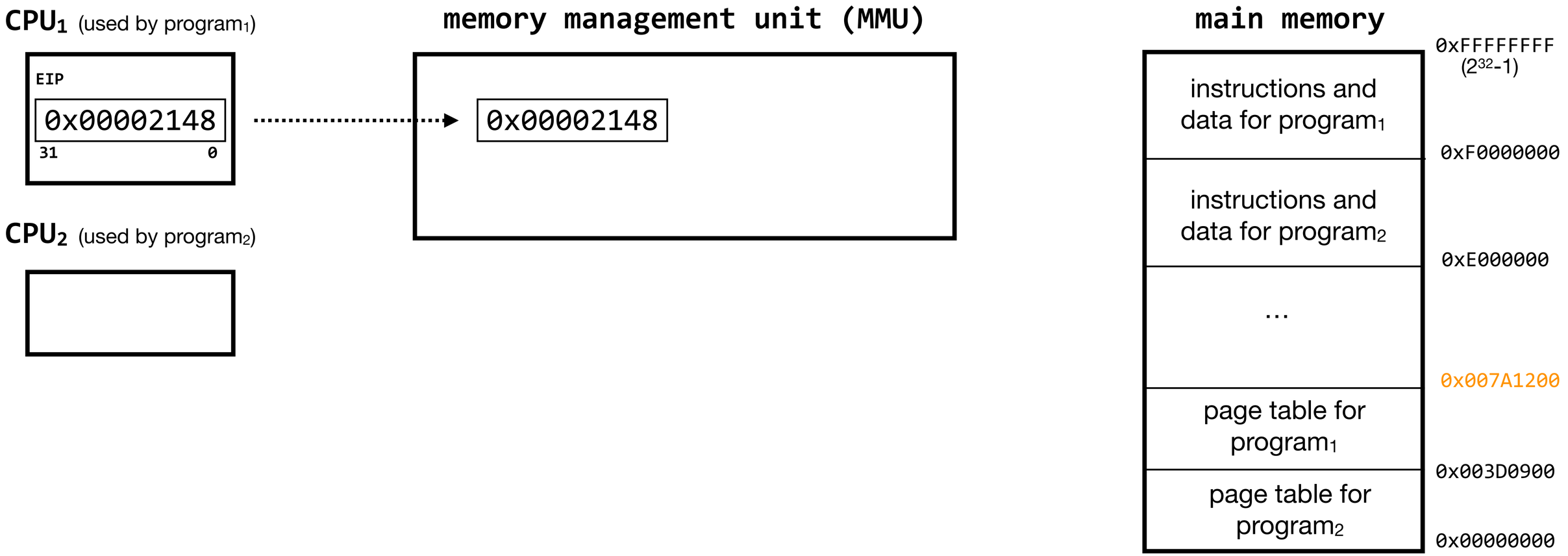

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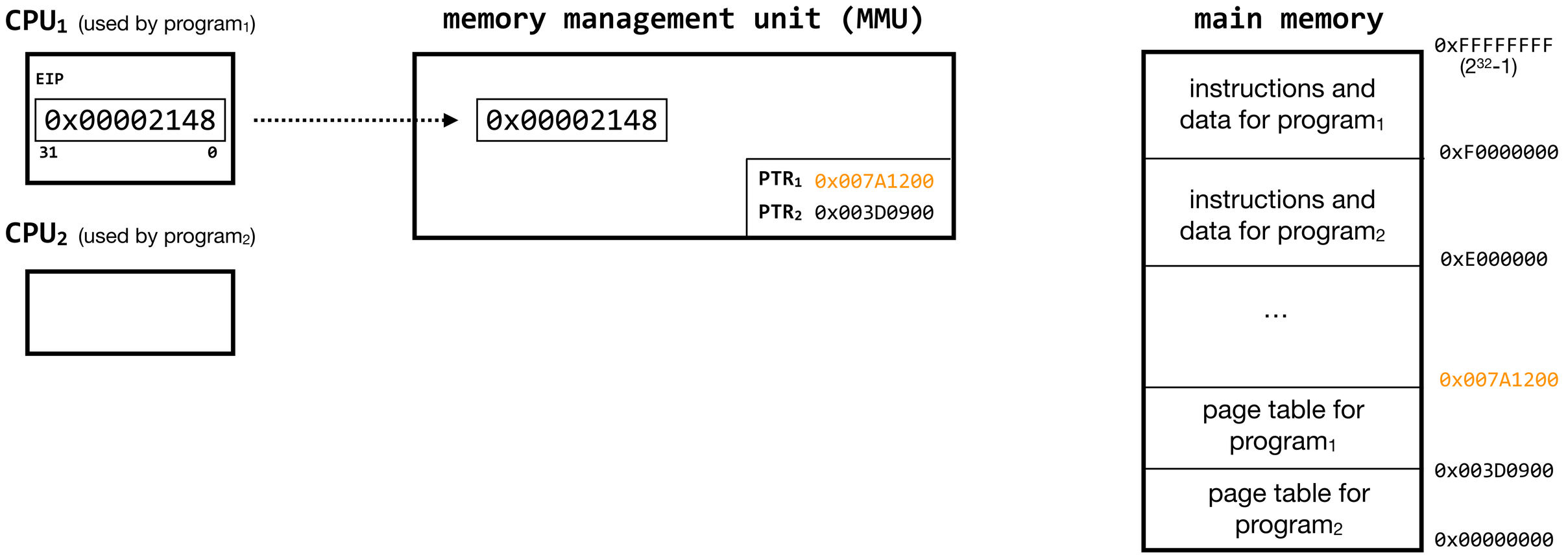

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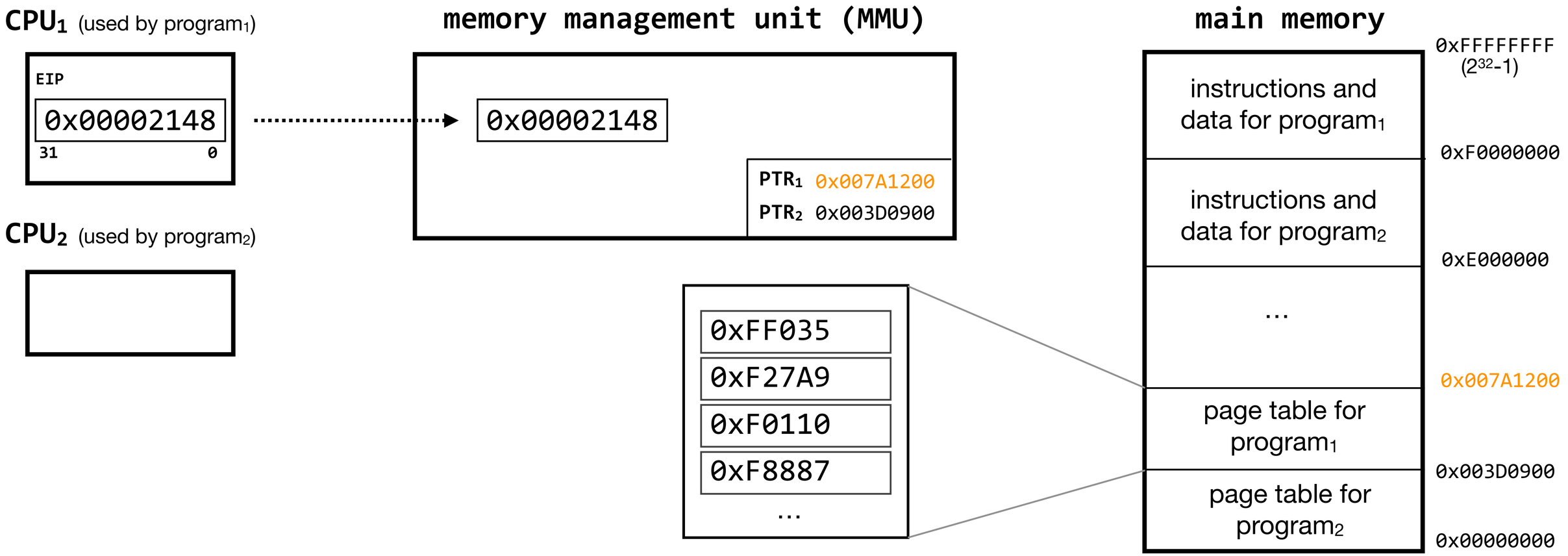

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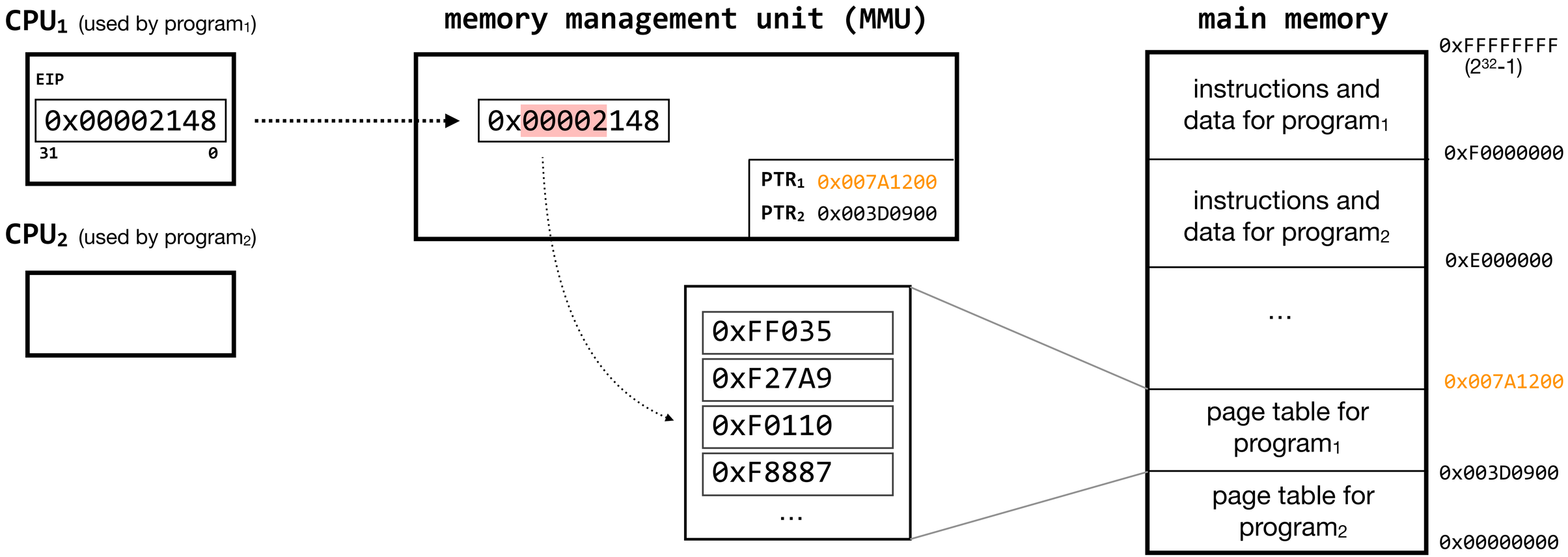

page tables: top 20 bits of the virtual address act as an index into this table

(a *page* of memory is $2^{32-20}=2^{12}$ bytes)

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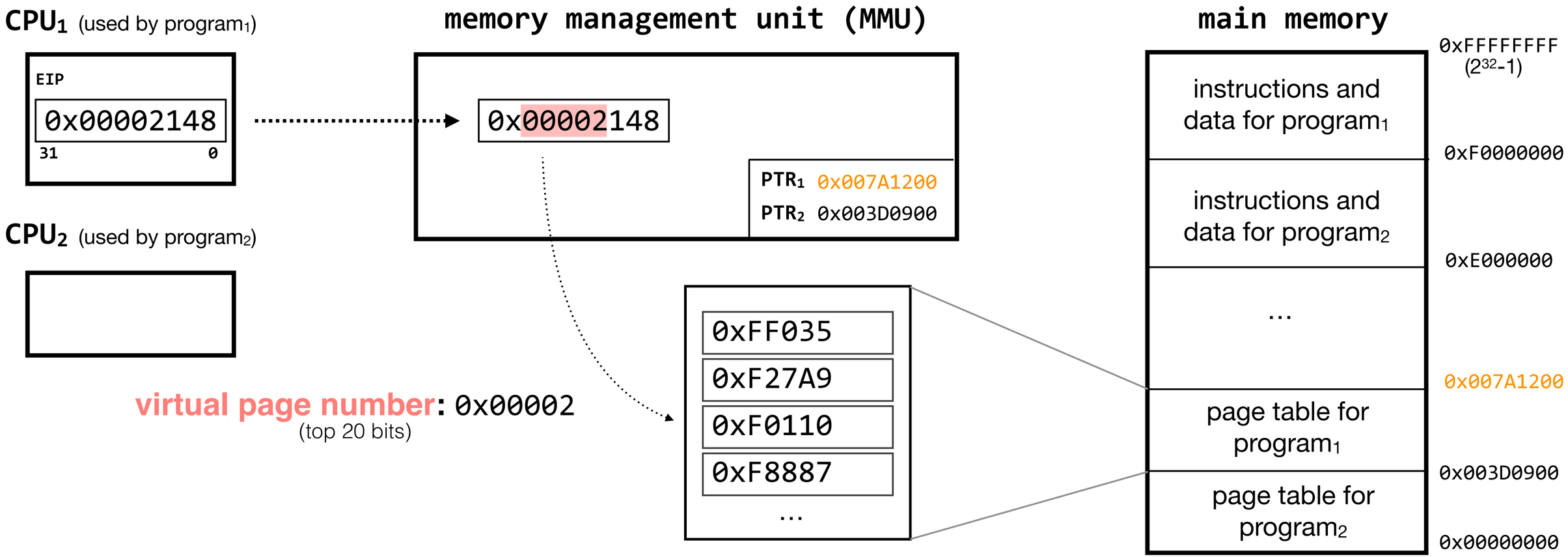

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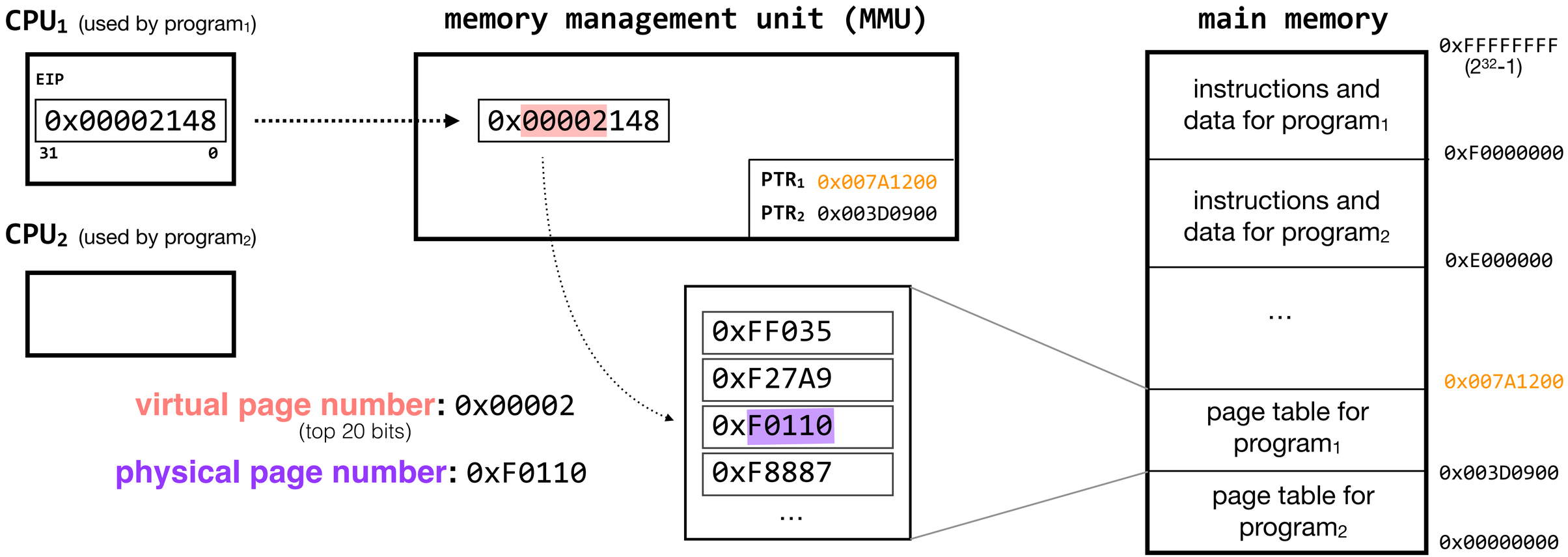

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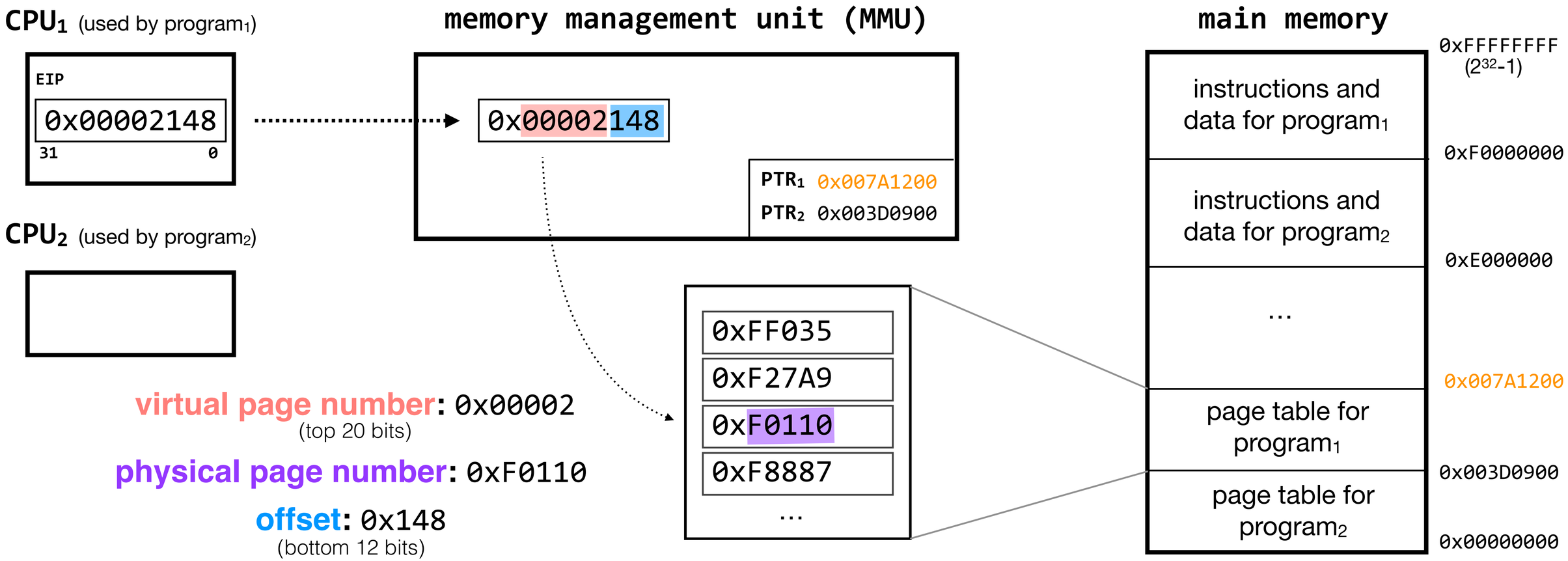

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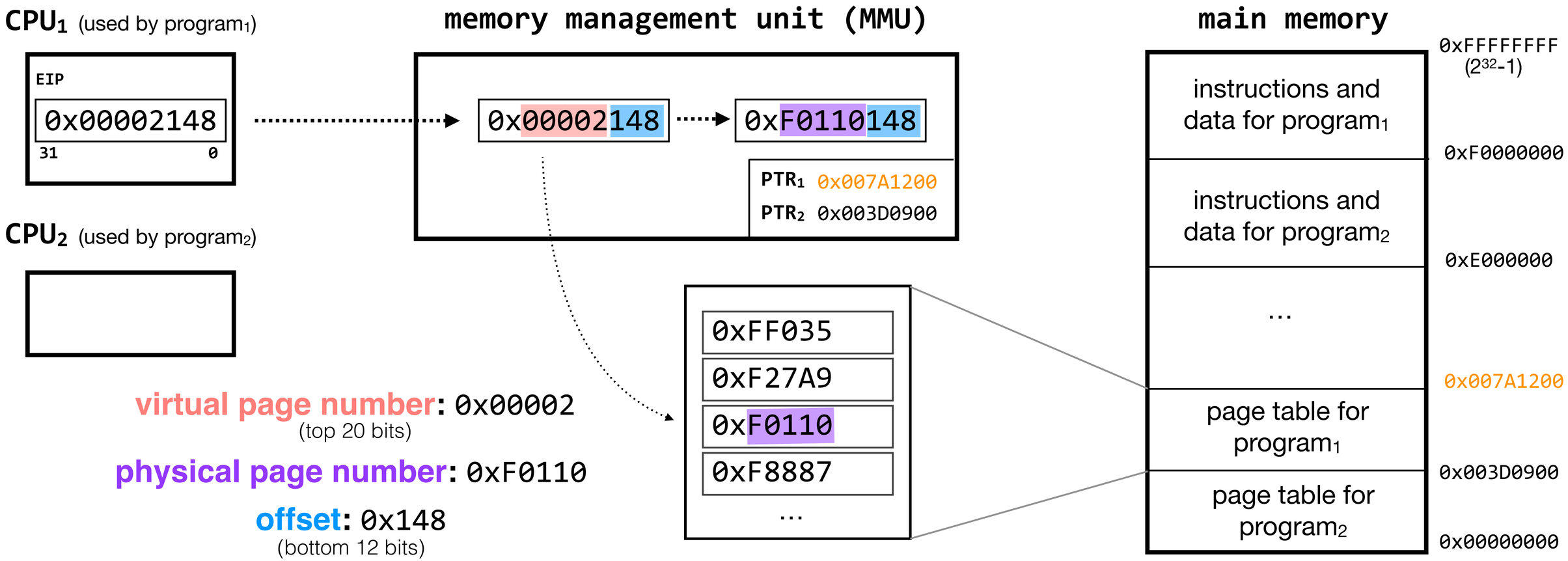

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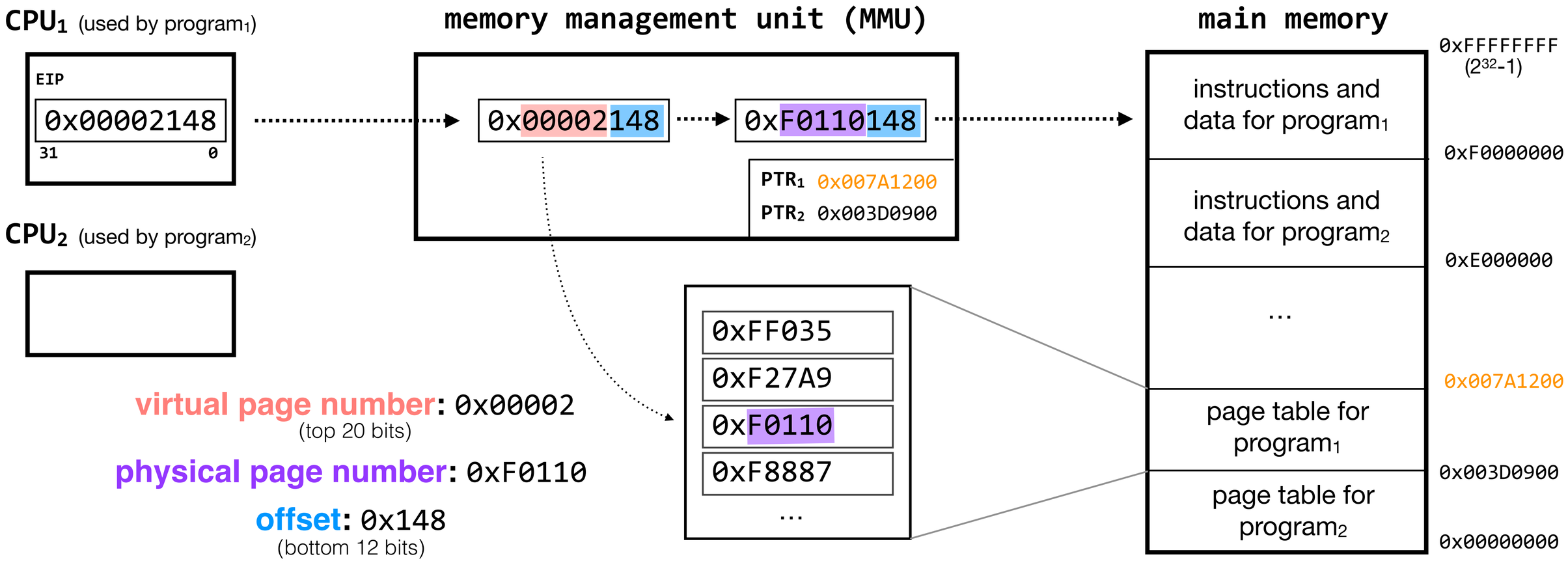

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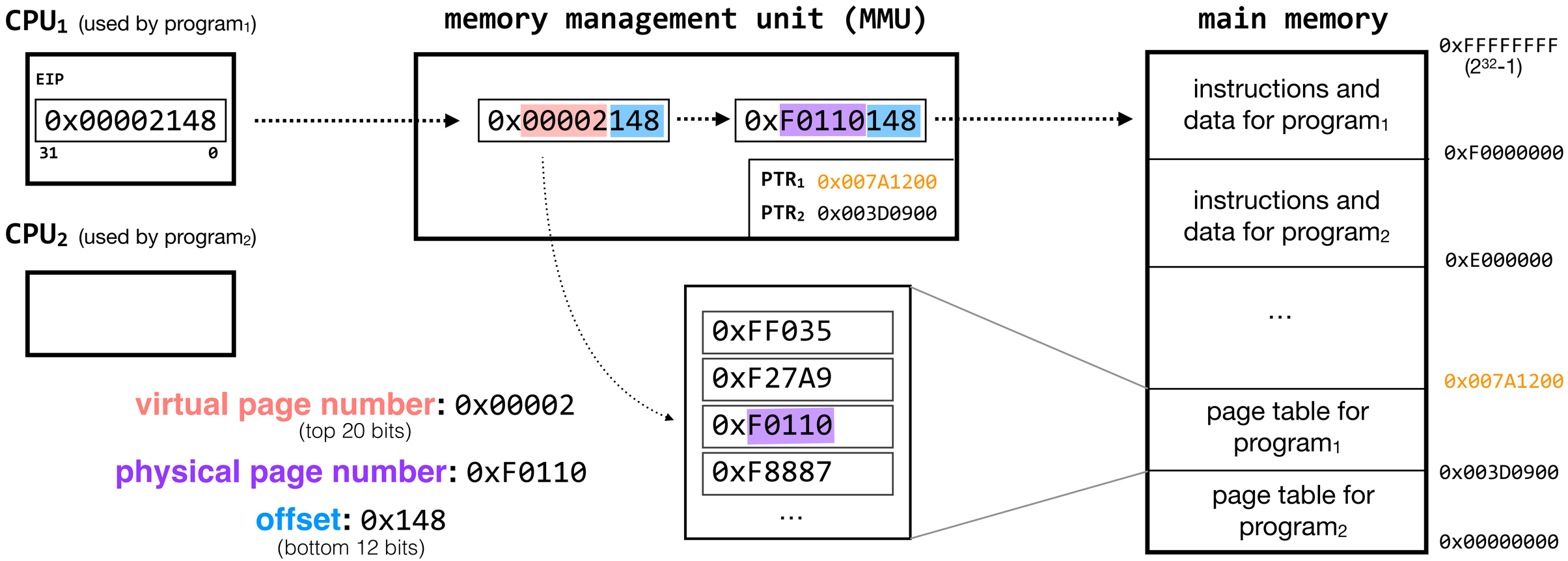

virtual page number: 0x00002
(top 20 bits)

physical page number: 0xF0110

offset: 0x148
(bottom 12 bits)

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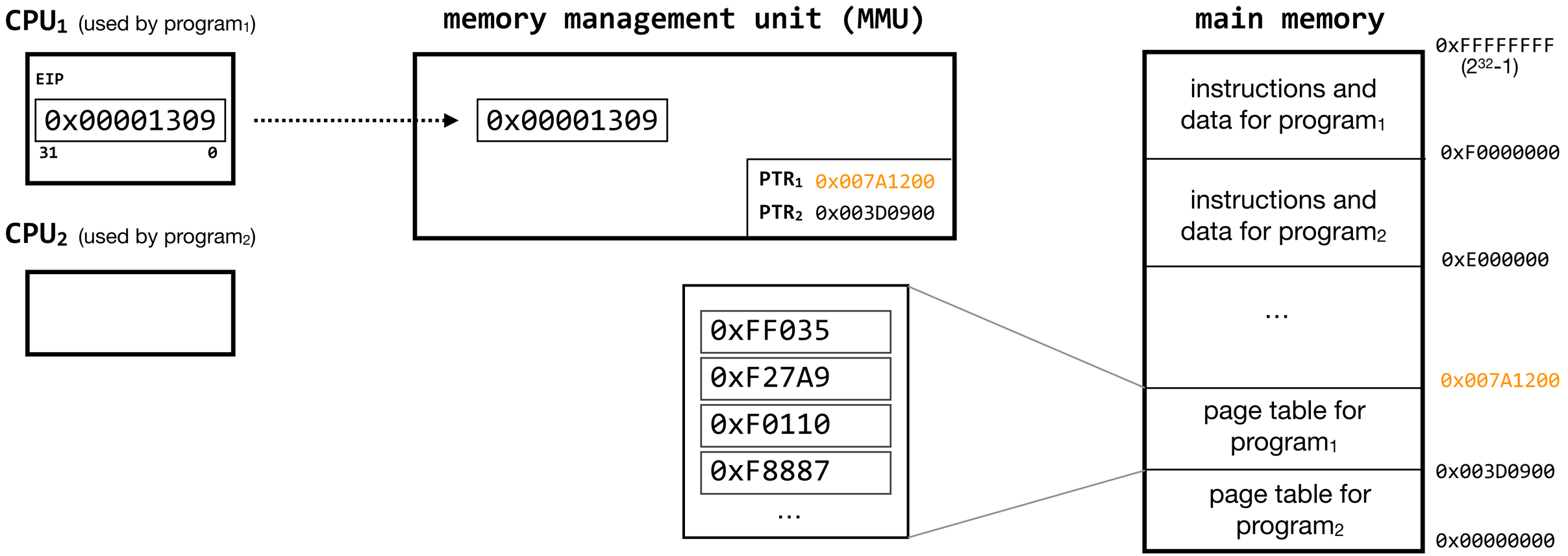

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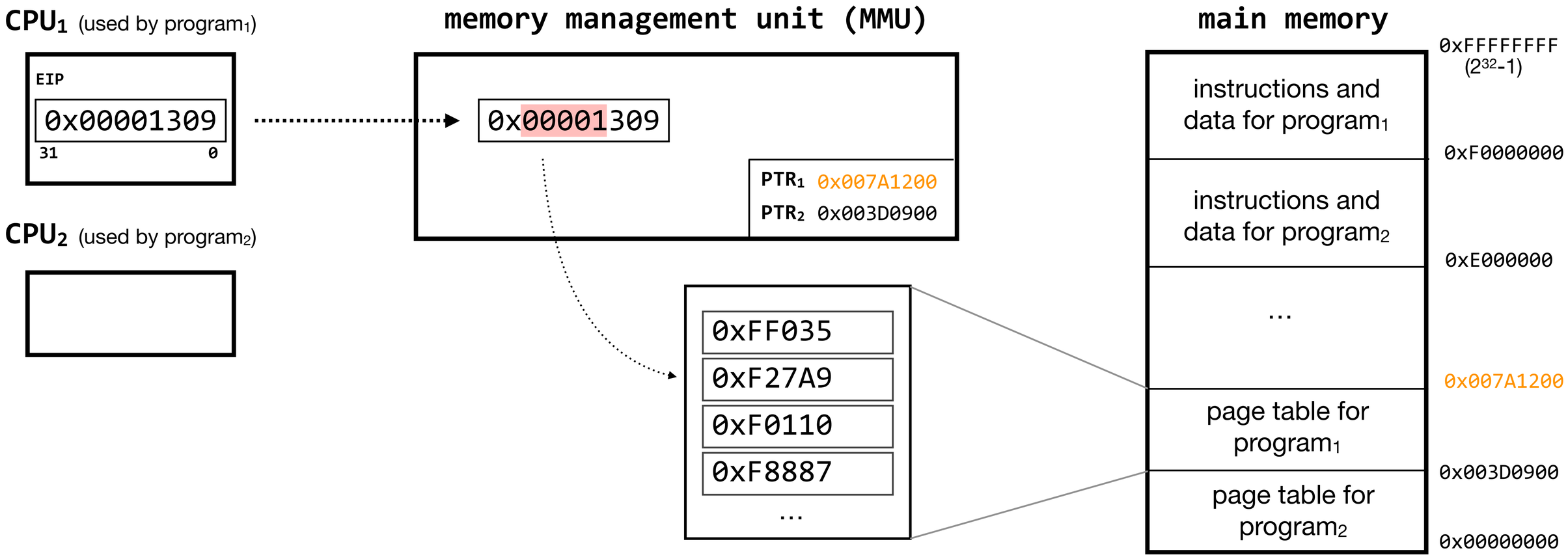

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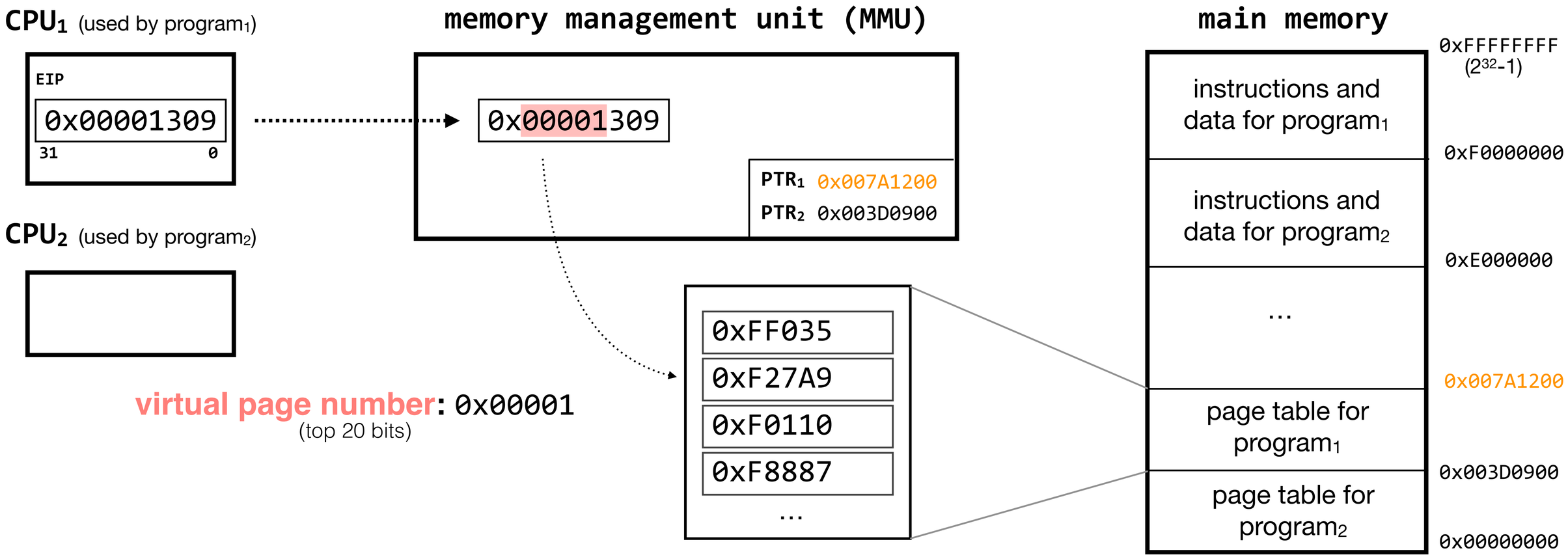

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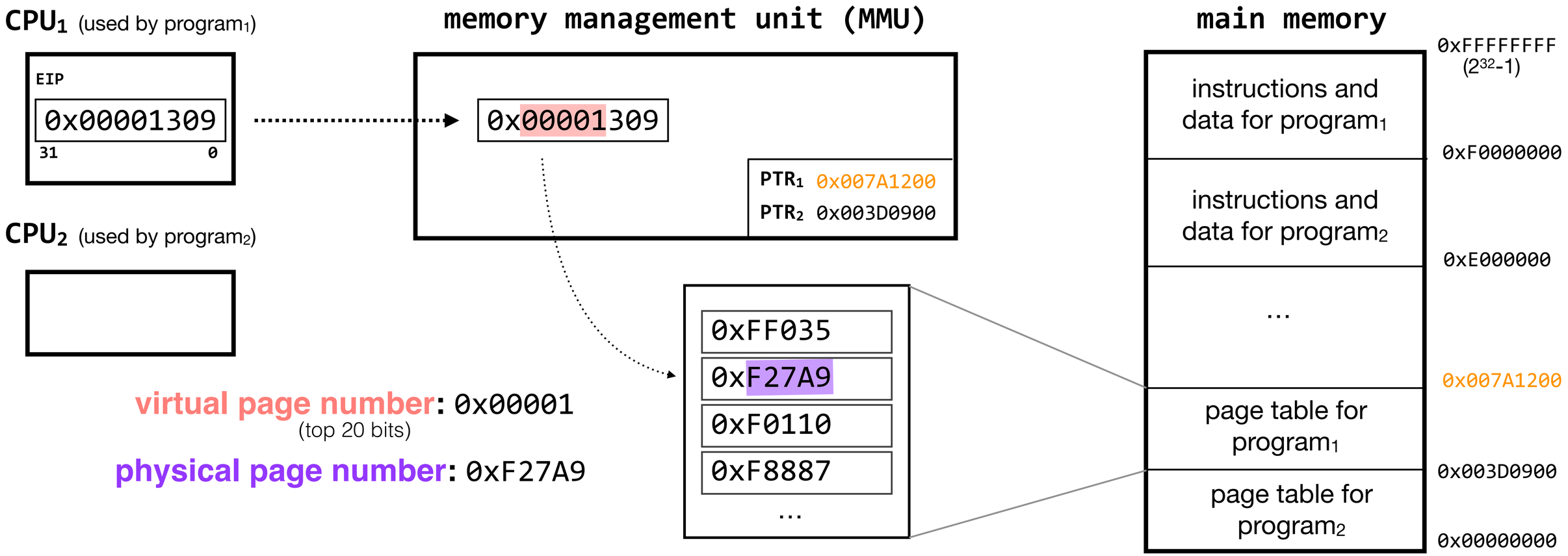

virtual page number: 0x00001
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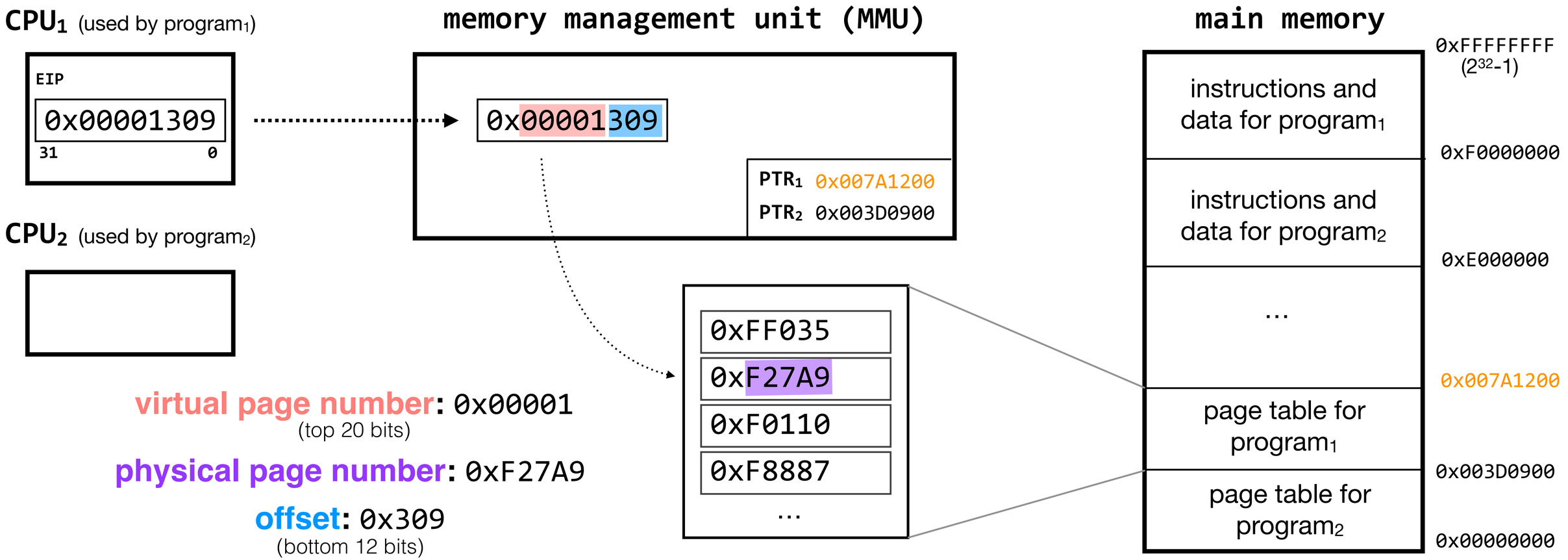

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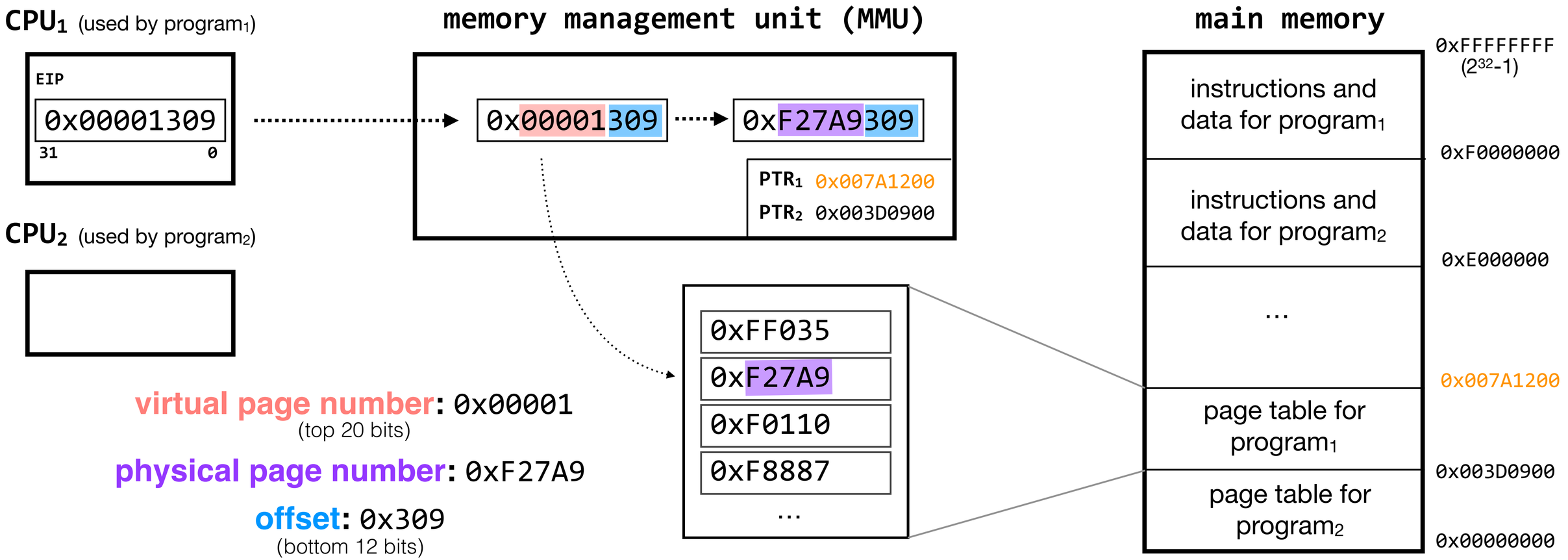

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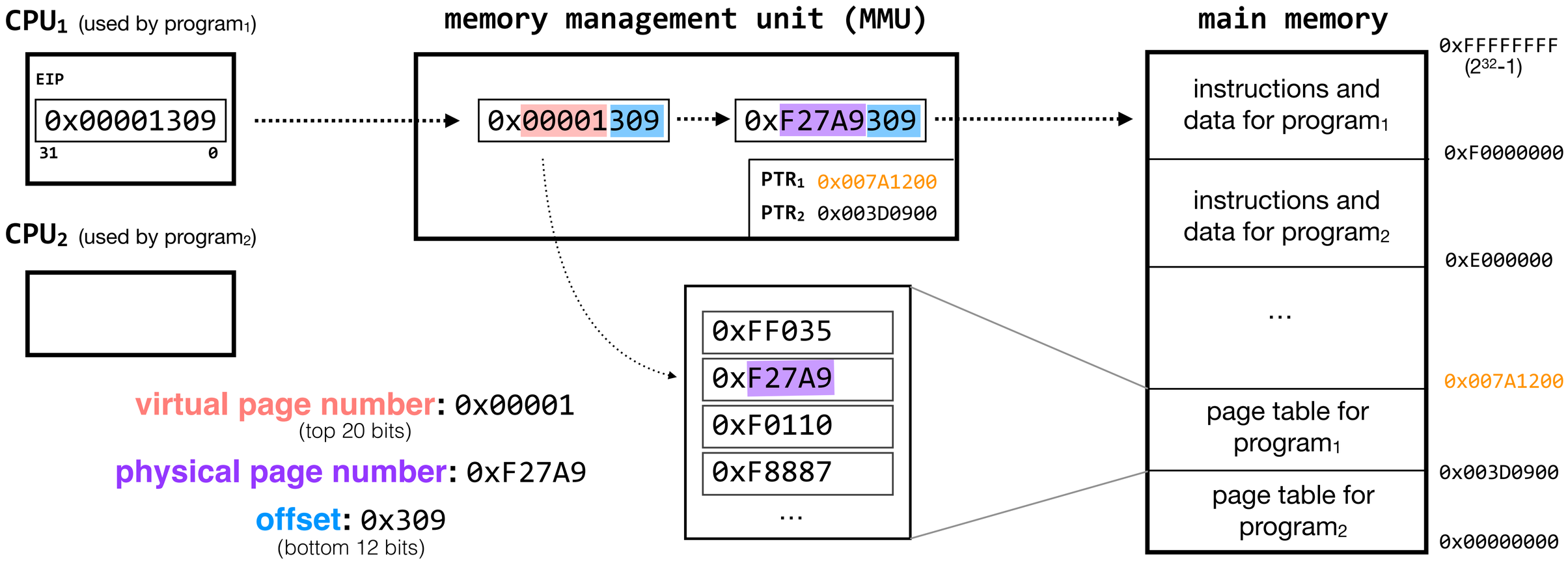

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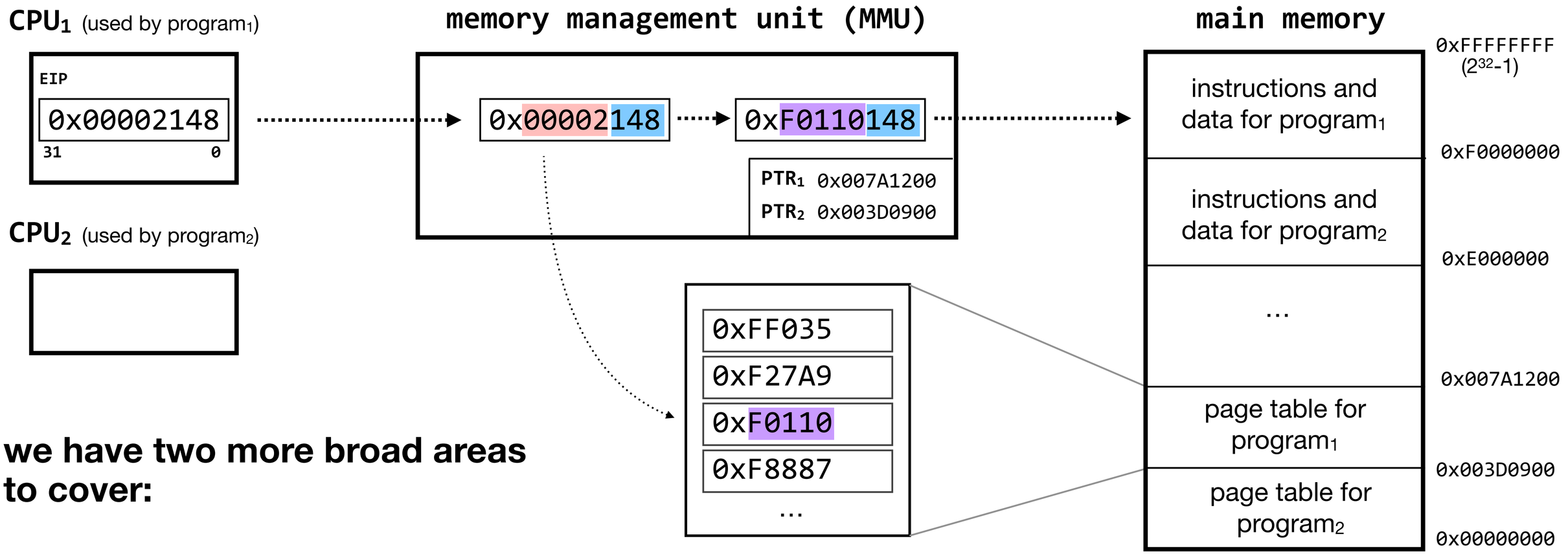

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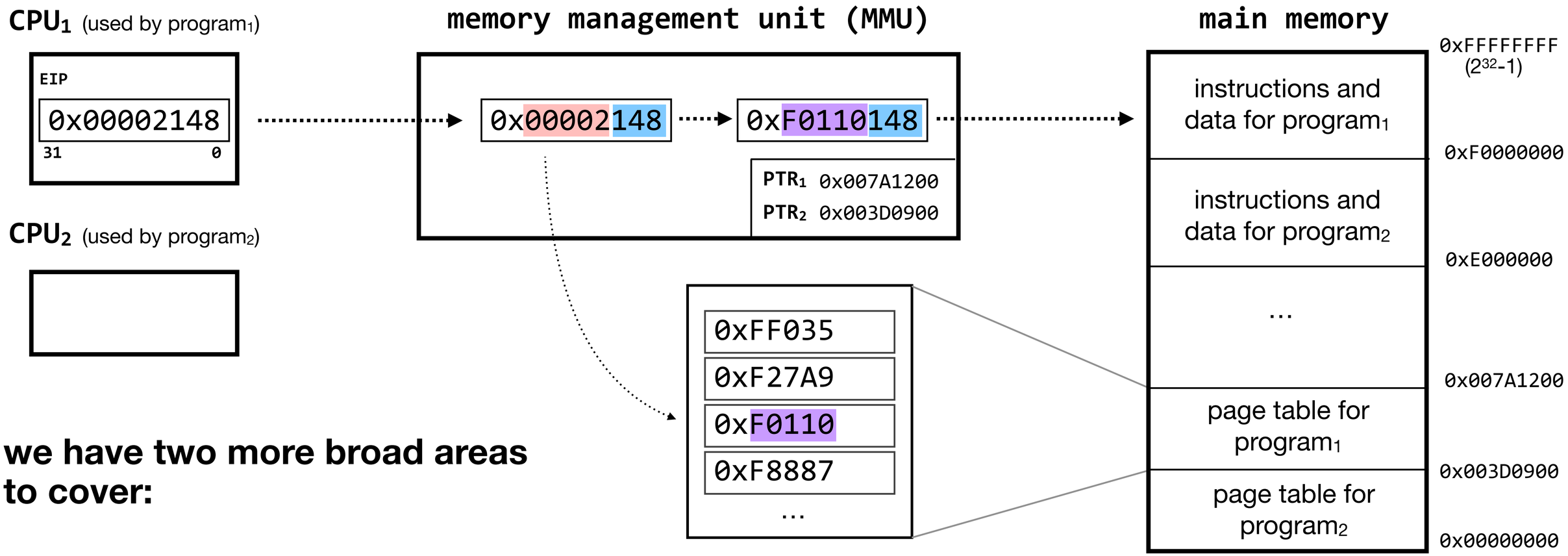

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does virtual memory protect programs from accessing each other's memory?
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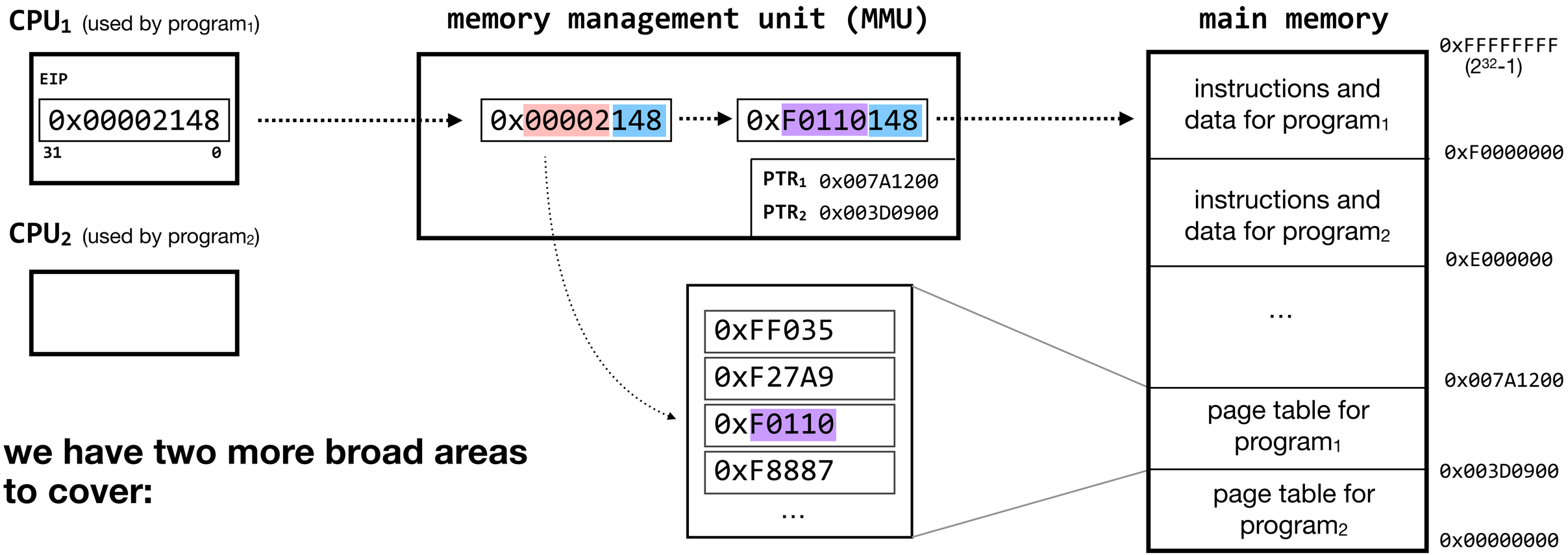

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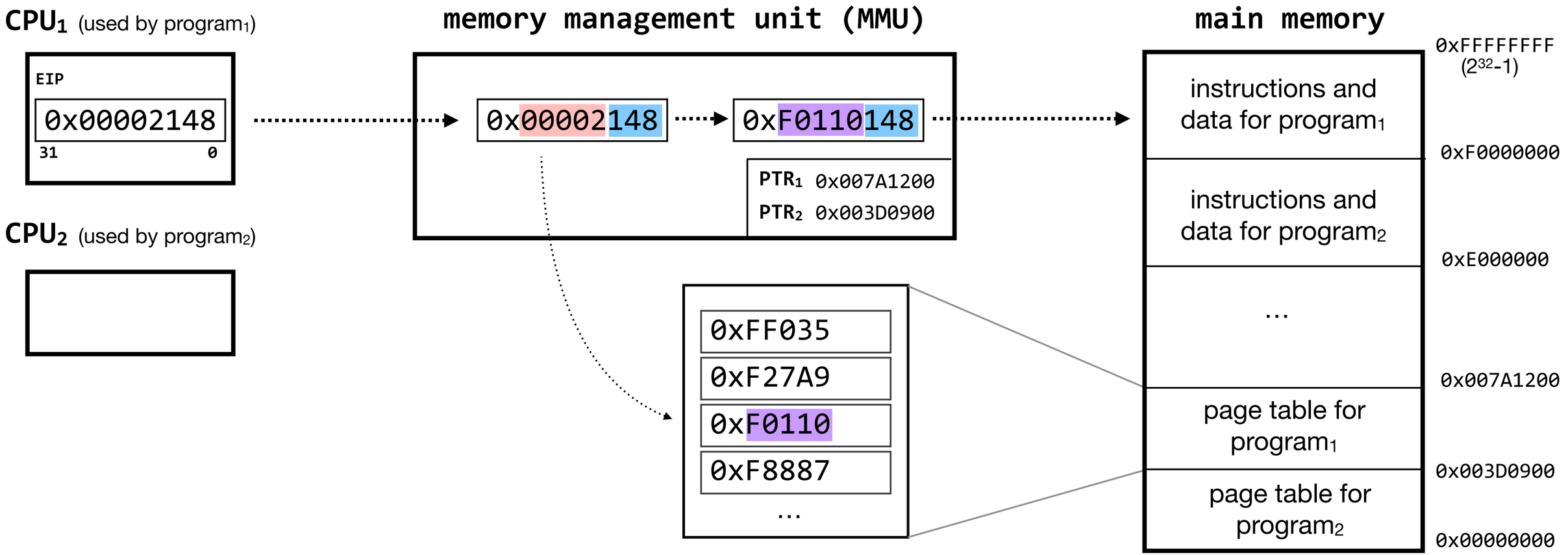

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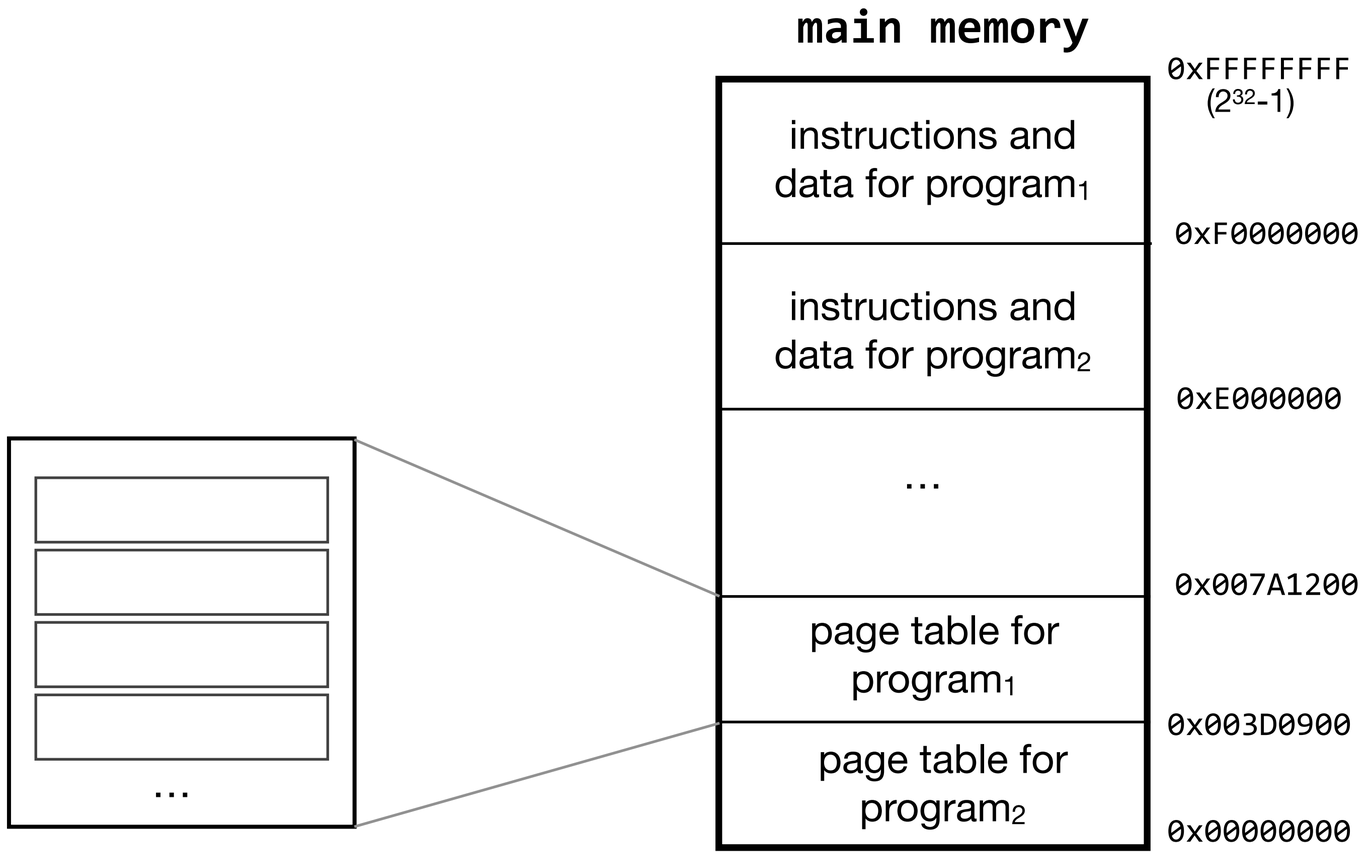

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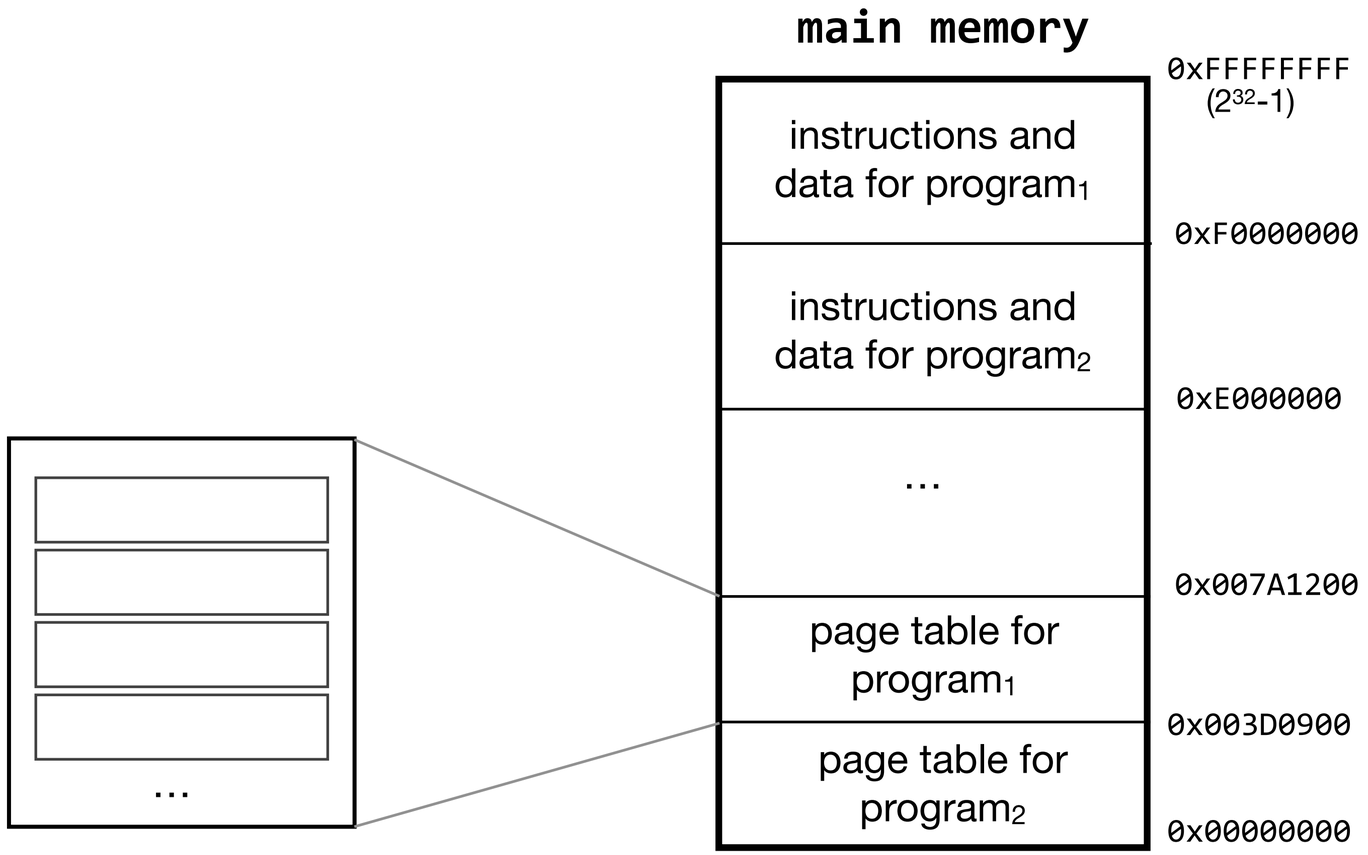

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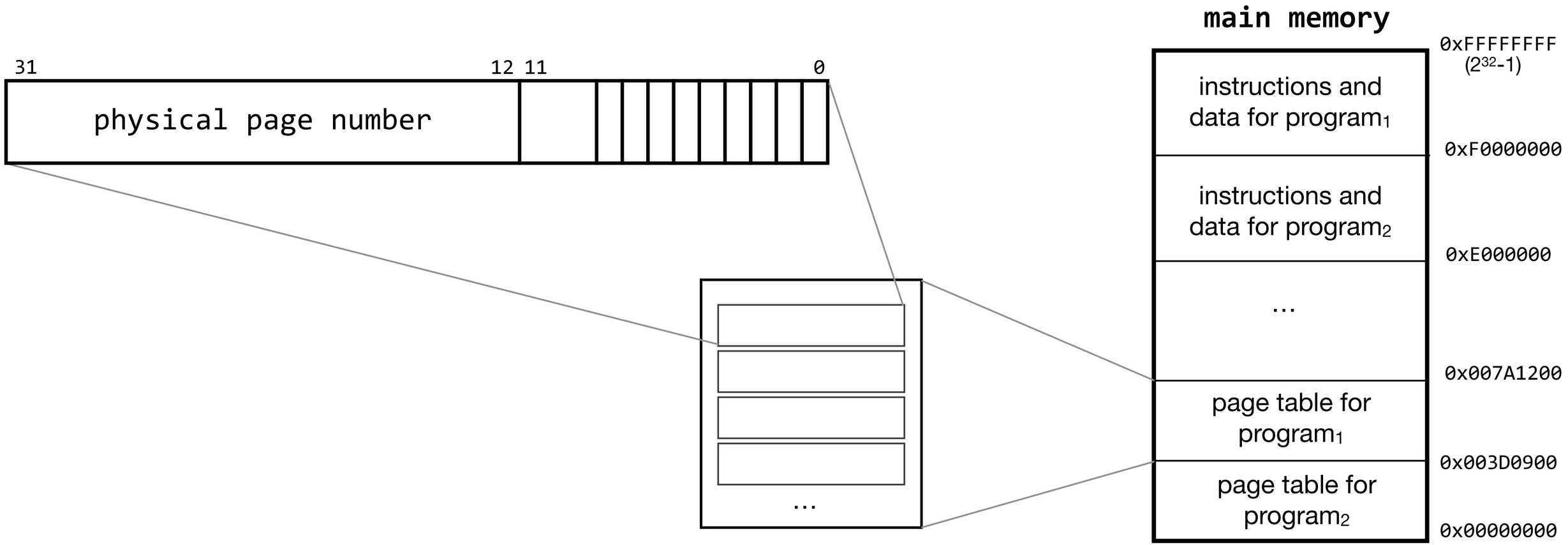

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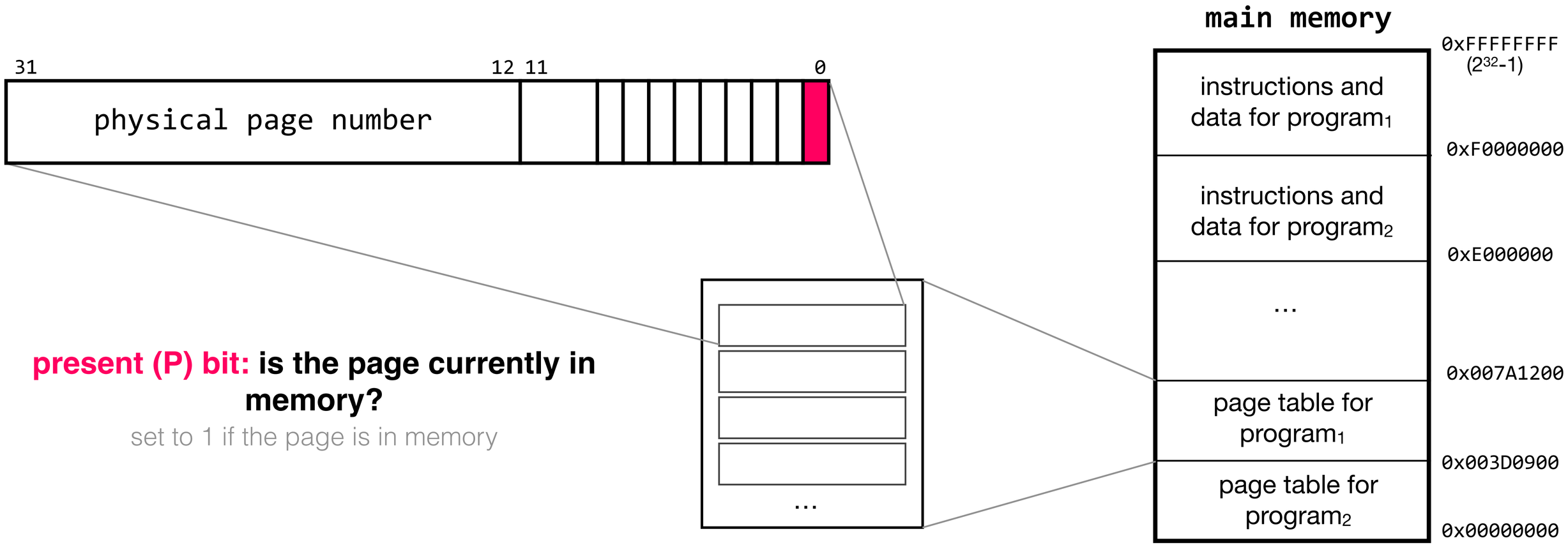

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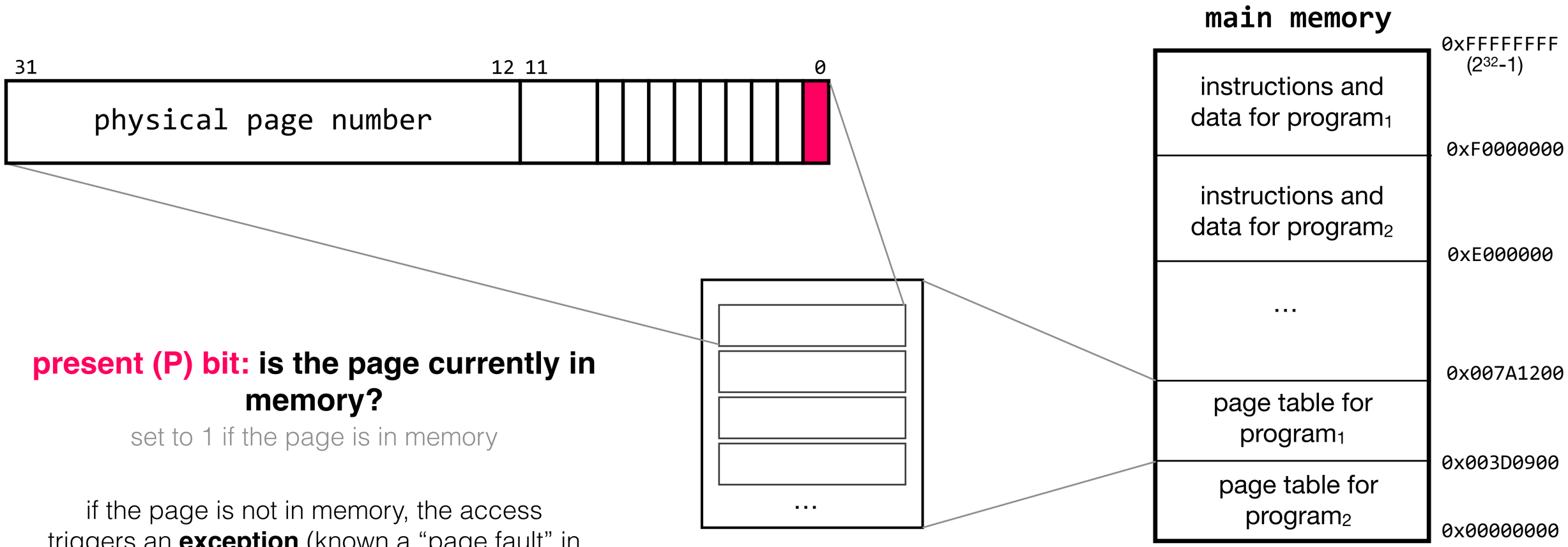

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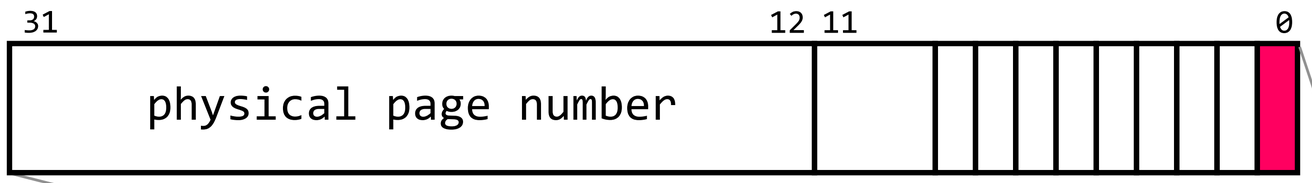

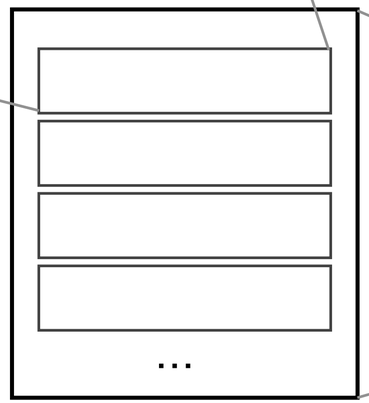

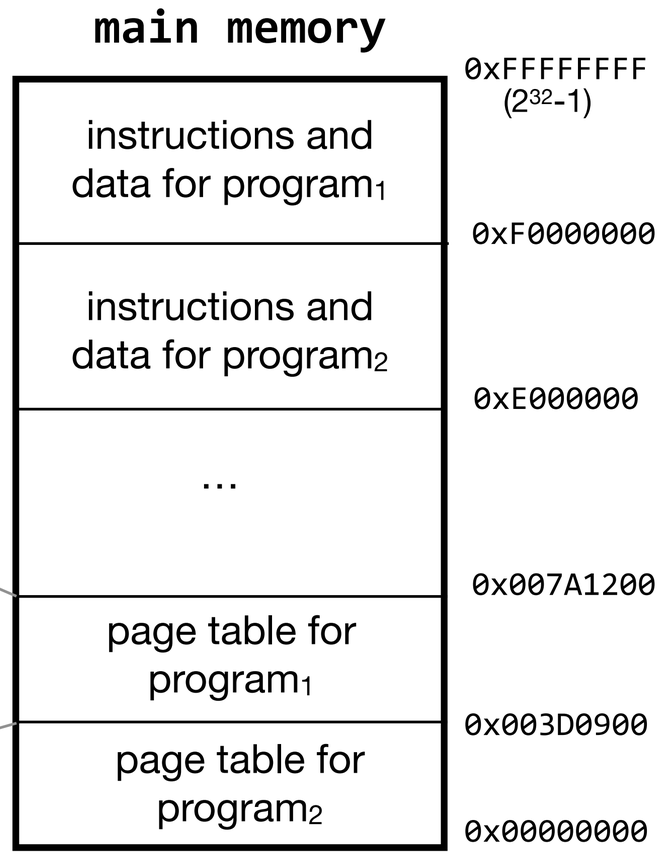

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this also answers the question of why PTEs are 32 bits, not 20: they store information beyond the page number

interlude: handling exceptions

(such as page faults)

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  // call the handler for this particular exception
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each handler is different. as an example, the page-fault handler would take care of bringing the requested page into memory

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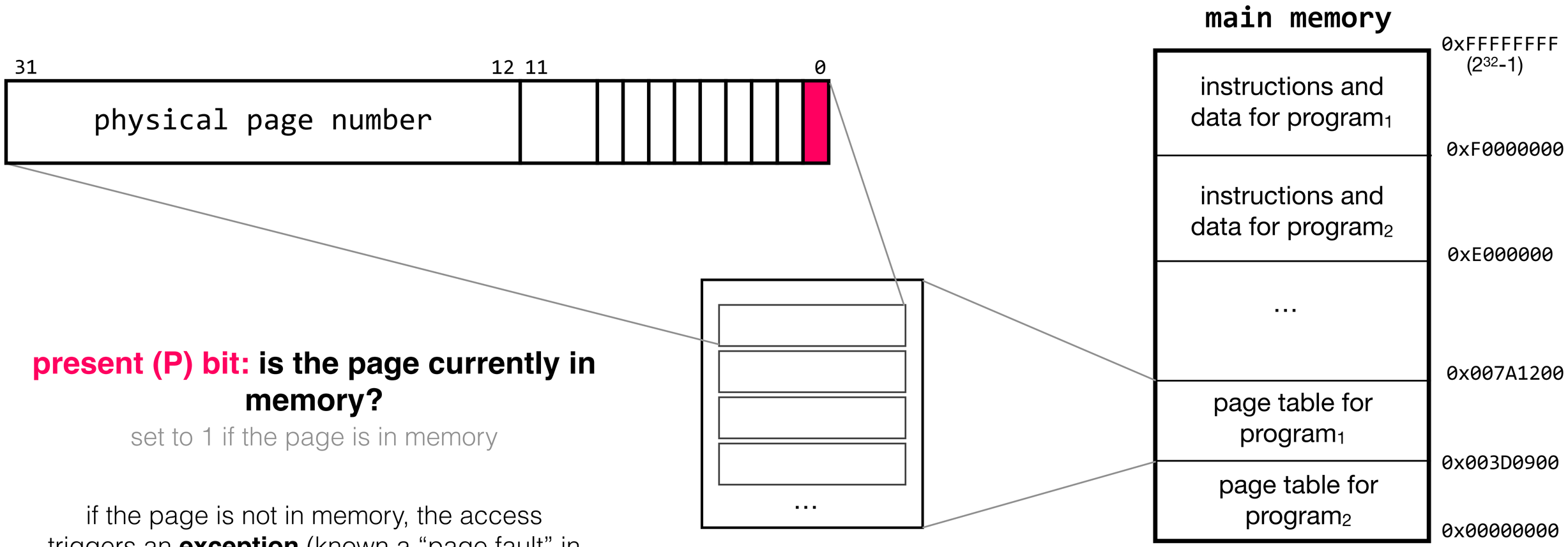

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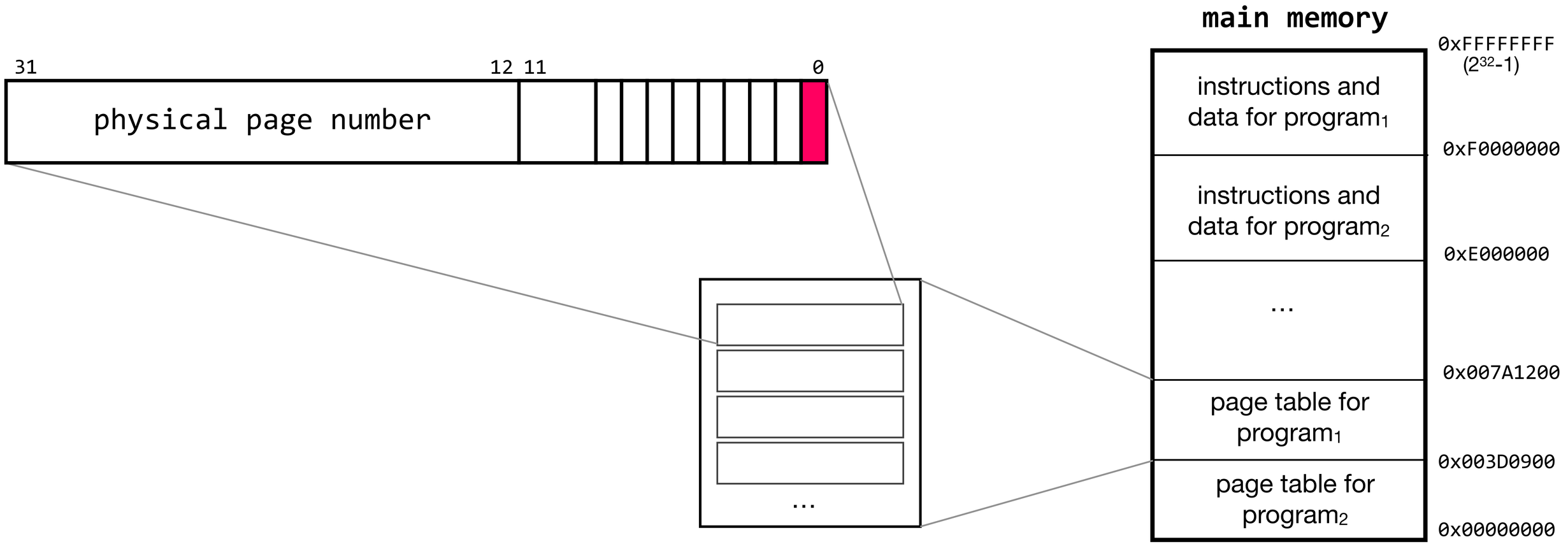

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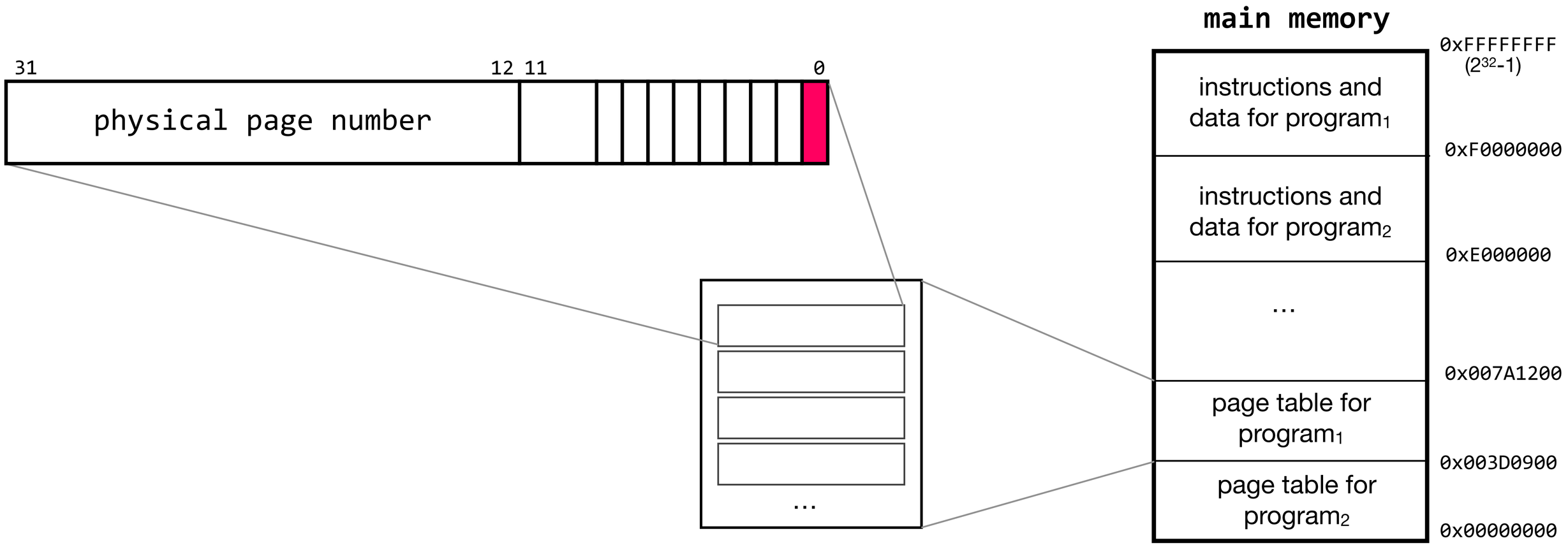

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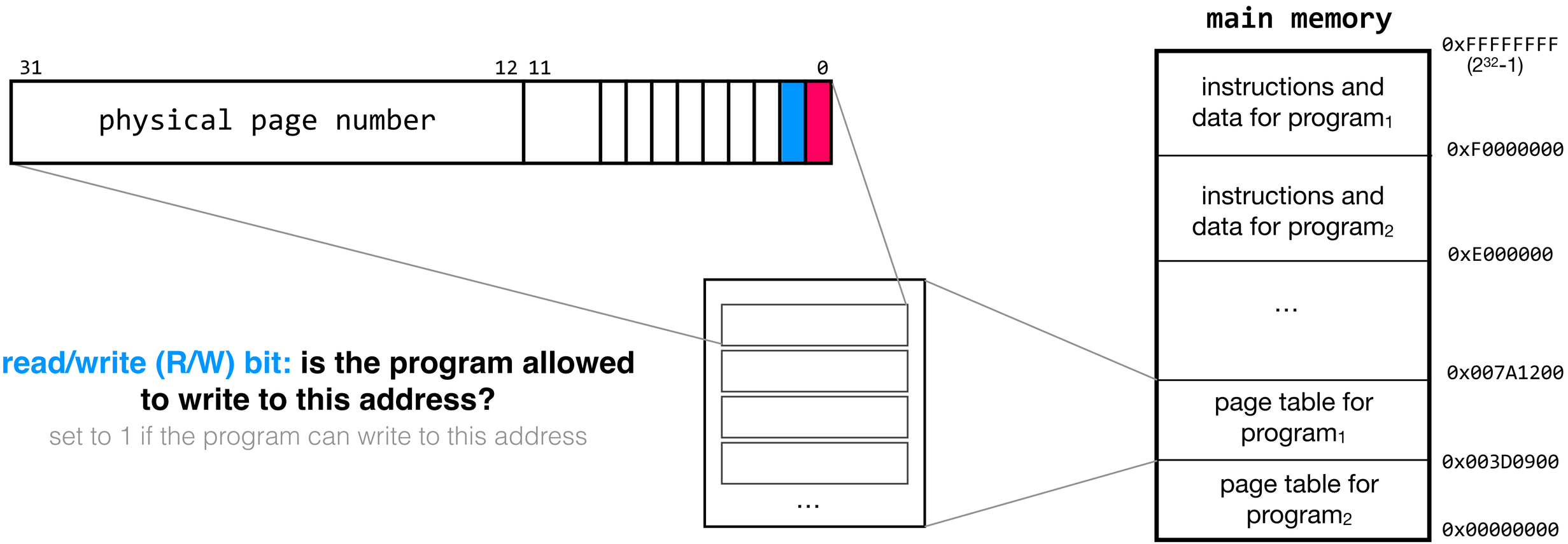

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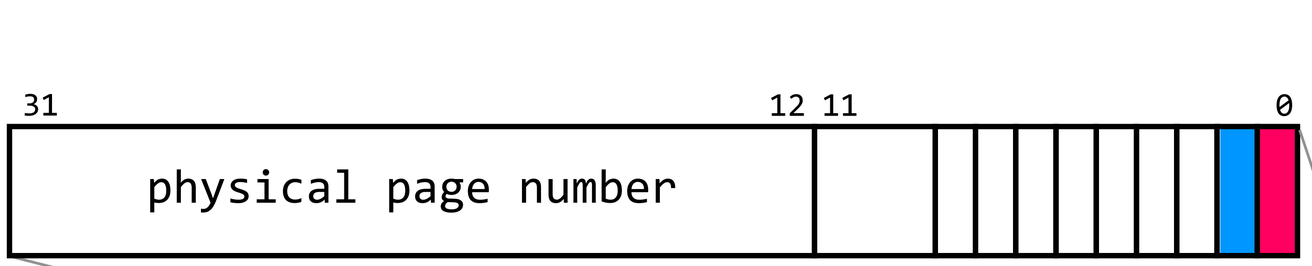

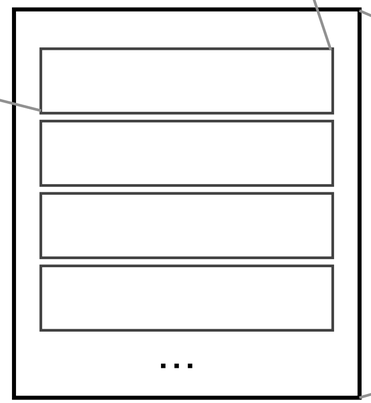

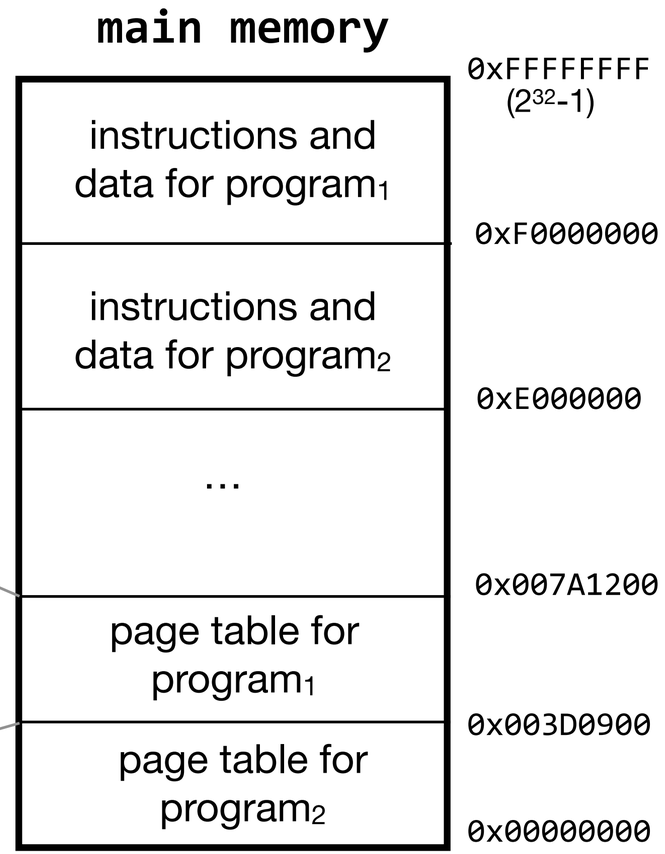

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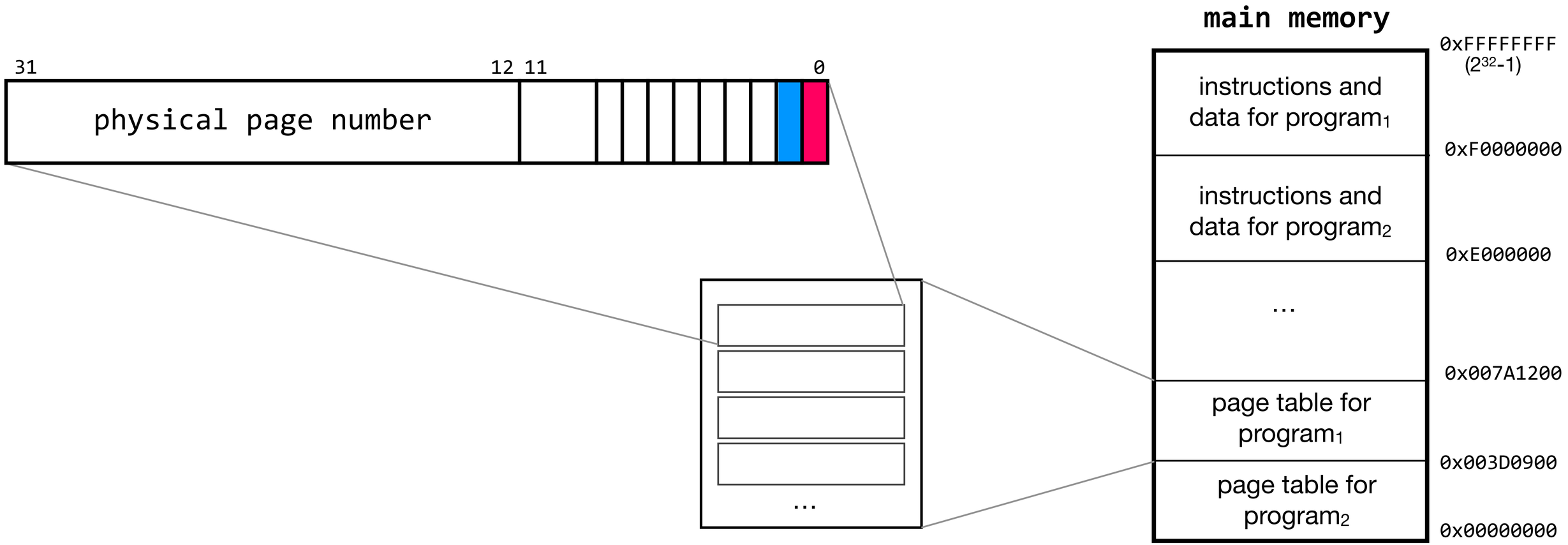
if the program doesn't have write-access to this page (and is trying to write to it), the access triggers an **exception**, which the kernel handles

what happens if a program tries to access memory that only the kernel should have access to?



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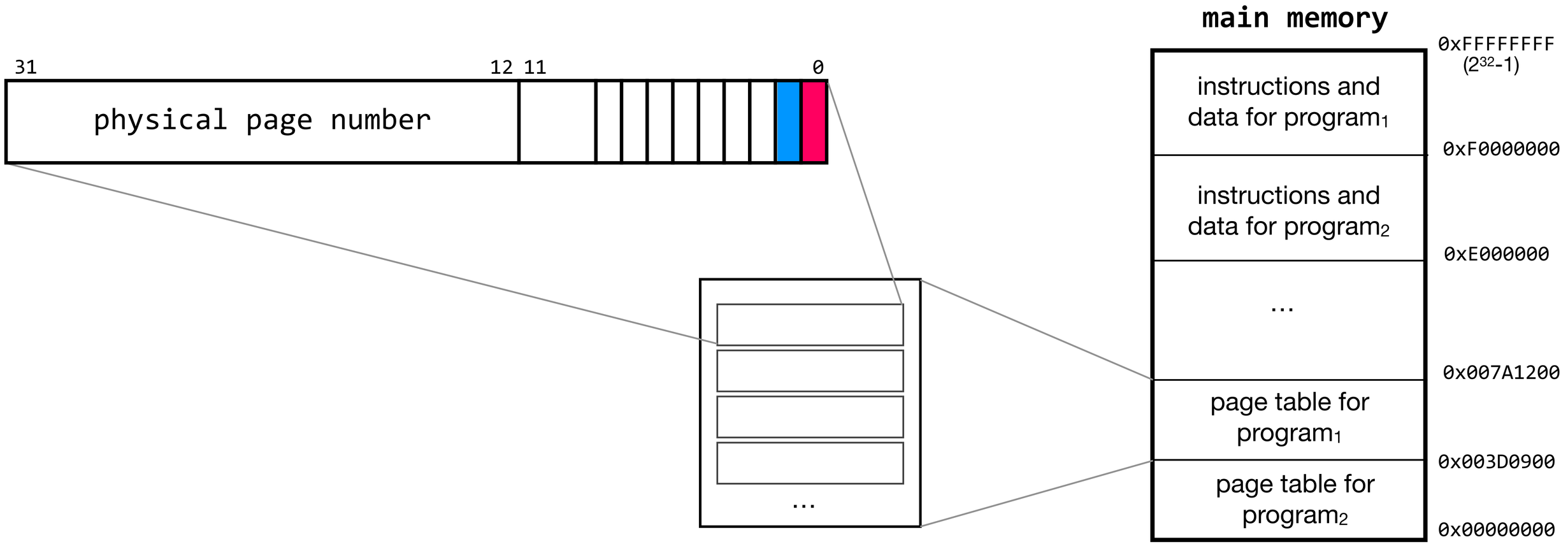

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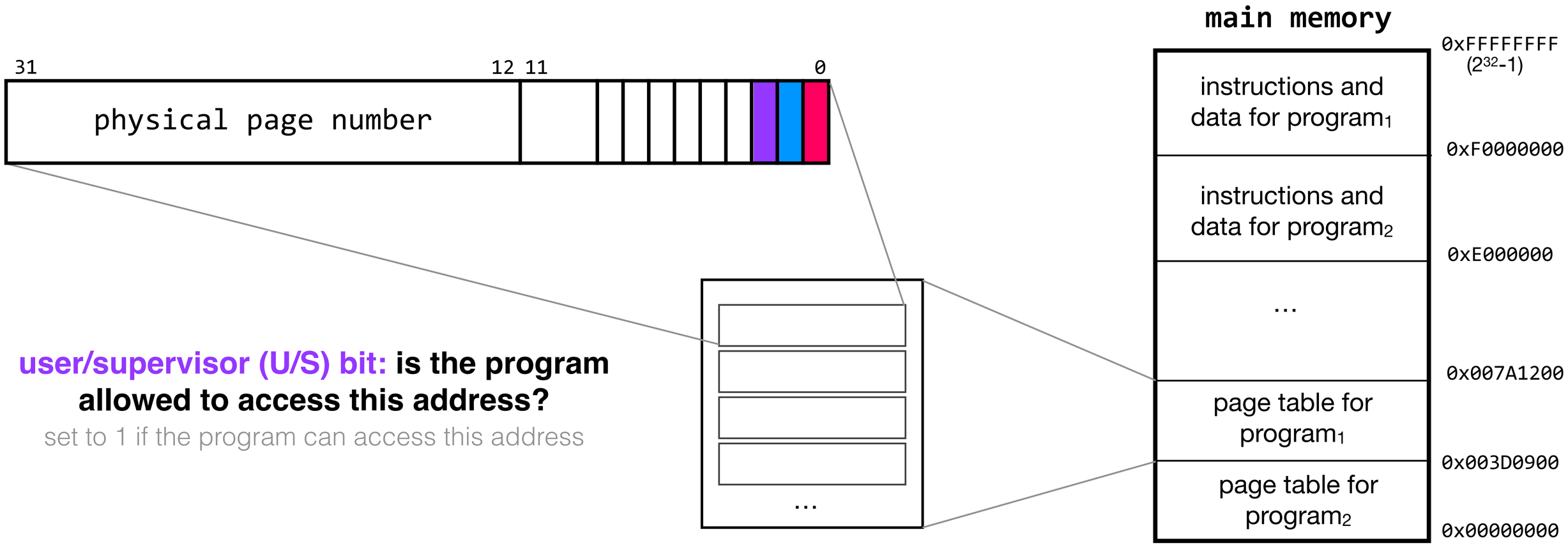

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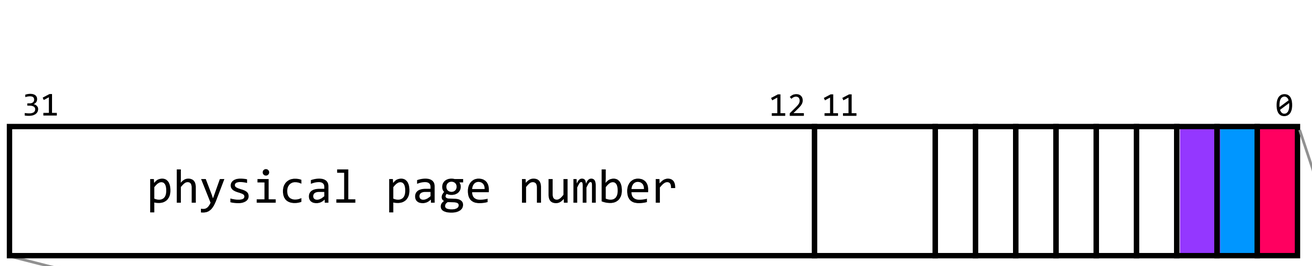

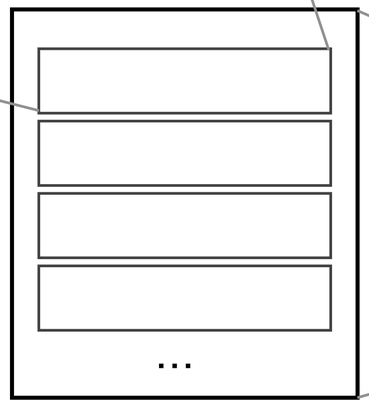

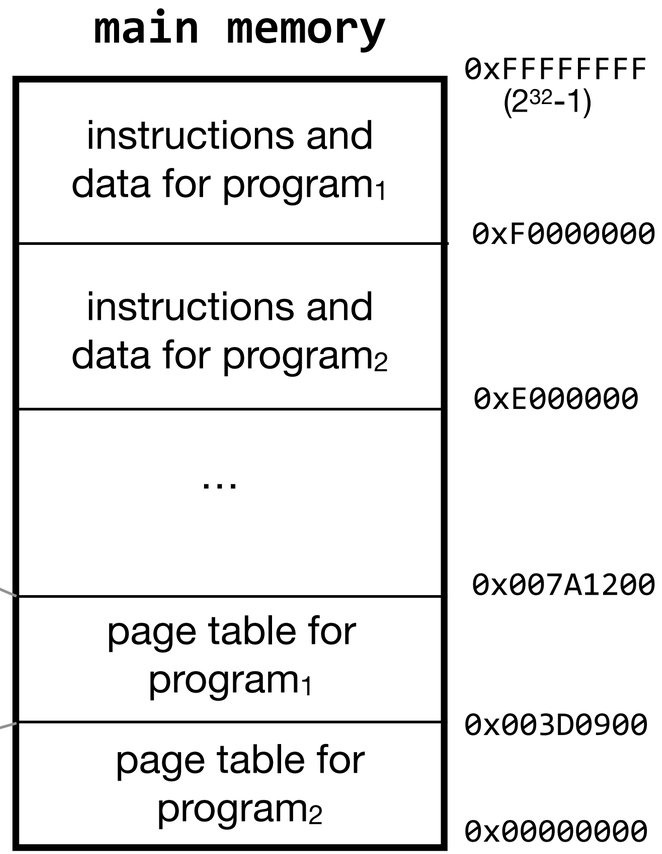

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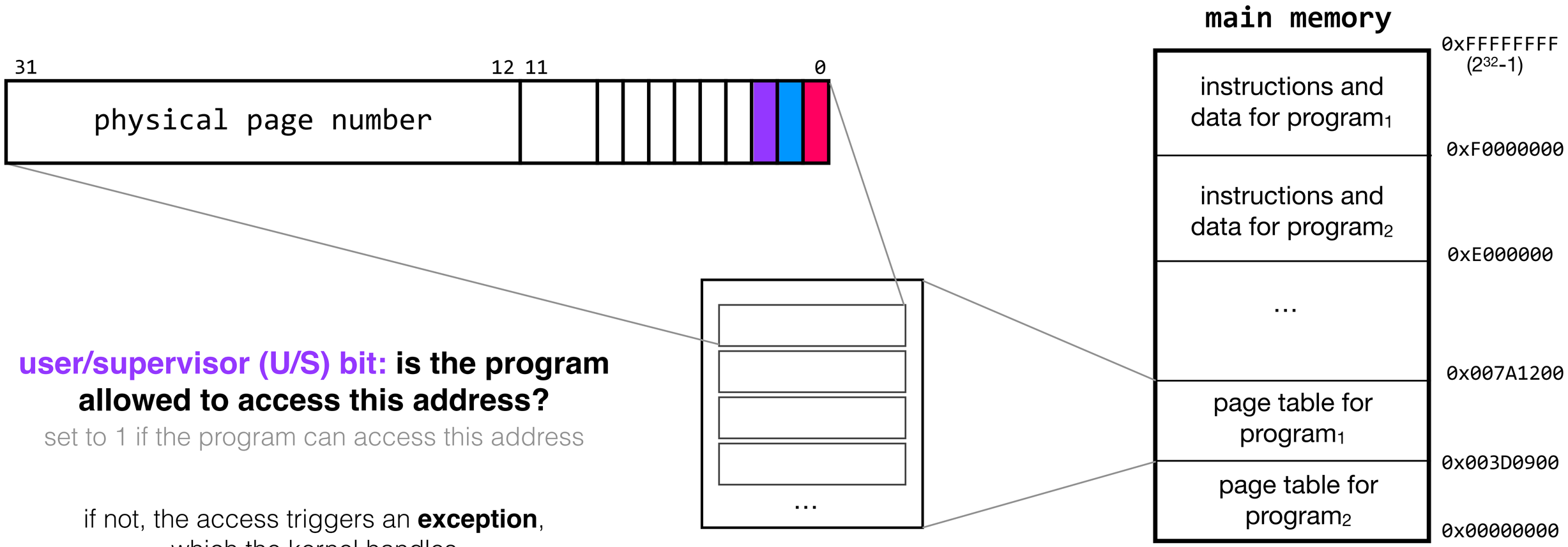

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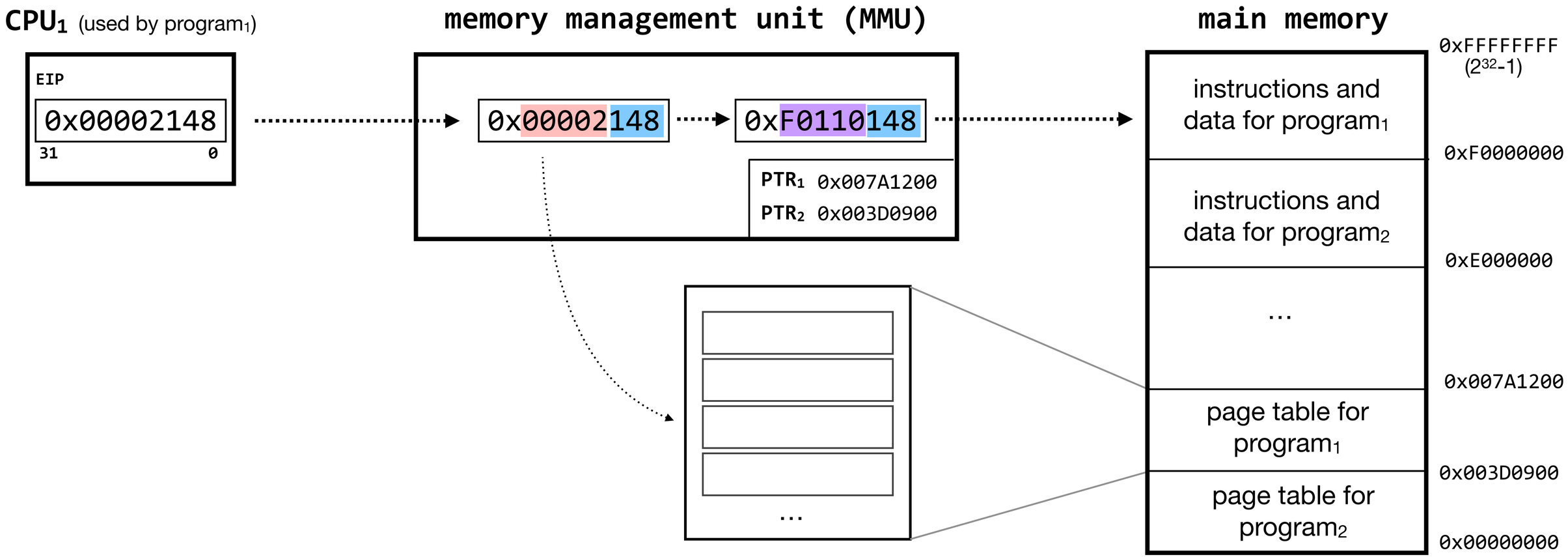
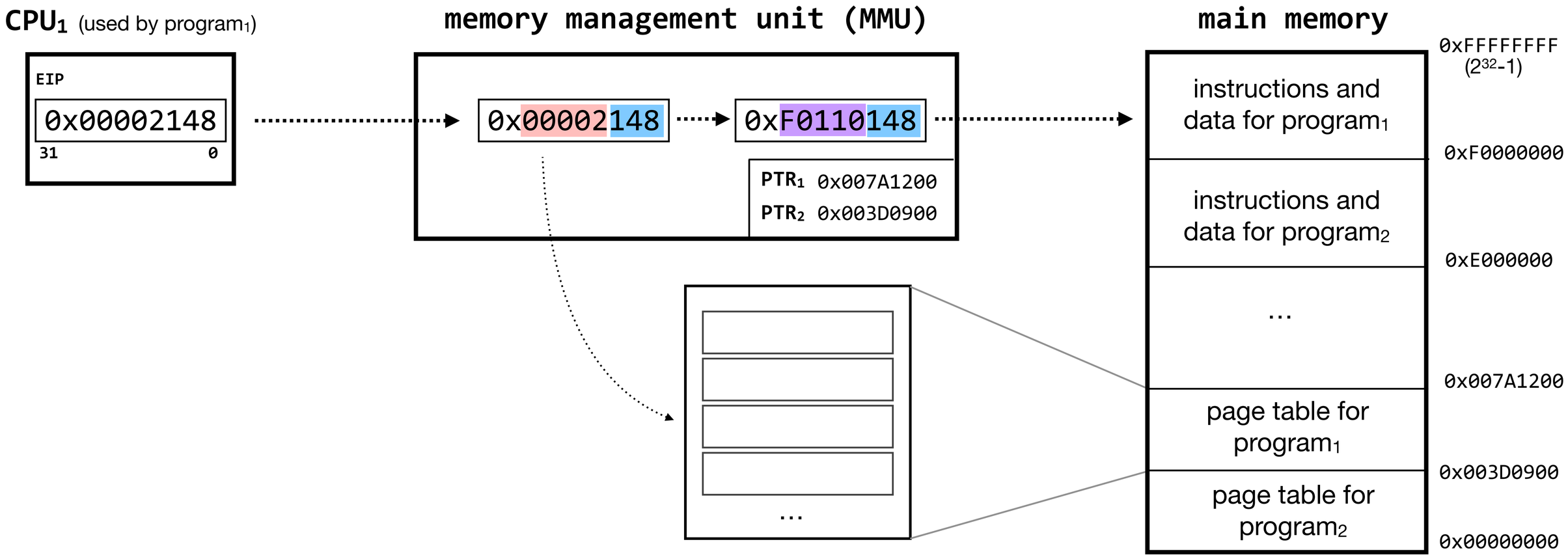
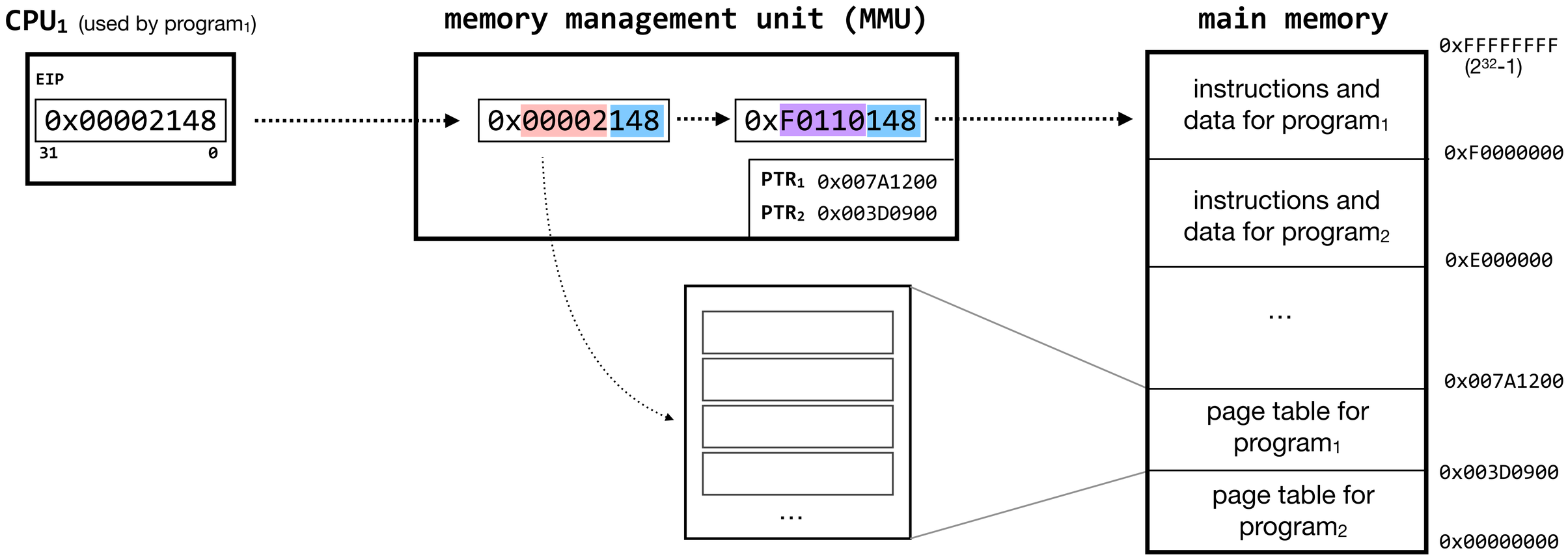
without this last piece, a determined program could still attempt to circumvent modularity by doing things such as modifying the page-table registers


CPU1 (used by program1)
EIP
0x00002148
31
0
memory management unit (MMU)
0x00002148
0xF0110148
PTR1 0x007A1200
PTR2 0x003D0900
...
main memory
0xFFFFFFFF
(2^32-1)
instructions and data for program1
0xF0000000
instructions and data for program2
0xE000000
...
0x007A1200
page table for program1
0x003D0900
page table for program2
0x00000000



2^{20} virtual addresses each mapping to a 32-bit page-table entry (PTE)
→ **4MB to store this table**

performance issue #1: page tables are allocated contiguously in memory so that access into them is extremely fast; this means that *every* page table is 4MB, even if the program only needs to make a few memory accesses



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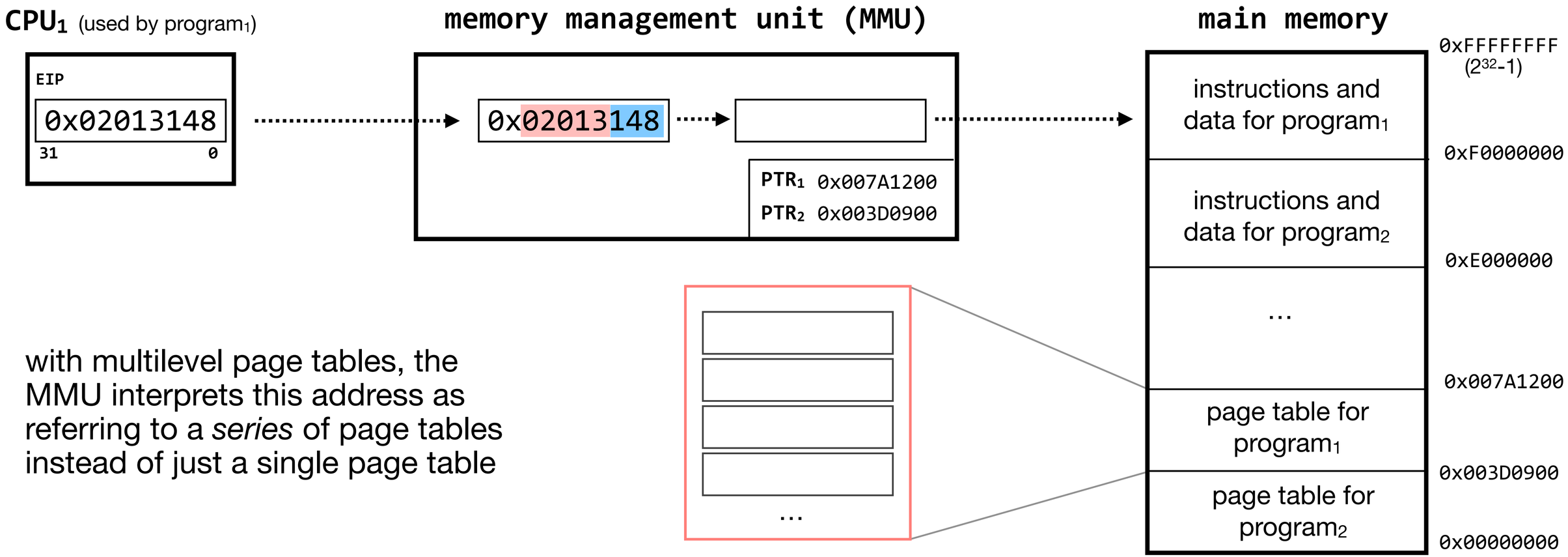
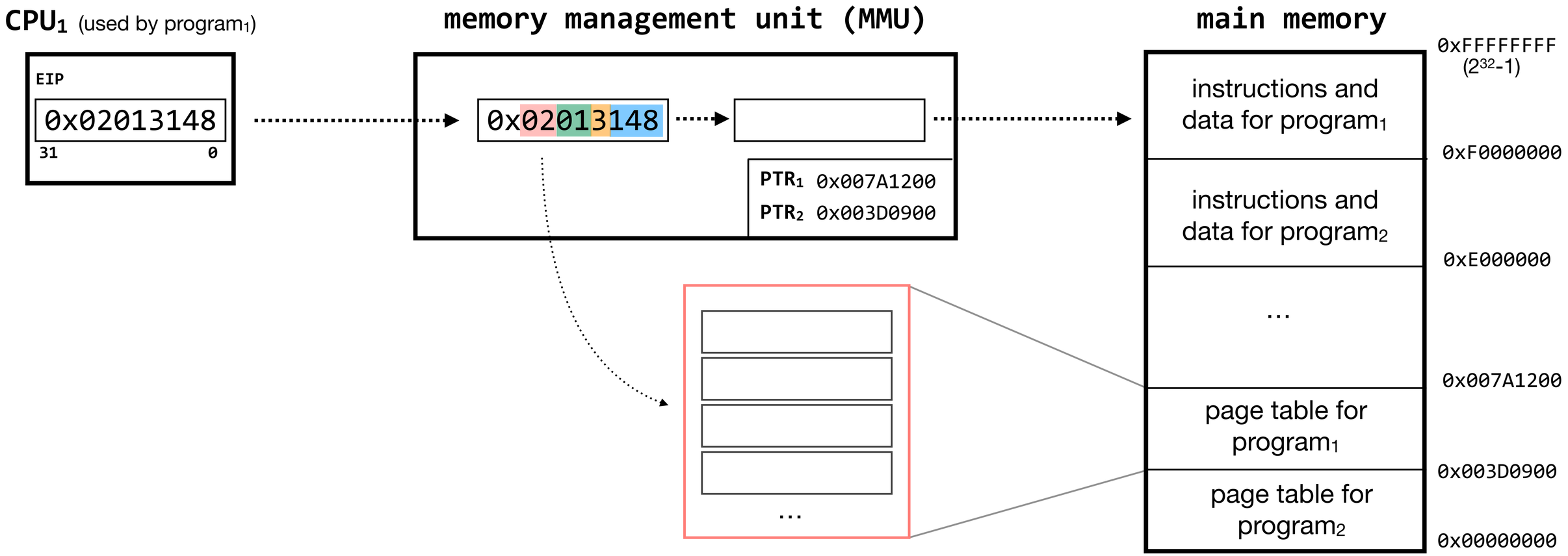
multilevel page tables often use less space



with multilevel page tables, the MMU interprets this address as referring to a *series* of page tables instead of just a single page table

multilevel page tables often use less space



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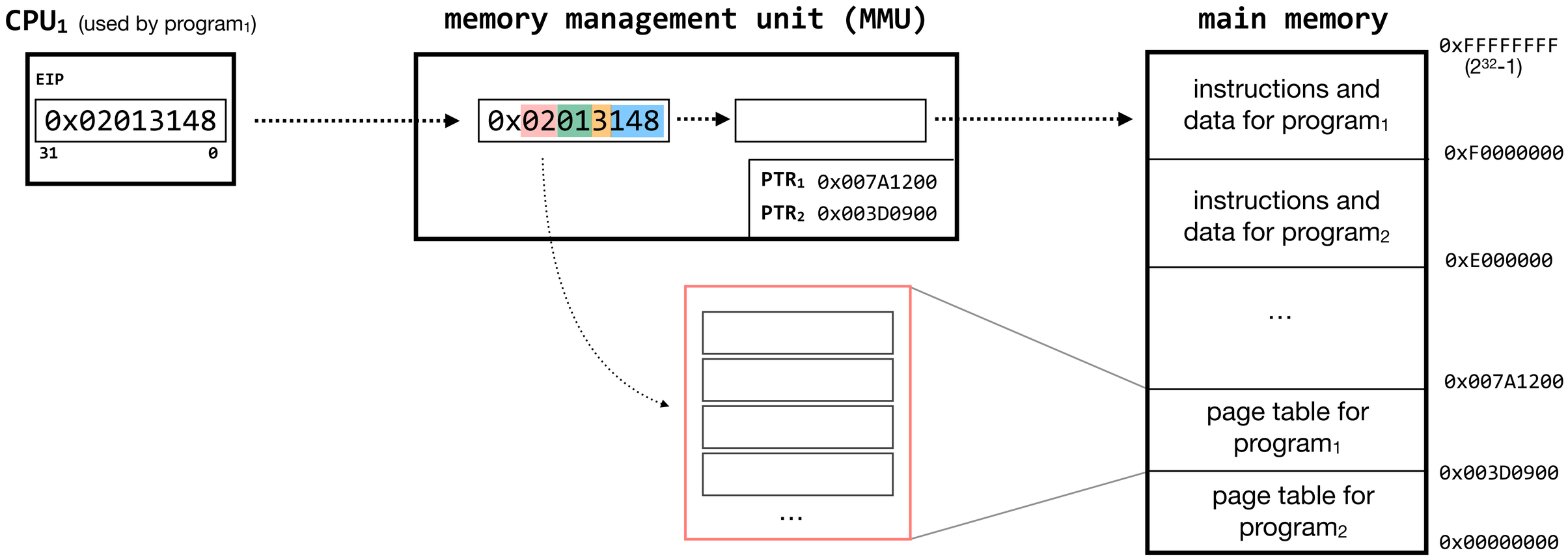

this **level 1 table** is the only one that will be allocated initially, and the top **eight** bits index into it. so it has 2^8 entries, not 2^{20}

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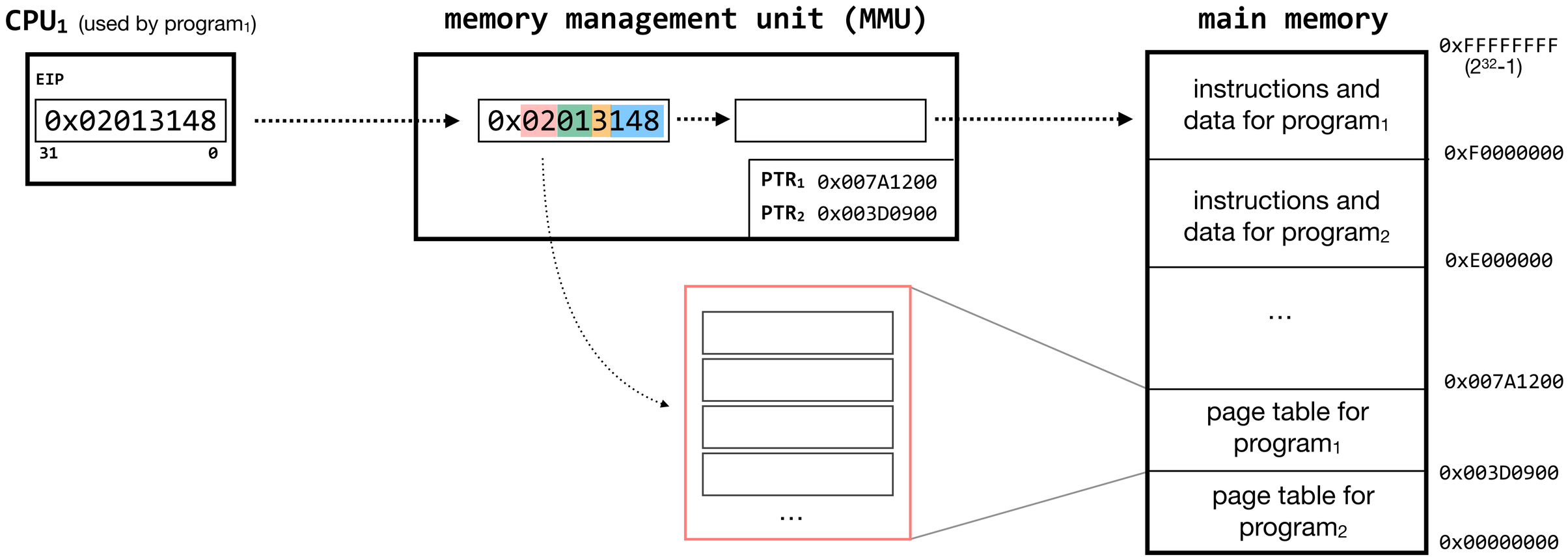

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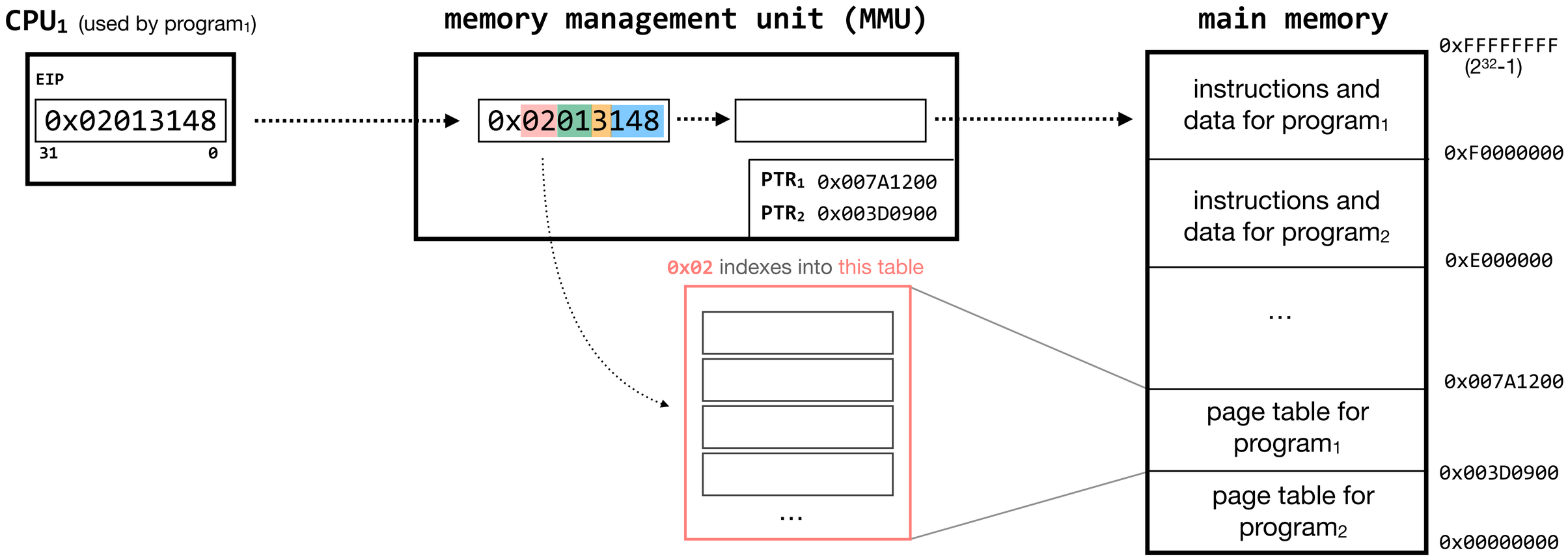

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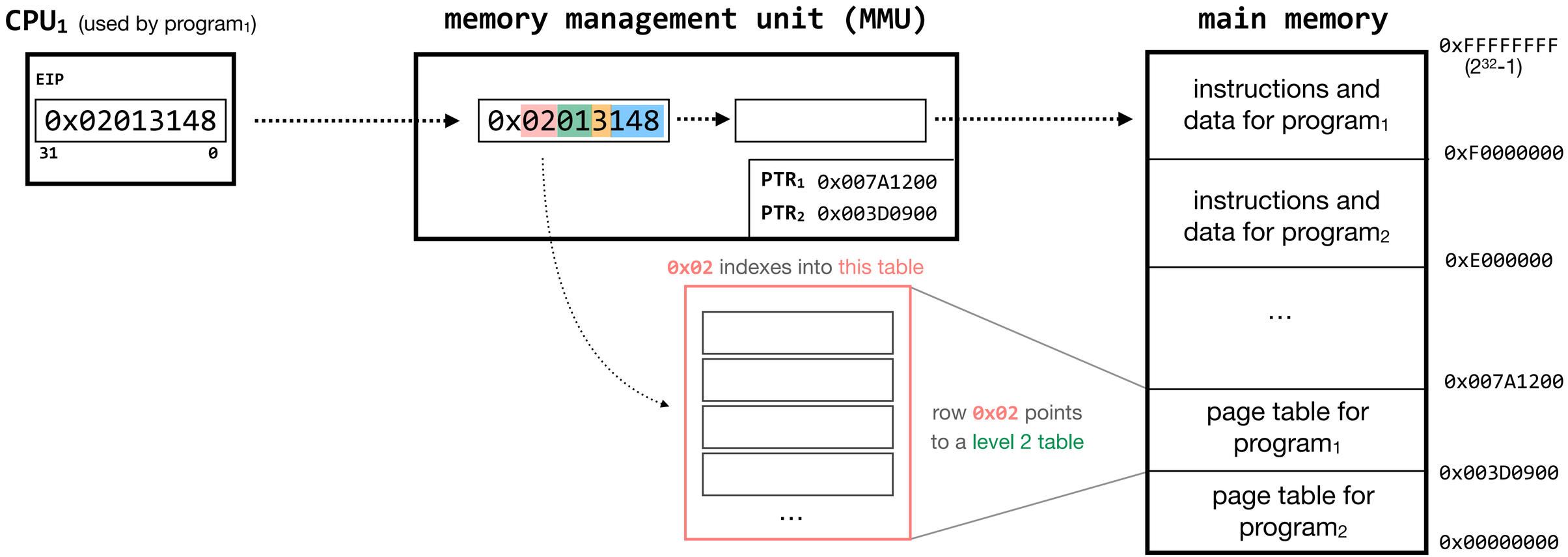

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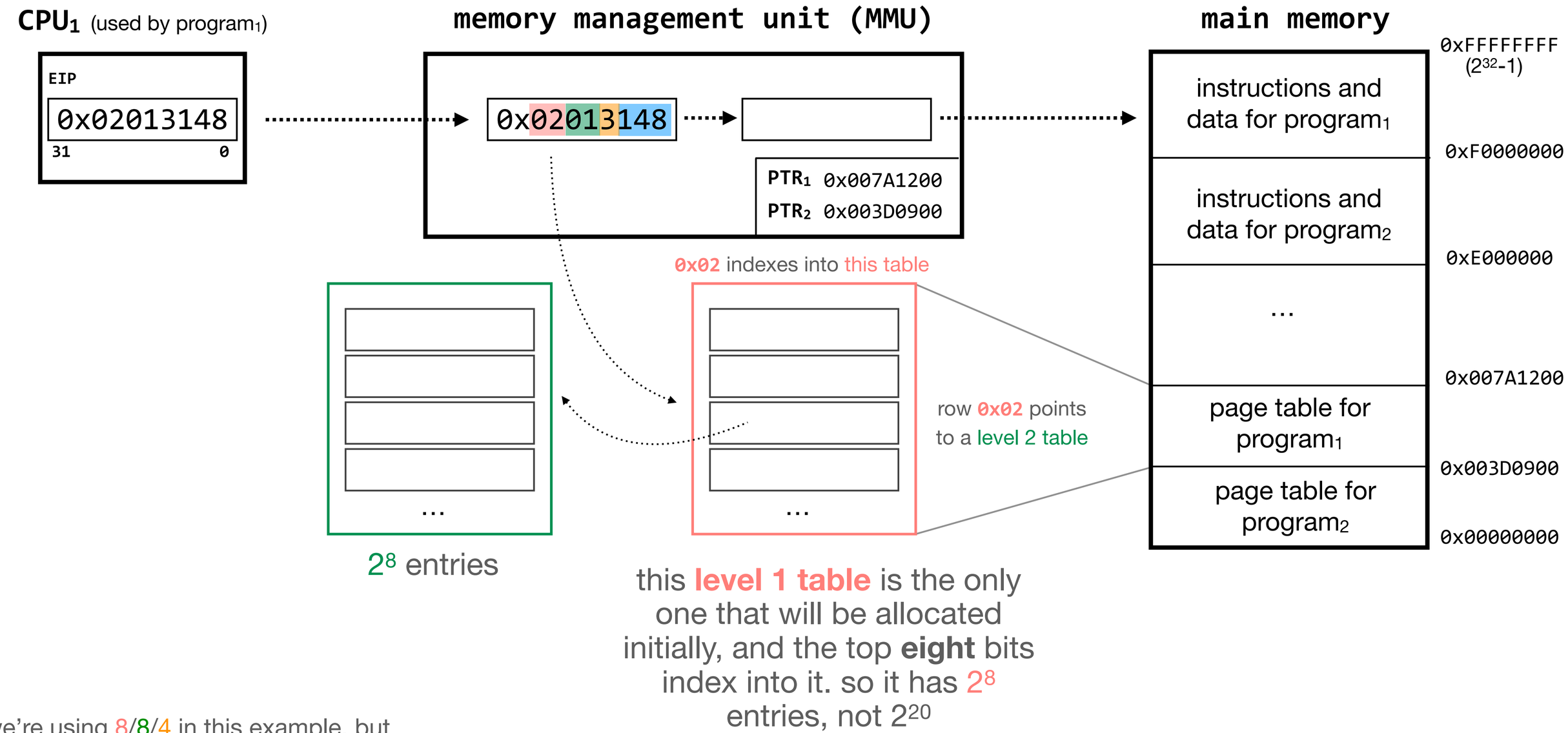

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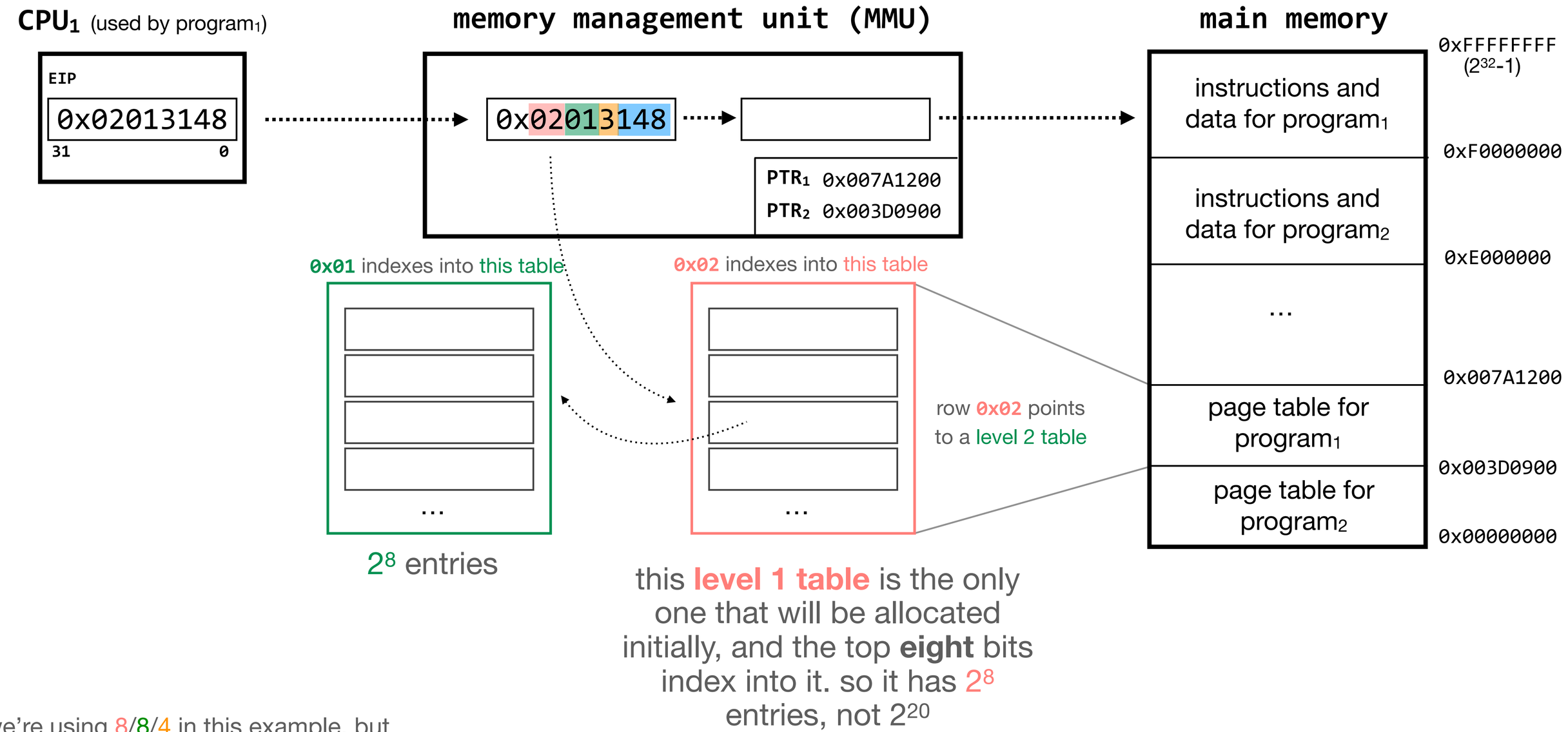

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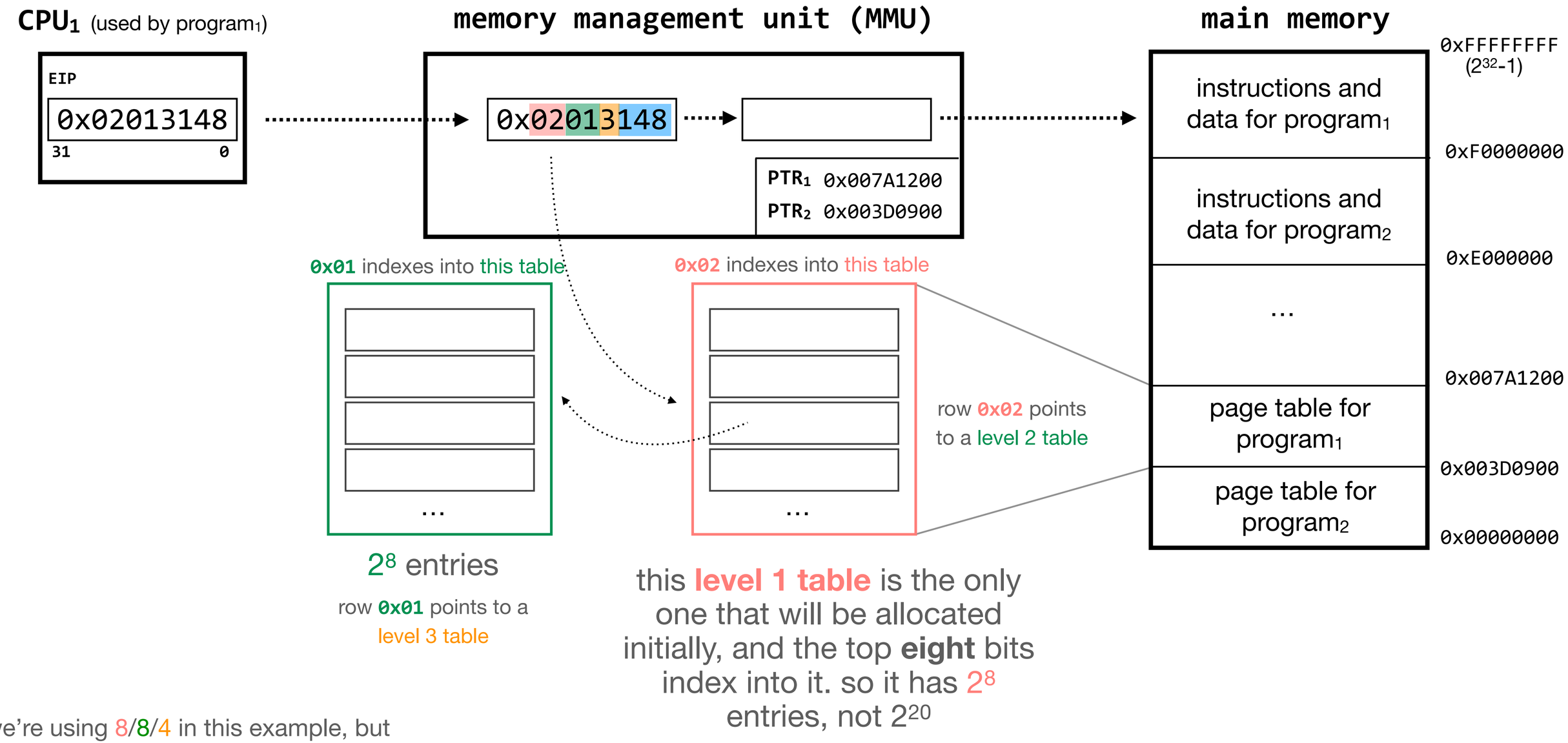

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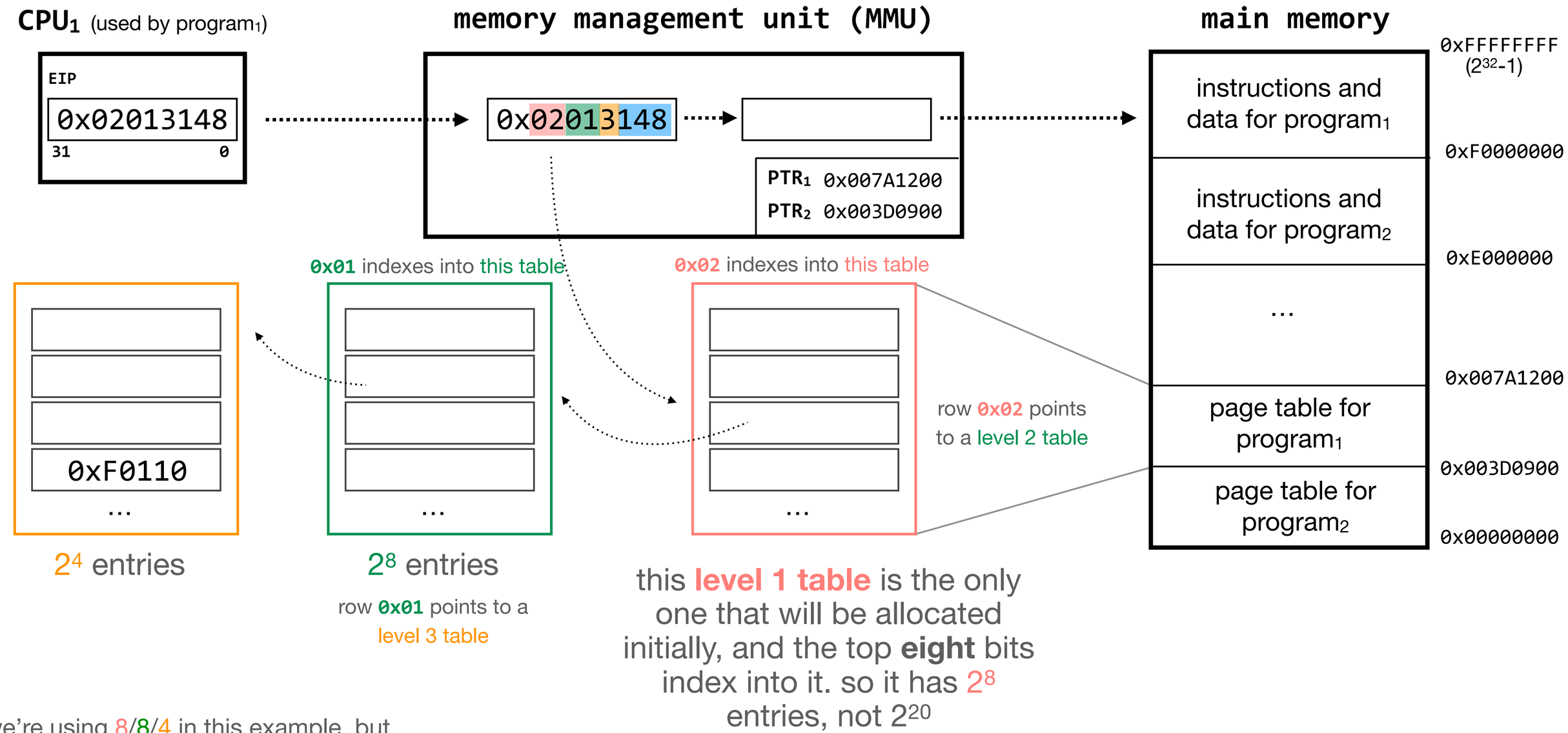

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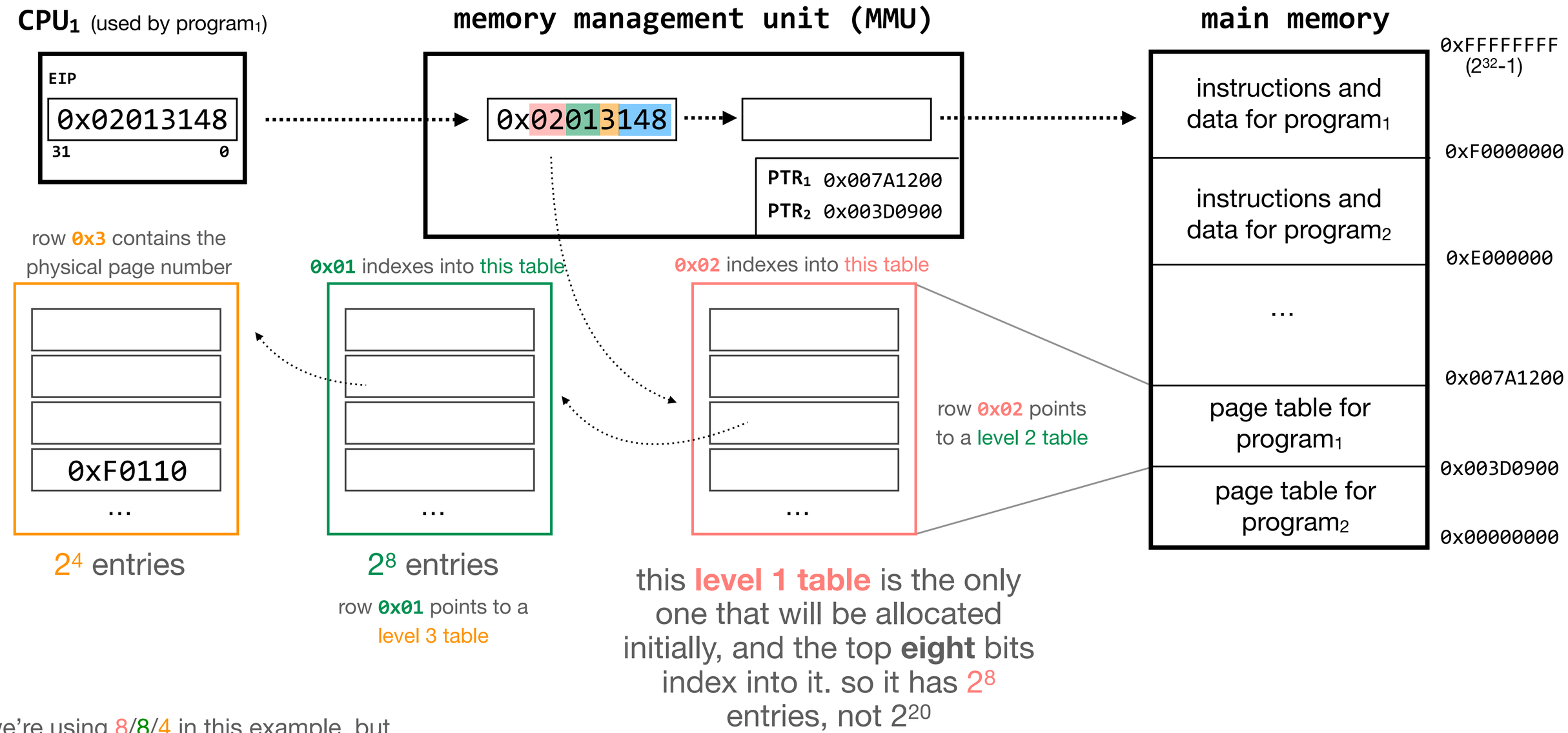

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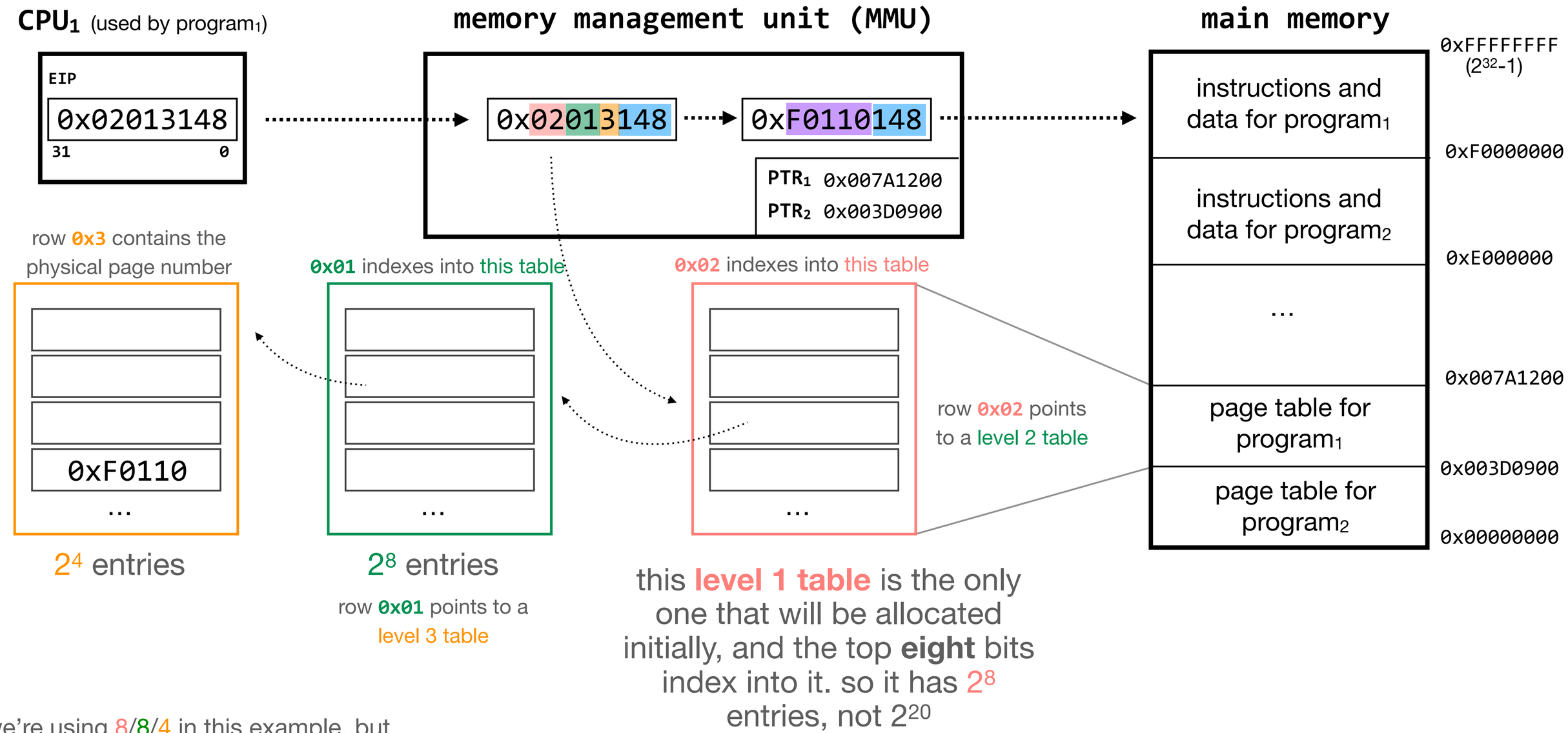

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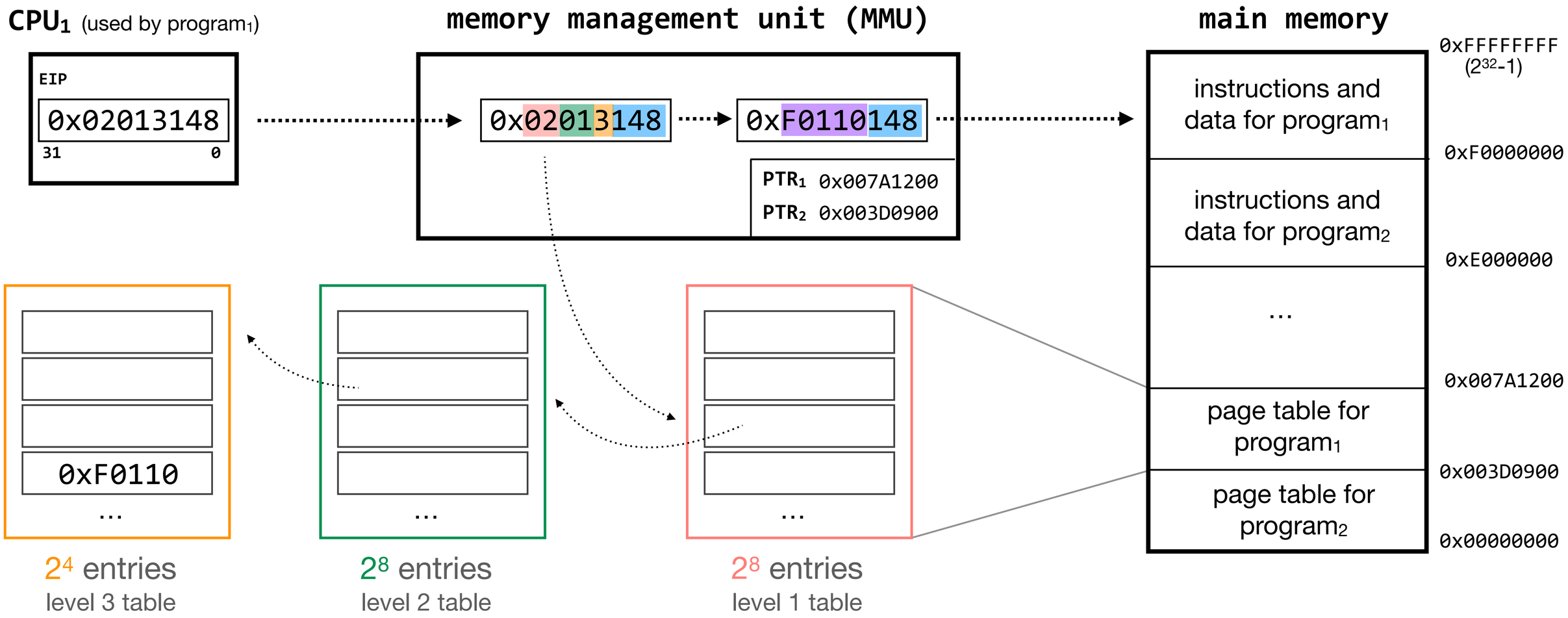

each row in the **level 1 table** (typically) corresponds to a different **level 2 table**, but each **level 2 table** (and **level 3 table**) is allocated as needed

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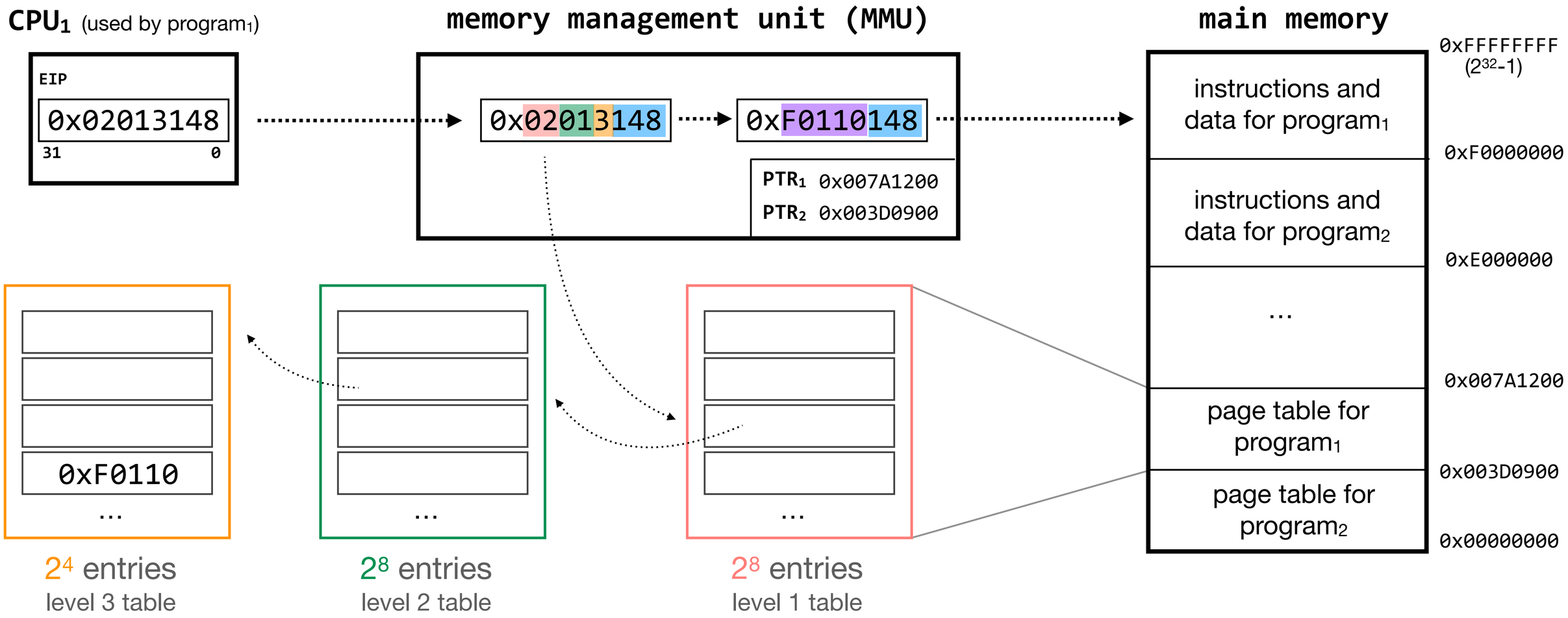
multilevel page tables often use less space, at the expense of more table look-ups and more exceptions (to allocate additional tables)



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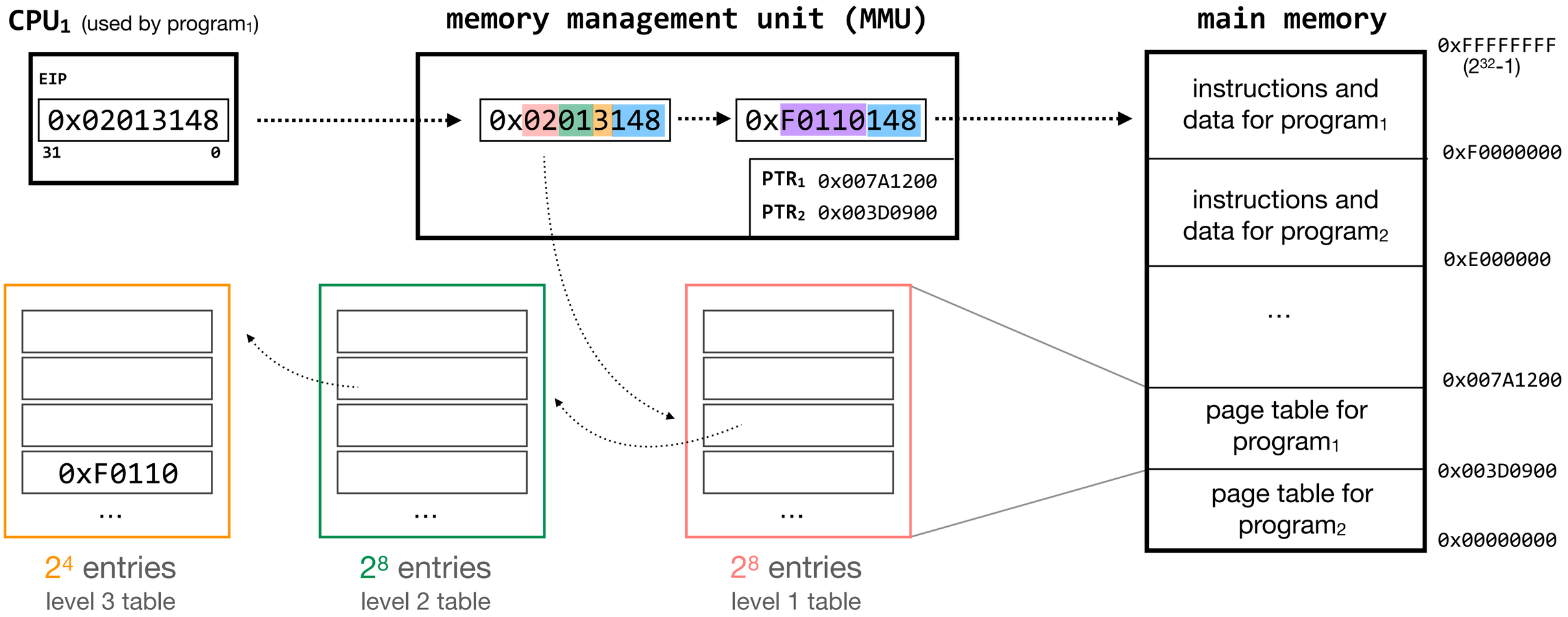
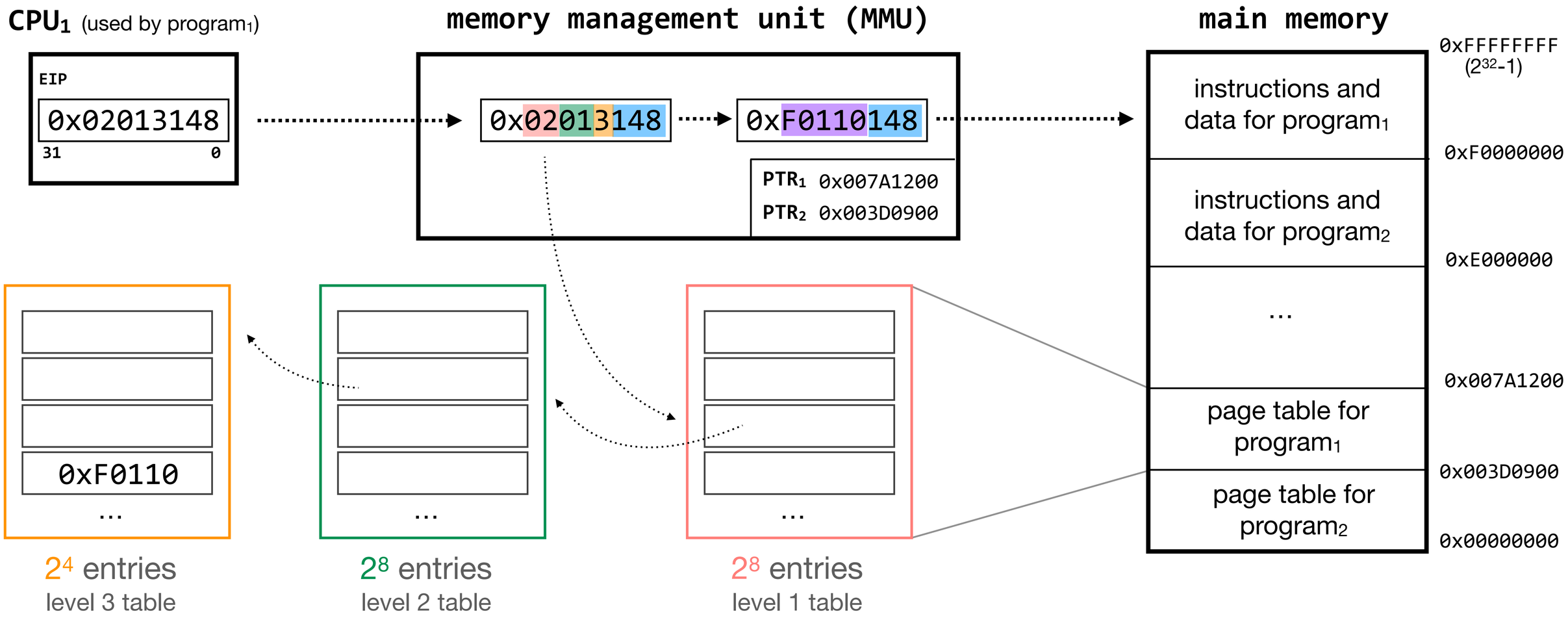

CPU1 (used by program1)
EIP
0x02013148
31
0
memory management unit (MMU)
0x02013148
0xF0110148
PTR1 0x007A1200
PTR2 0x003D0900
main memory
0xFFFFFFFF
(2^32-1)
instructions and data for program1
0xF0000000
instructions and data for program2
0xE000000
...
0x007A1200
page table for program1
0x003D0900
page table for program2
0x00000000
0xF0110
...
...
...
2^4 entries
level 3 table
2^8 entries
level 2 table
2^8 entries
level 1 table

performance issue #2: looking up the same piece of data over and over again takes time; can we make it faster?



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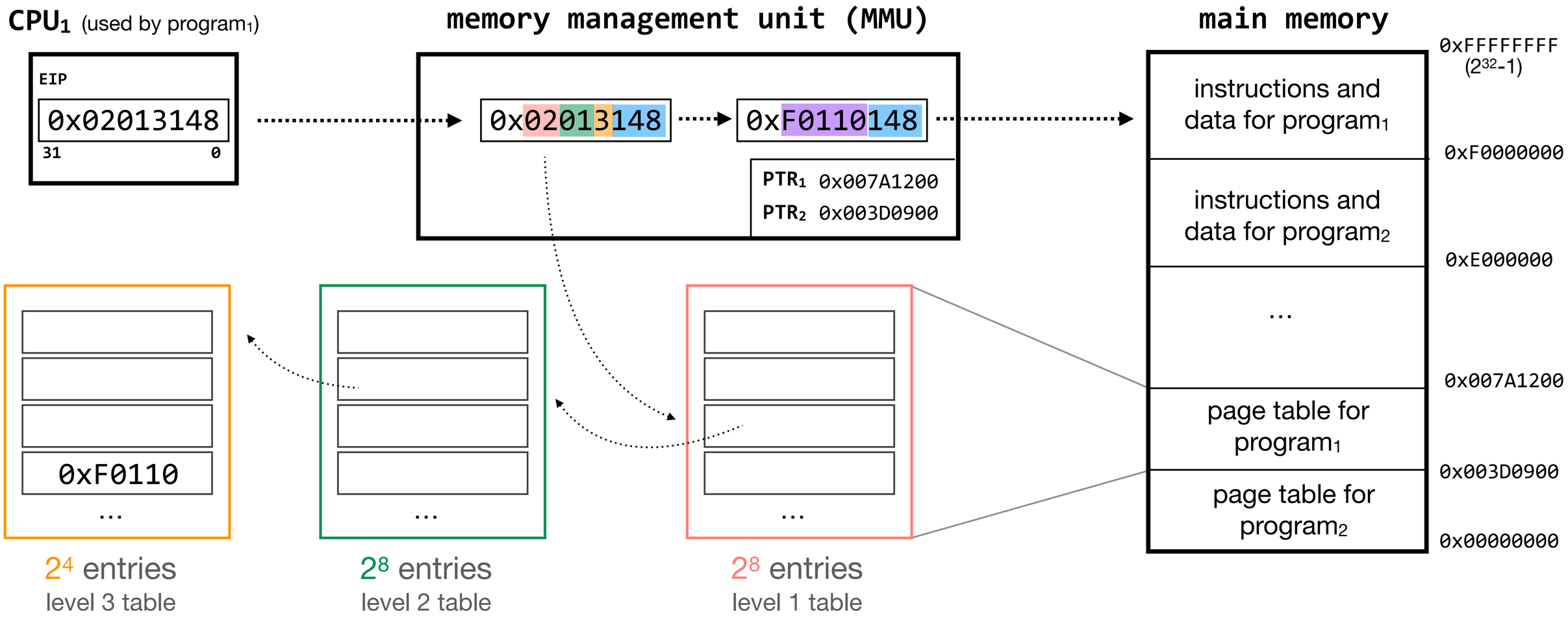

yes. caches are involved in a variety of places here, to (in theory) make common look-ups faster. you've also seen caching in the context of DNS.

operating systems enforce modularity on a single machine

in order to enforce modularity + have an effective operating system, a few things need to happen

1. programs shouldn't be able to refer to (and corrupt) each others' **memory** → virtualize **memory**
2. programs should be able to **communicate** with each other → assume they don't need to (for today)
3. programs should be able to **share a CPU** without one program halting the progress of the others → assume one program per CPU (for today)

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the primary technique that an operating system uses to enforce modularity is **virtualization**. some components are difficult to virtualize (e.g., the disk); for those, the operating system presents **abstractions**

operating systems enforce modularity on a single machine via **virtualization** and **abstraction**

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the **kernel** handles any exceptions triggered in this process; protecting the kernel from user programs is just as important as protecting user programs from each other