6.033 ~~in the news~~ on Mars

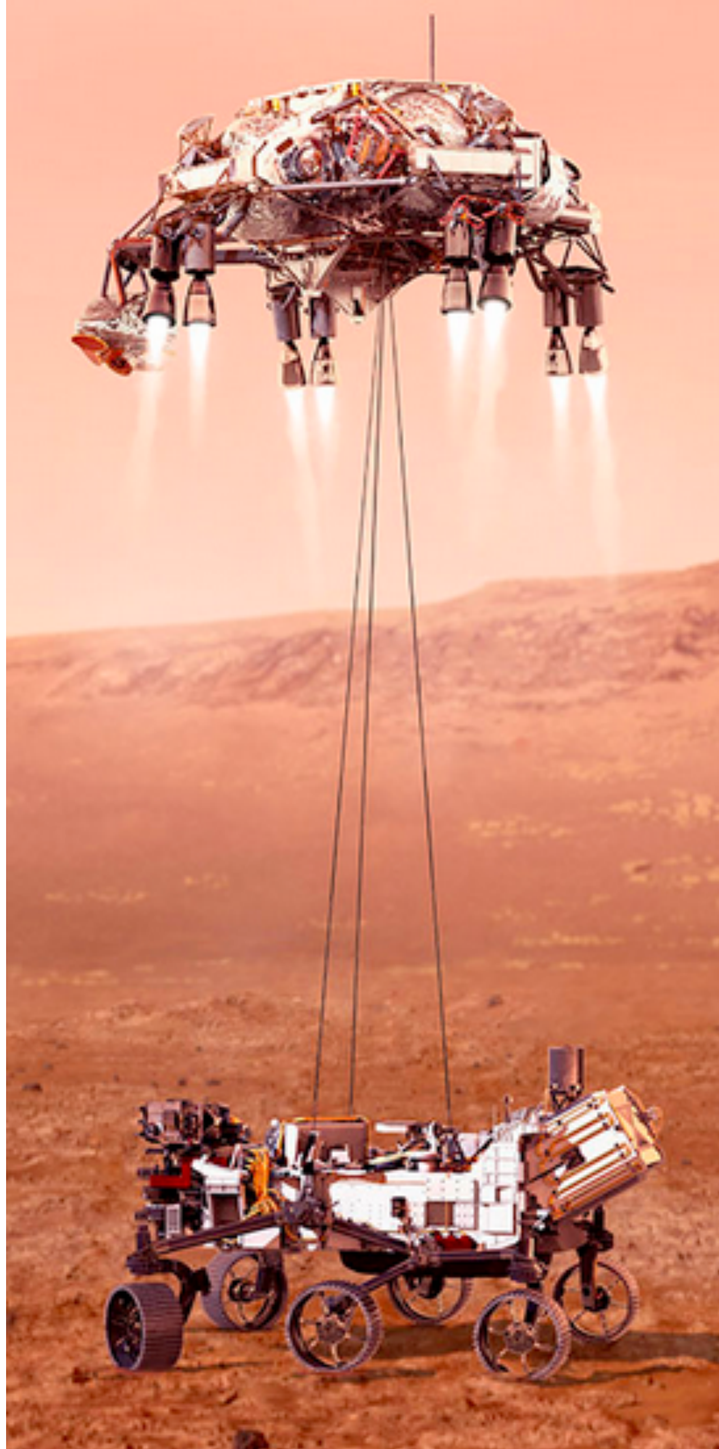
Tech Specs

Processor	• Radiation-hardened central processor with PowerPC 750 Architecture: a BAE RAD 750 • Operates at up to 200 megahertz speed, 10 times the speed in Mars rovers Spirit and Opportunity's computers
Memory	• 2 gigabytes of flash memory (~8 times as much as Spirit or Opportunity) • 256 megabytes of dynamic random access memory • 256 kilobytes of electrically erasable programmable read-only memory

https://mars.nasa.gov/mars2020/spacecraft/rover/brains/

It generally takes about 5 to 20 minutes for a radio signal to travel the distance between Mars and Earth, depending on planet positions. Using orbiters to relay messages is beneficial because they are much closer to Perseverance than the Deep Space Network (DSN) antennas on Earth. The mass- and power-constrained rover can achieve high data rates of up to 2 megabits per second on the relatively short-distance relay link to the orbiters overhead. The orbiters then use their much larger antennas and transmitters to relay that data on the long-distance link back to Earth.

https://mars.nasa.gov/mars2020/spacecraft/rover/communications/



https://mars.nasa.gov/mars2020/

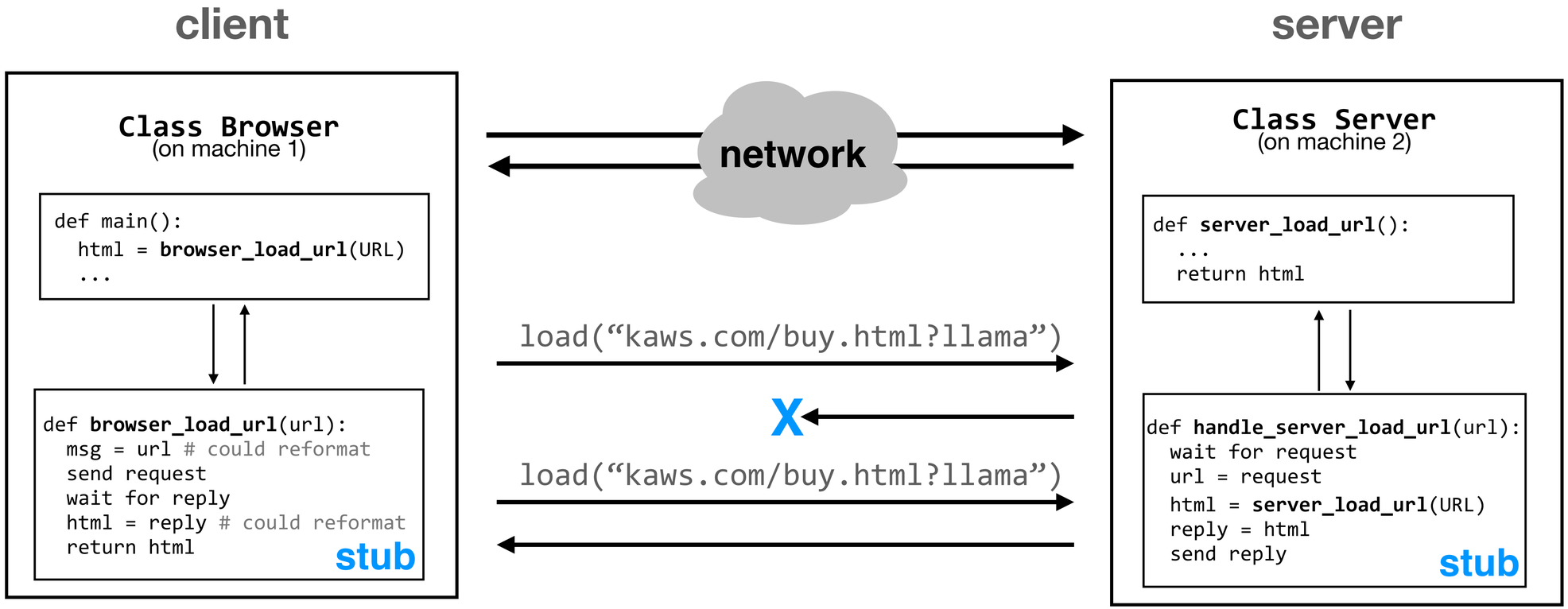
6.033 Spring 2021

Lecture #3: Virtual Memory

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

Katrina LaCurts | lacurts@mit.edu | 6.033 2021

last time: enforced modularity via client/server + naming



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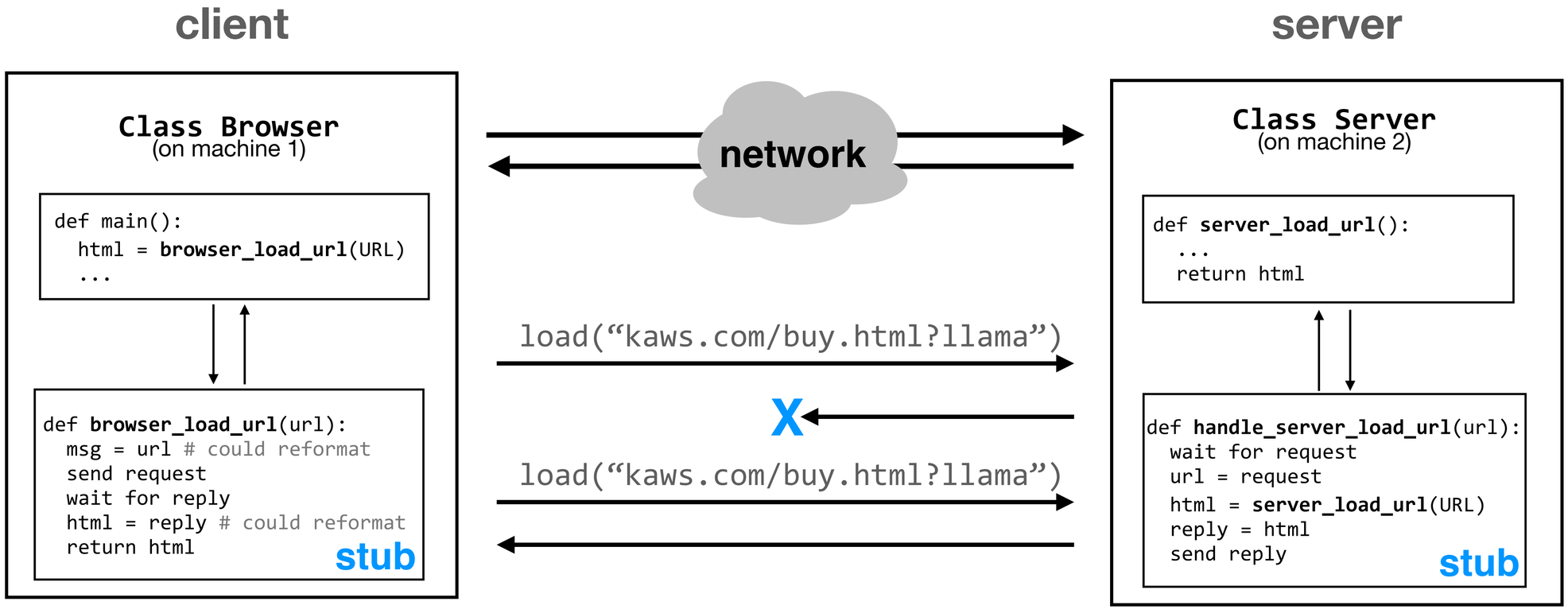

today: what if we *don't* want to put each module on a separate machine?

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

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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CPU_2 (used by $program_2$)

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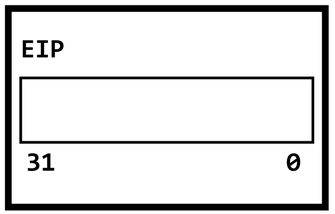
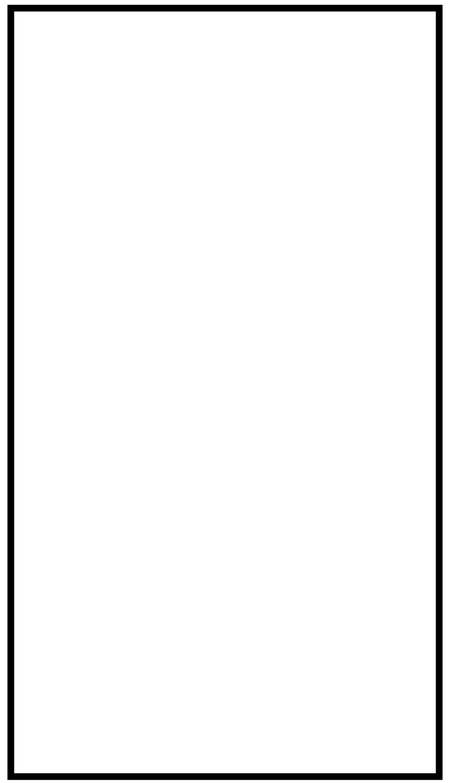


CPU_2 (used by $program_2$)

main memory



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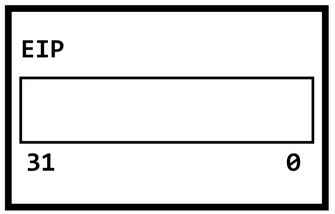

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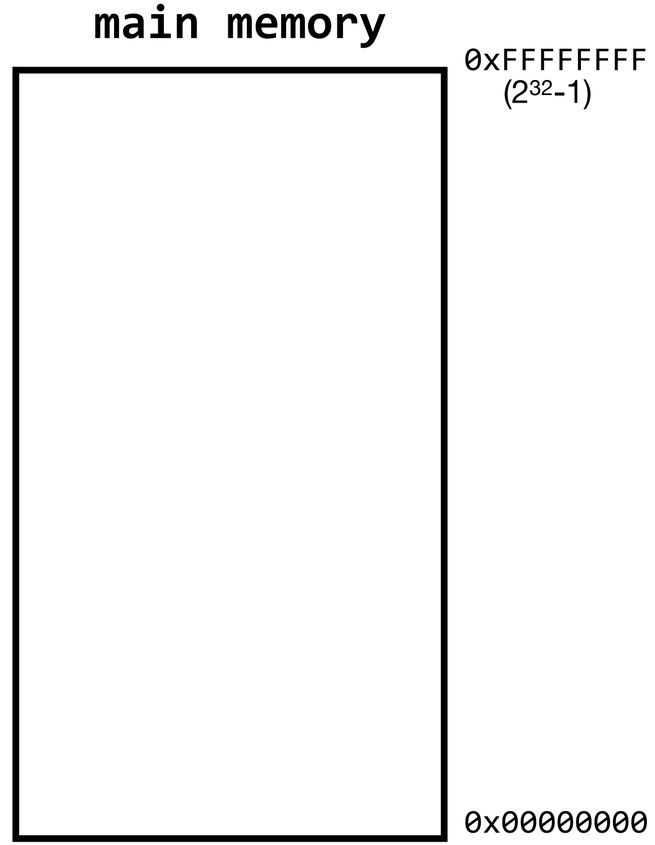

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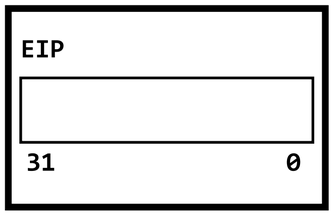
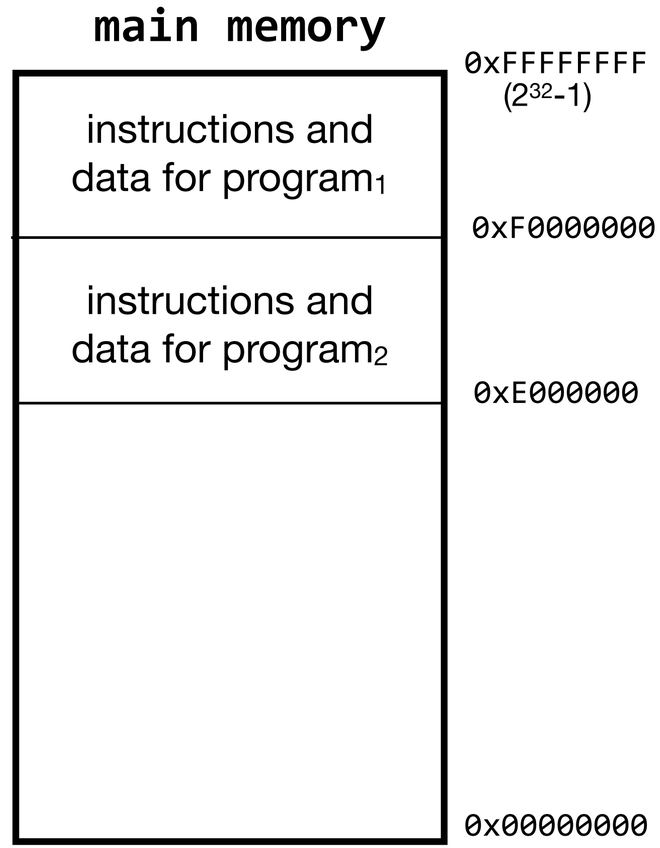


CPU$_2$ (used by program$_2$)



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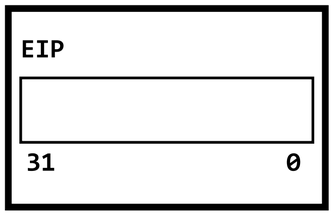
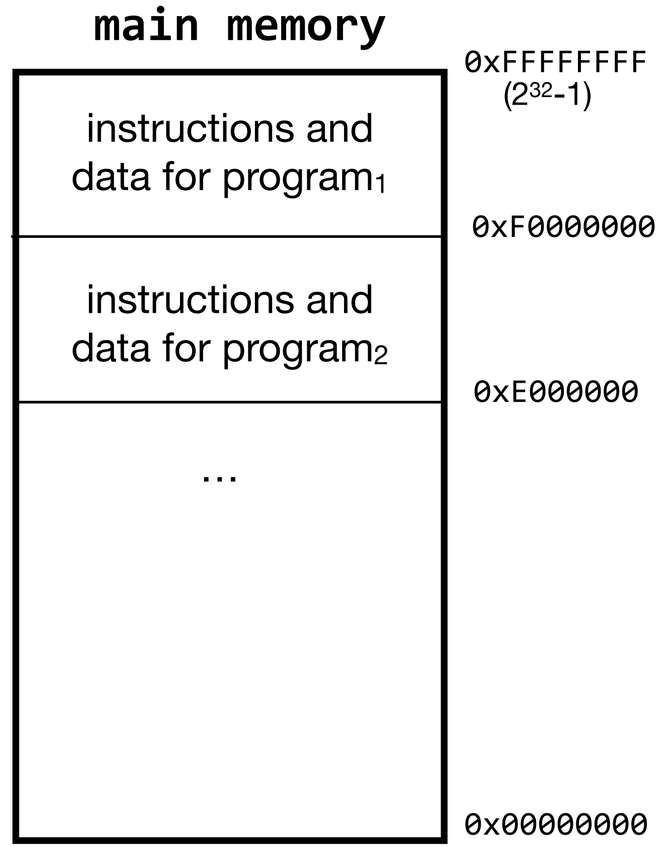


CPU$_2$ (used by program$_2$)



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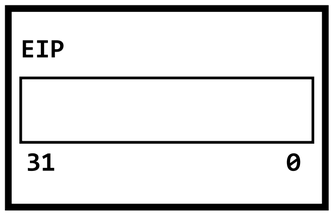
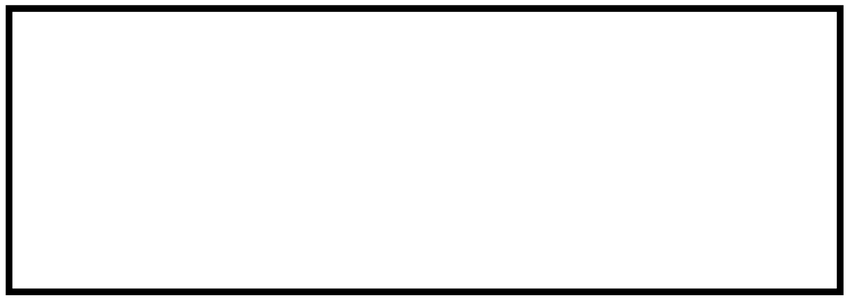
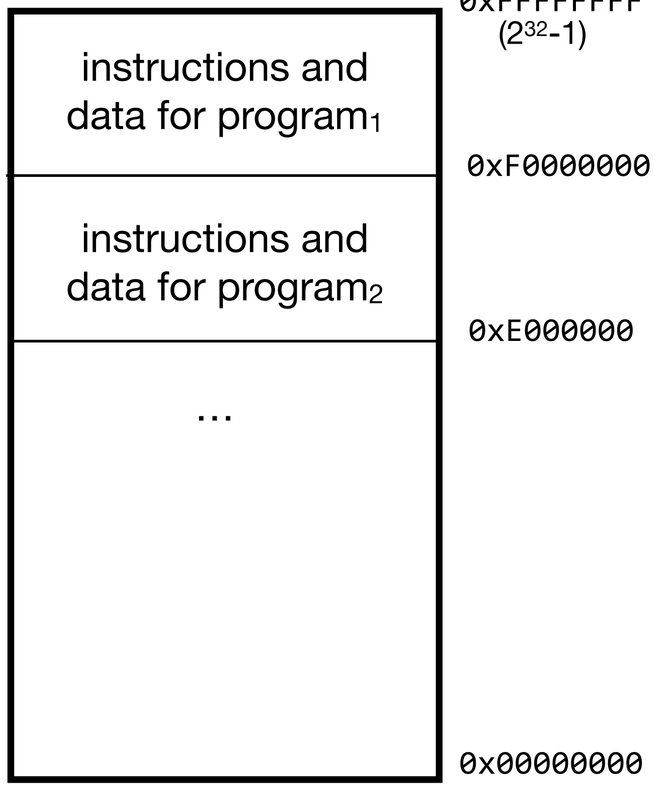


CPU$_2$ (used by program$_2$)

memory management unit (MMU)



main memory



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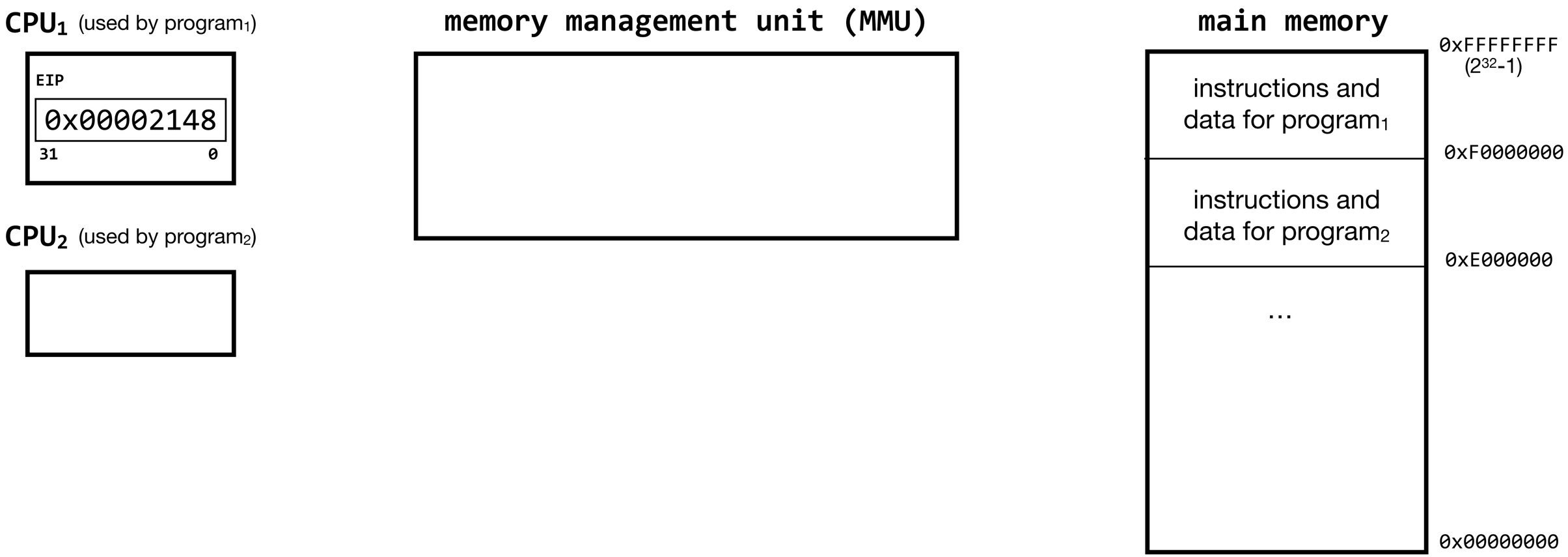

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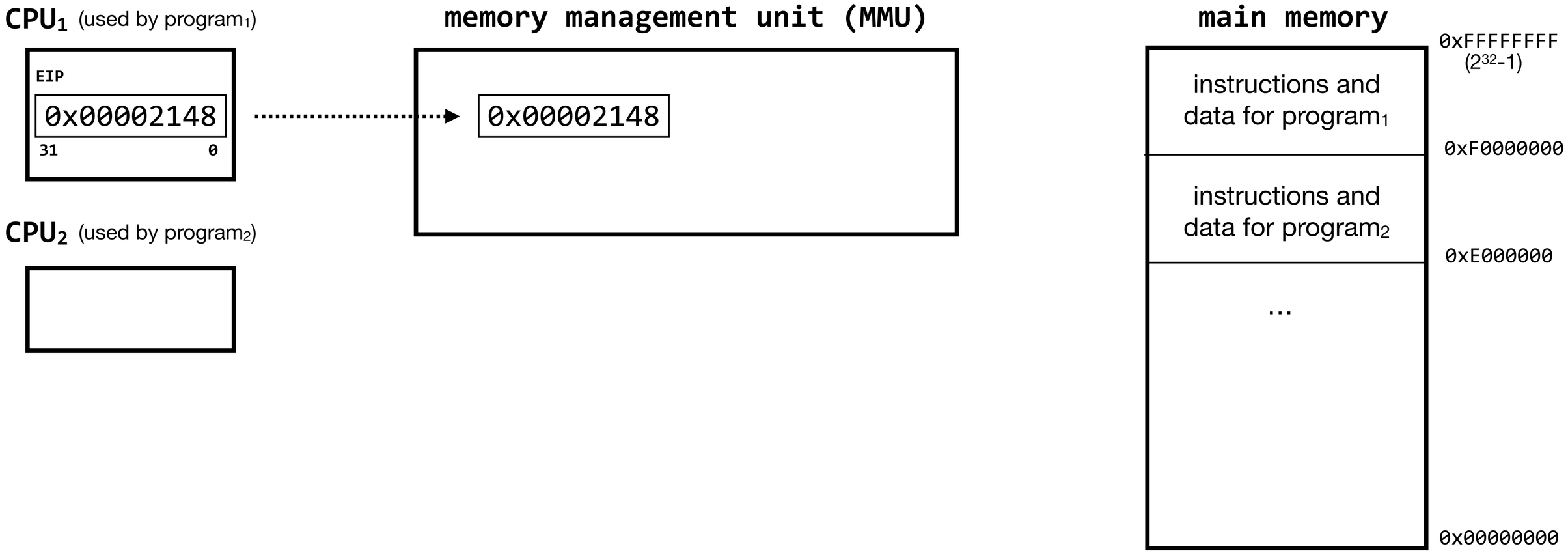

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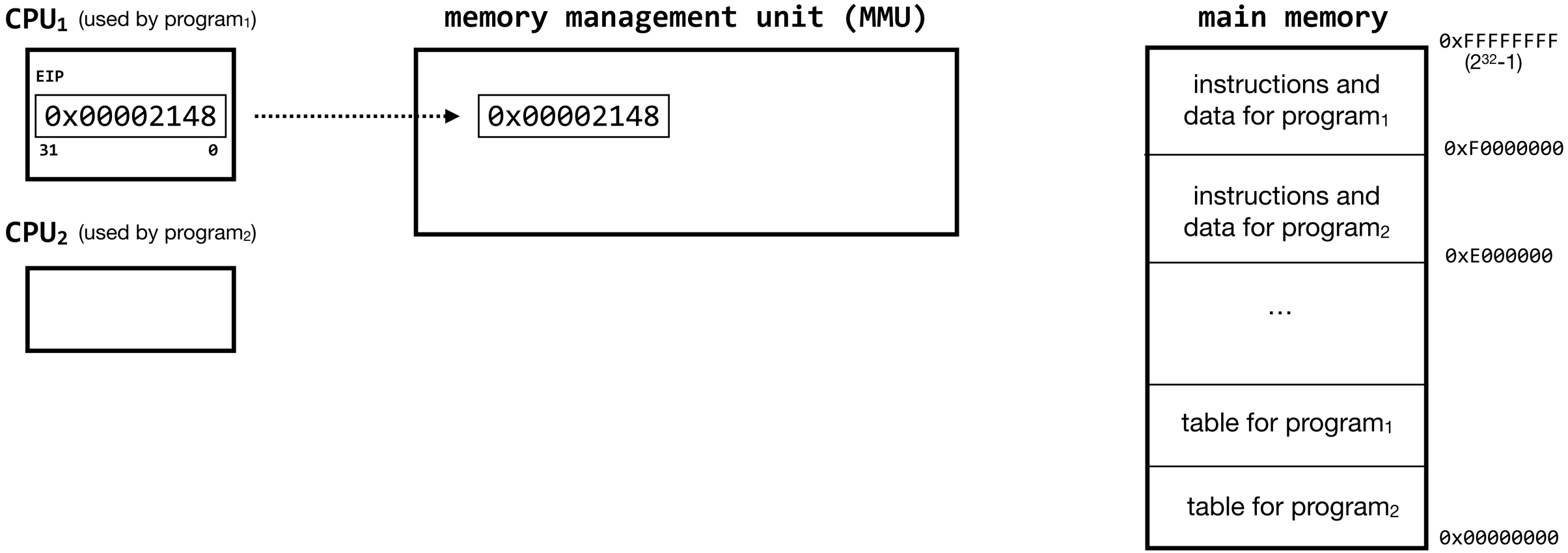

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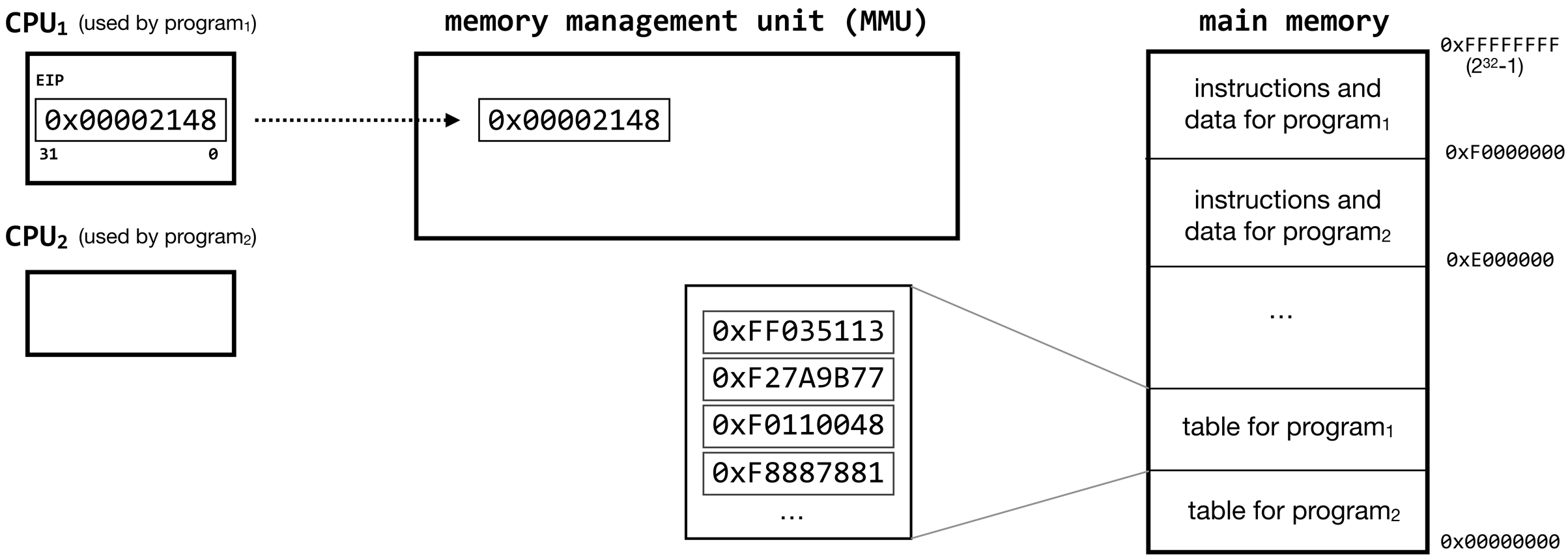

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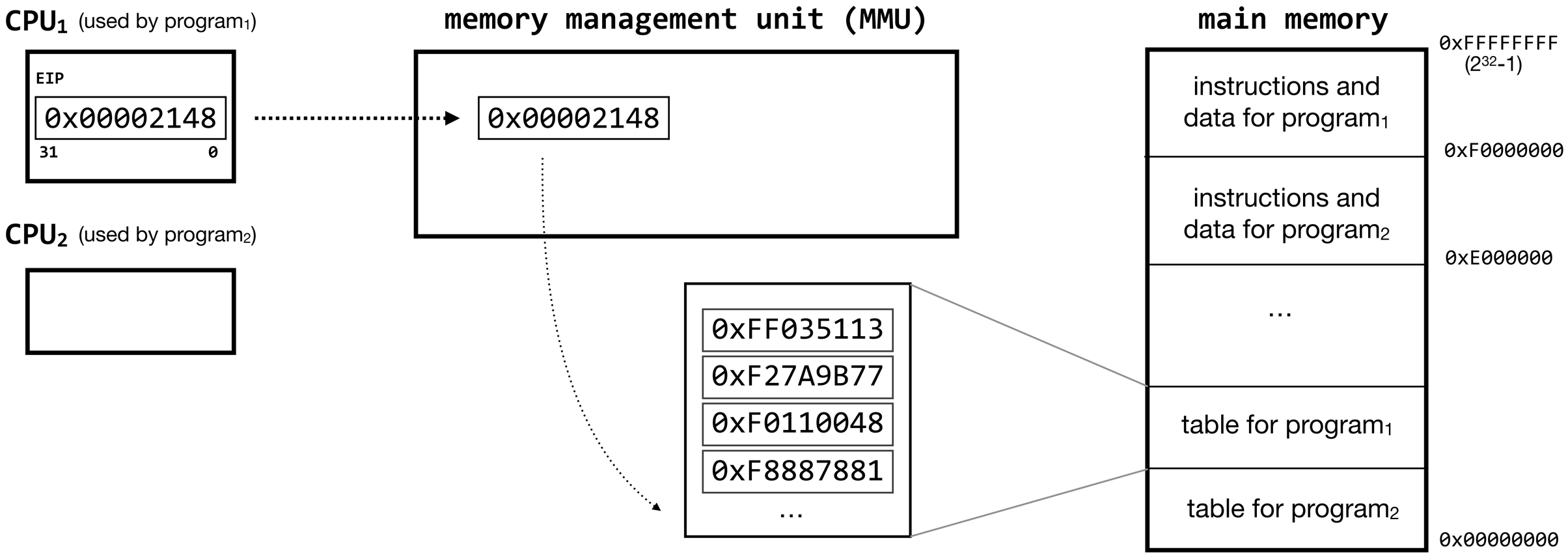

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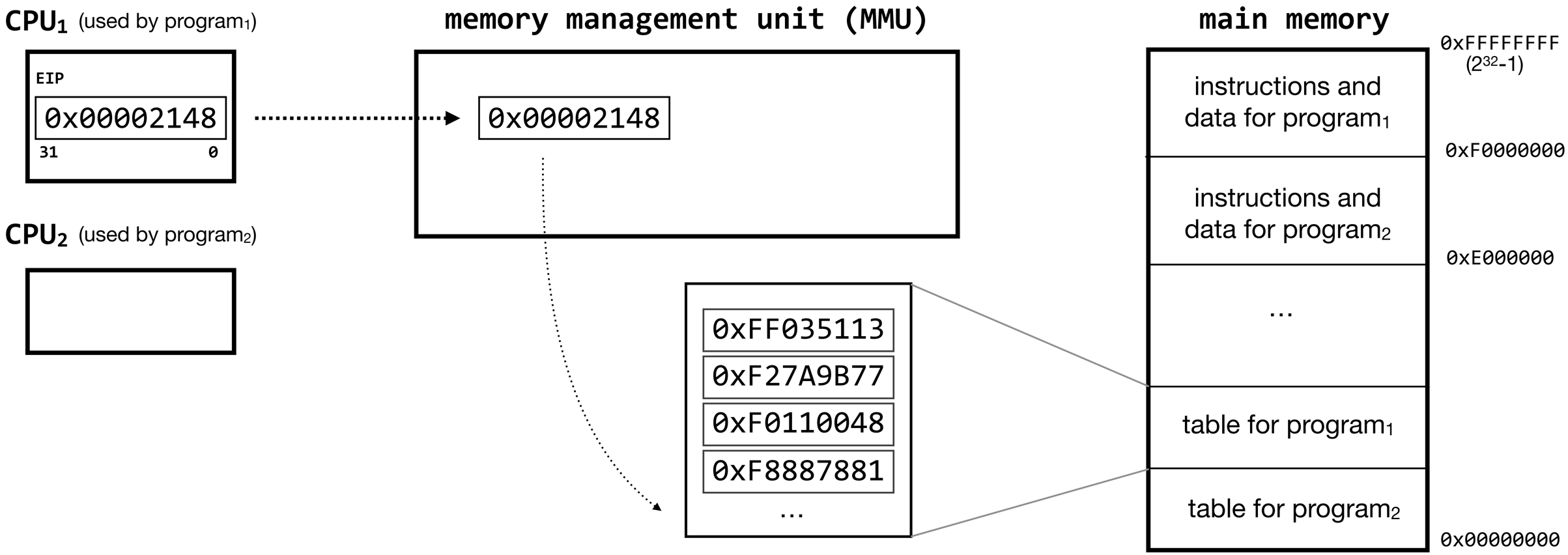

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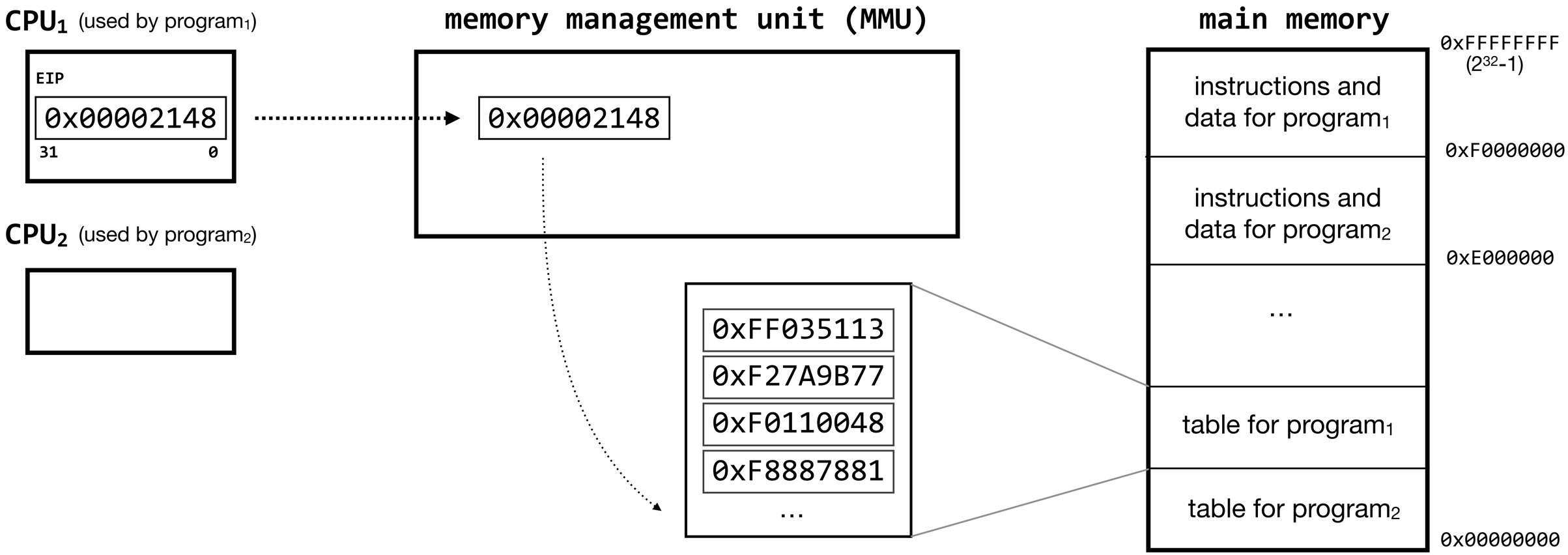

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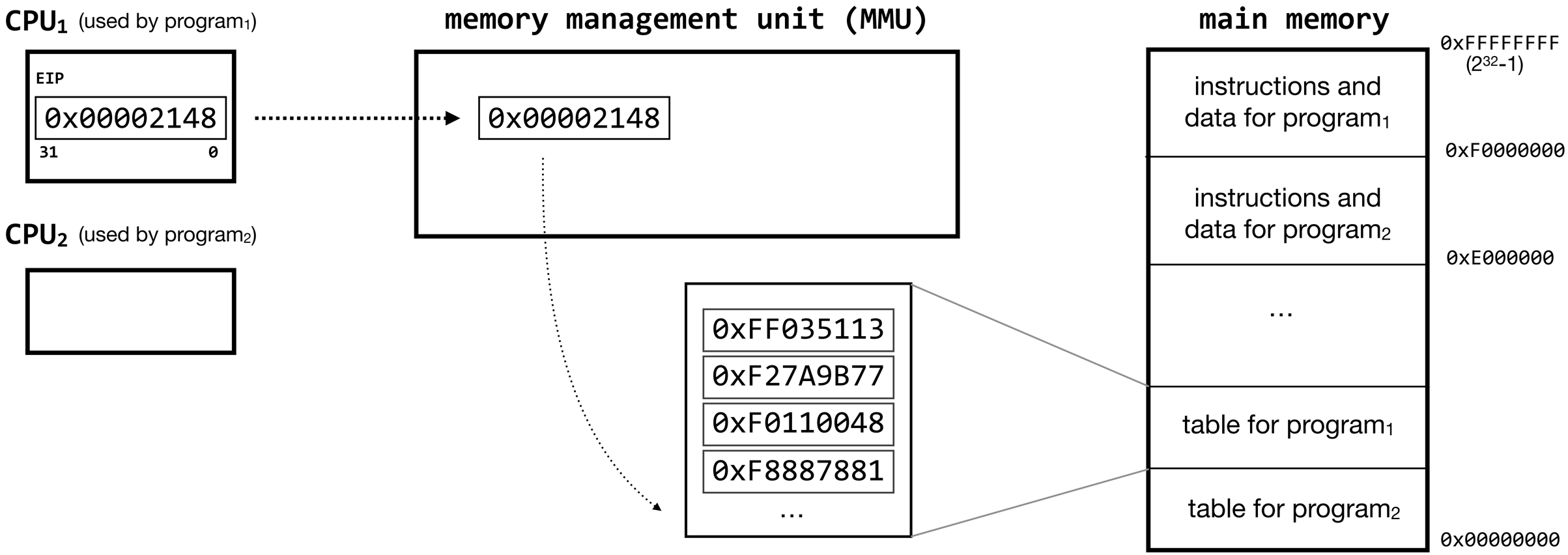

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we don't even have 16GB of memory

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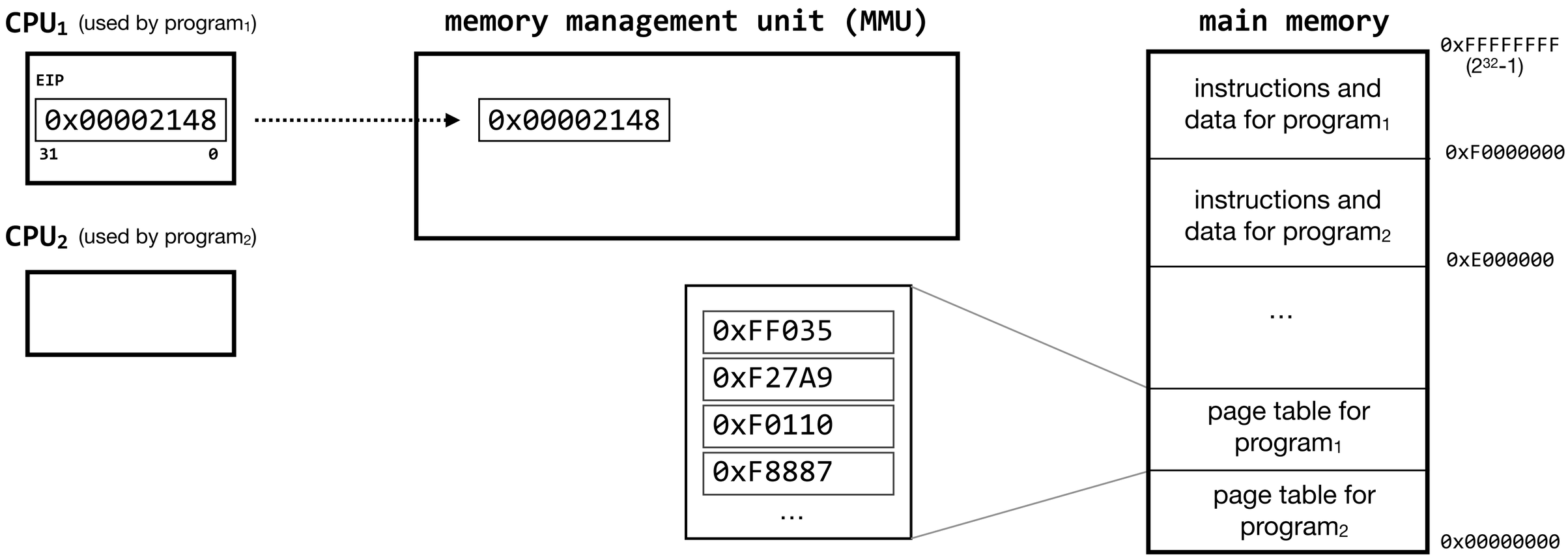

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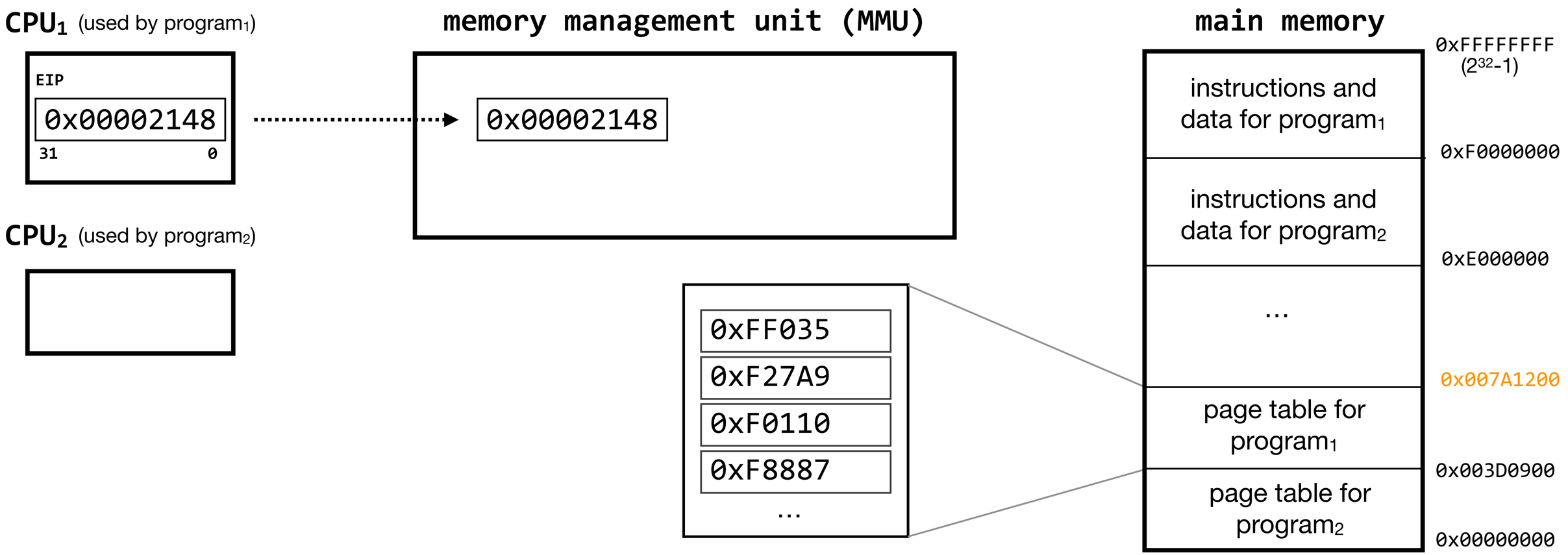

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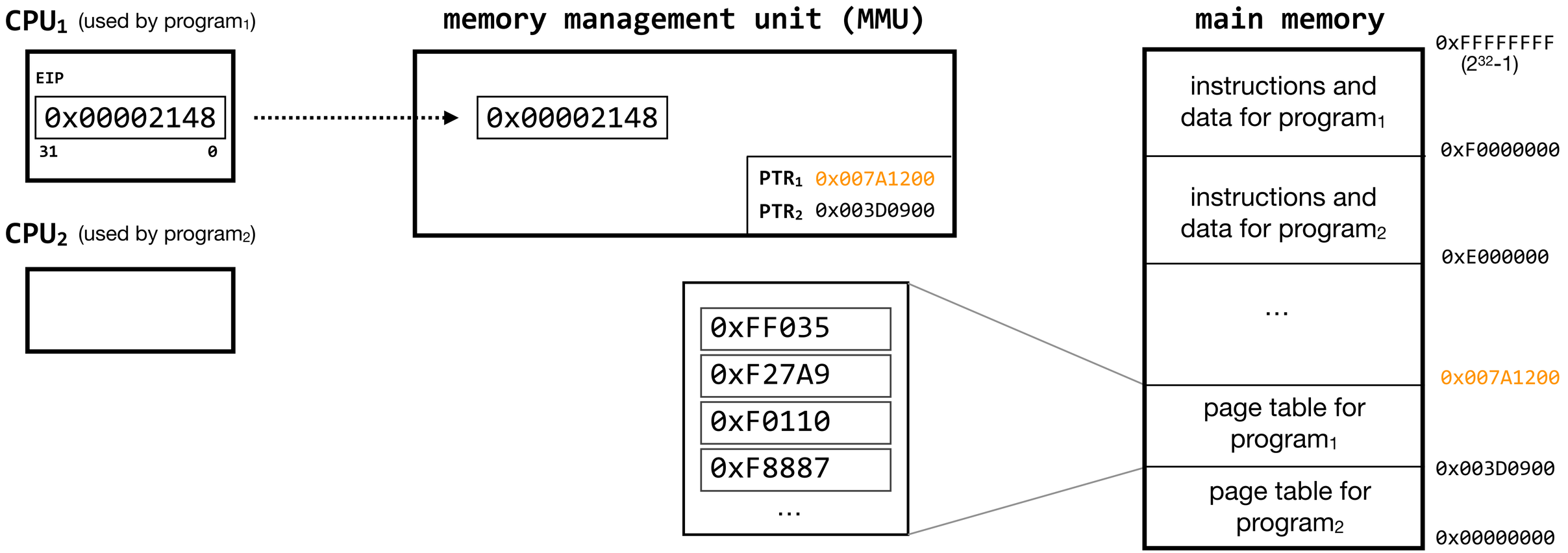

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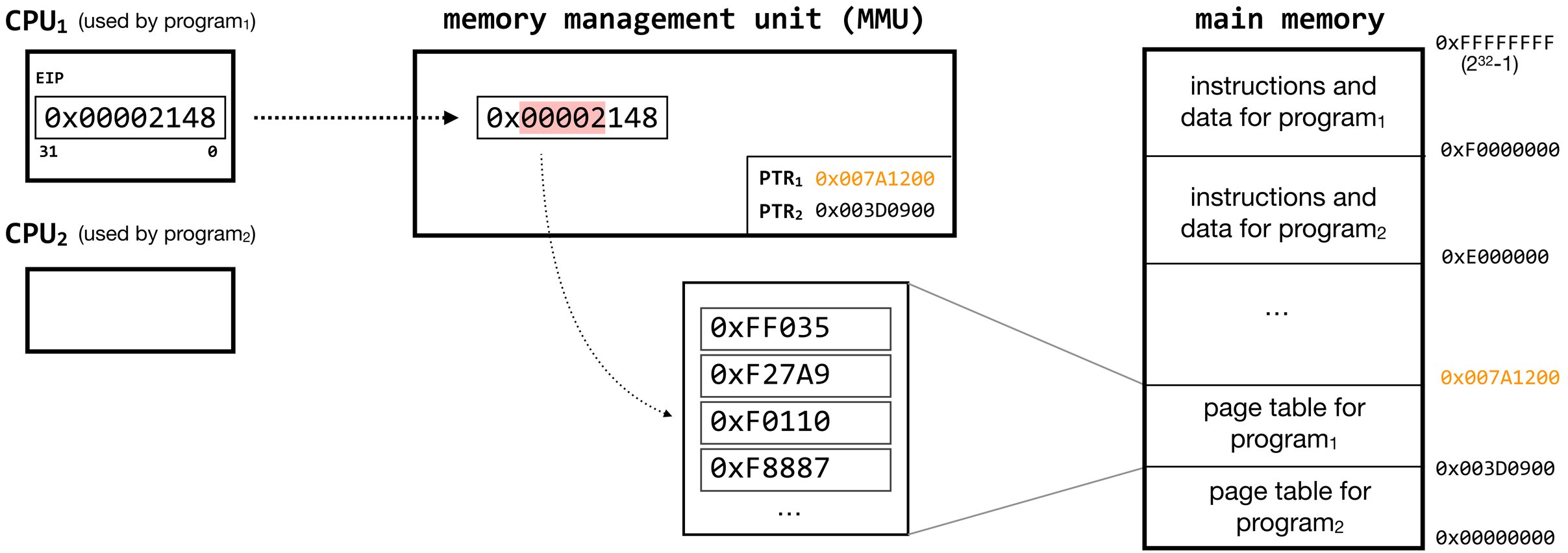

page tables: top 20 bits of the virtual address act as an index into this table

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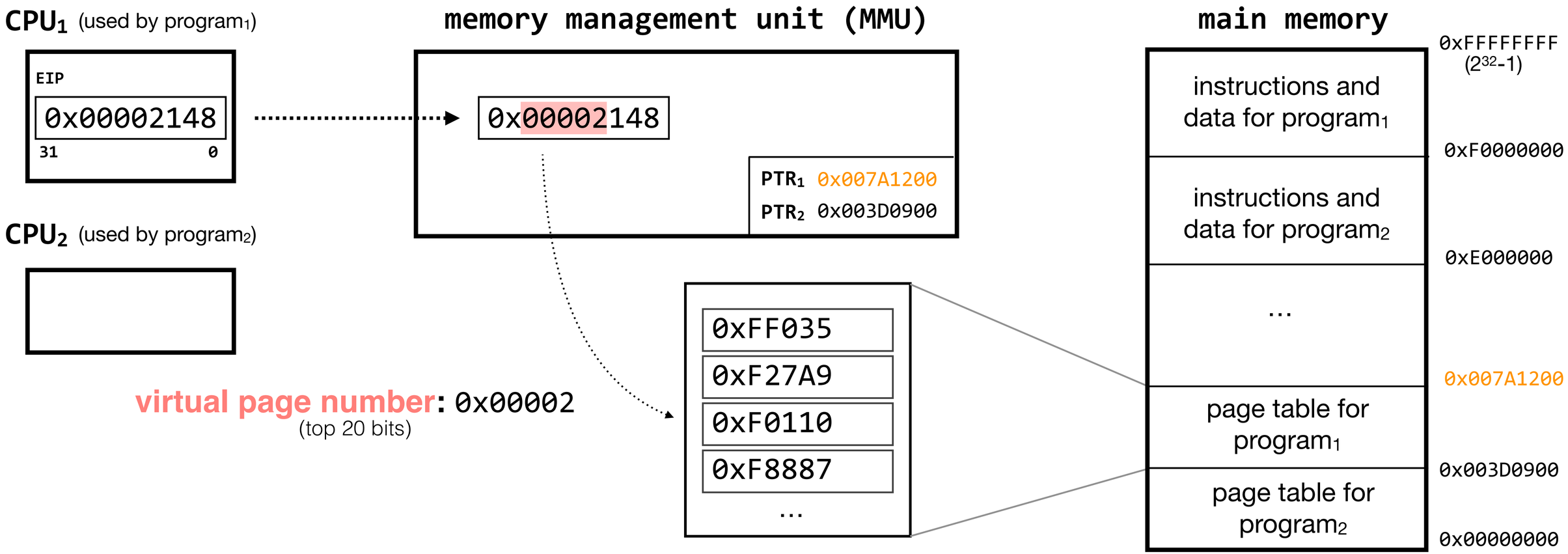

virtual page number: 0x00002
(top 20 bits)

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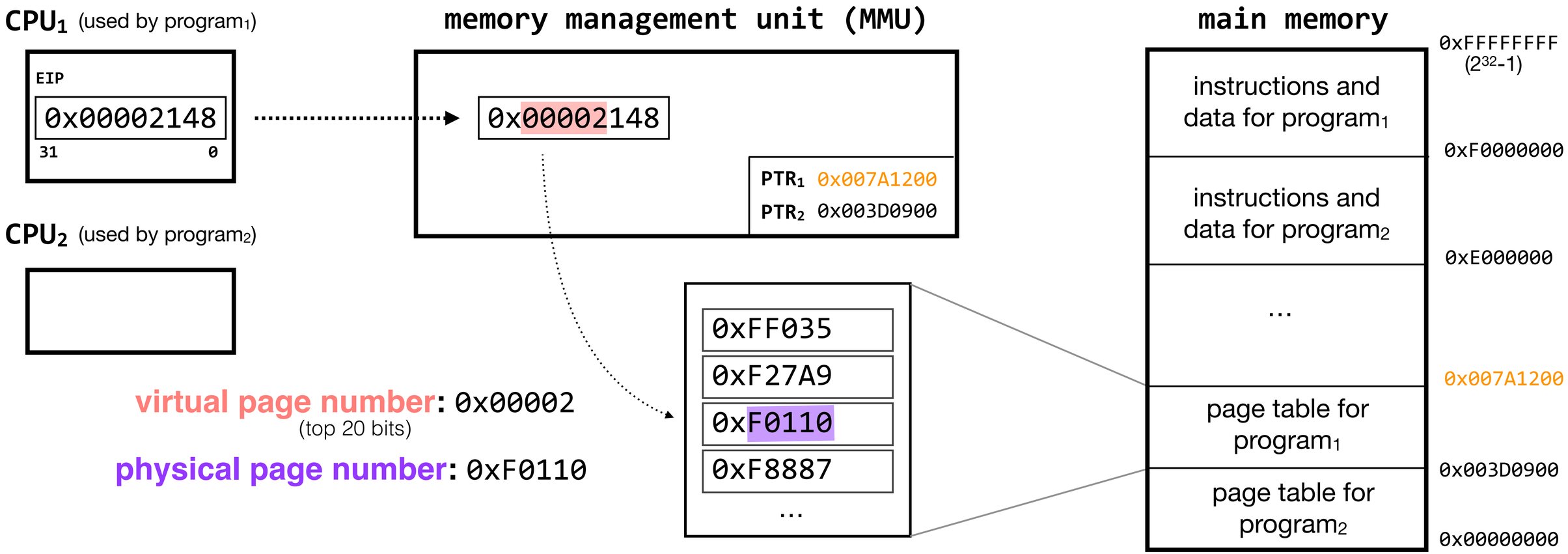

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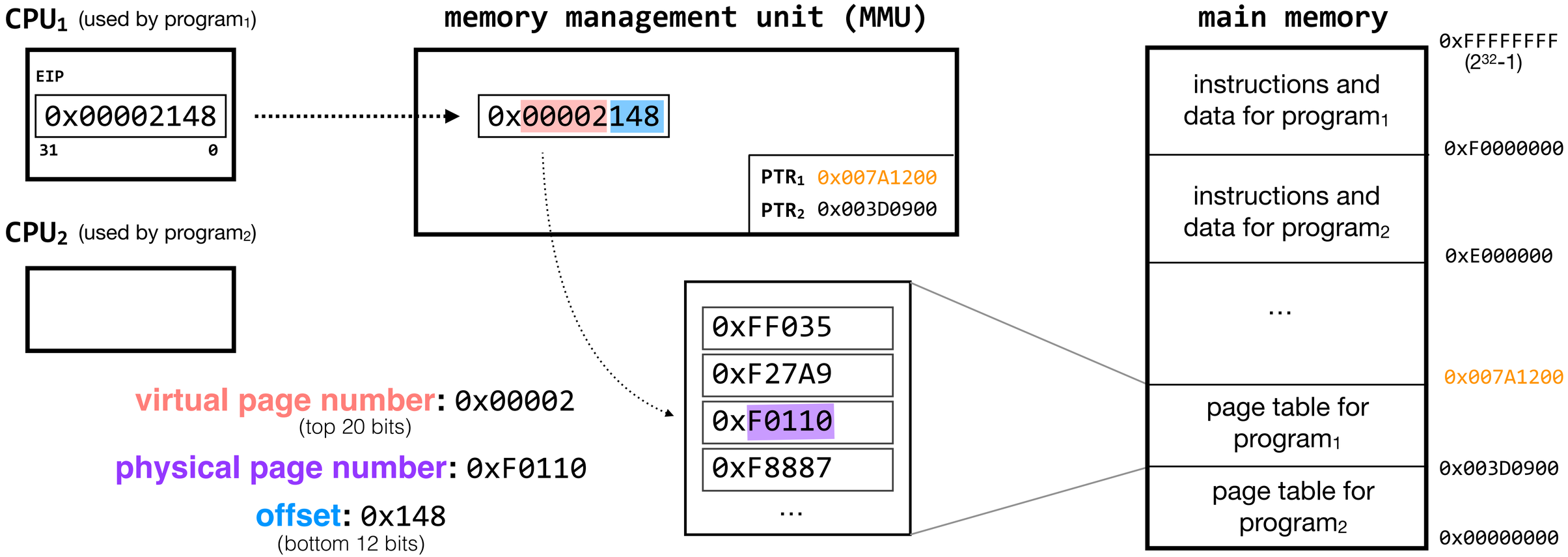

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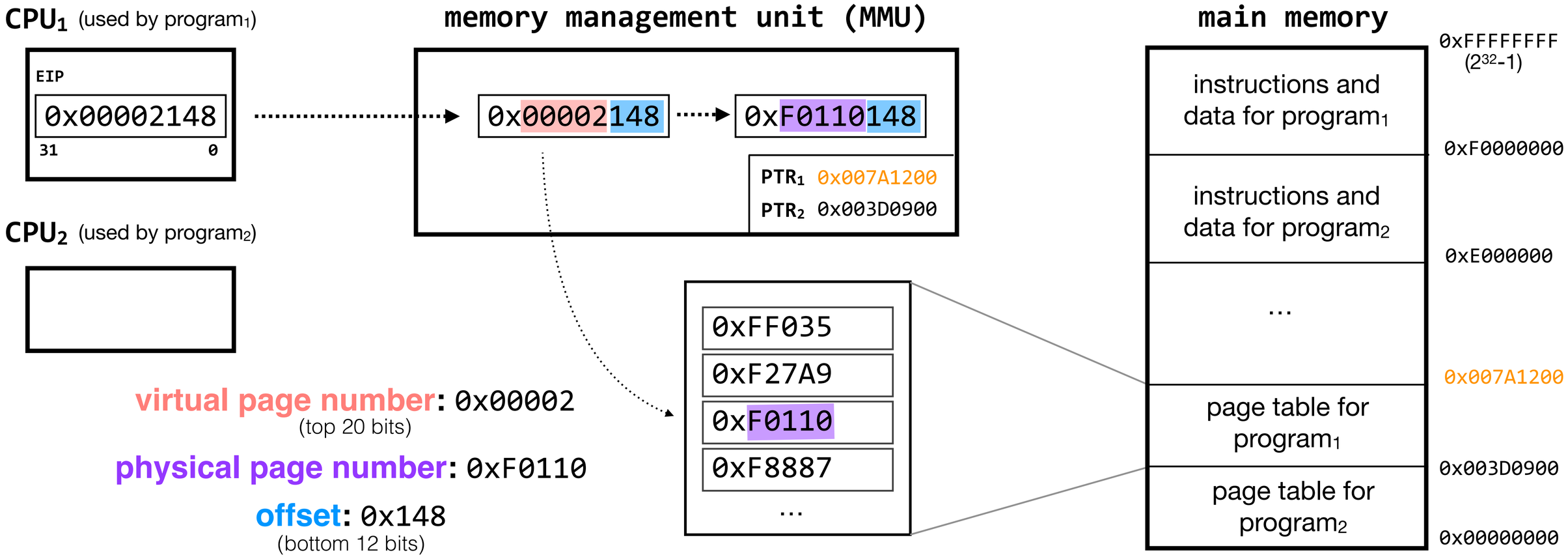

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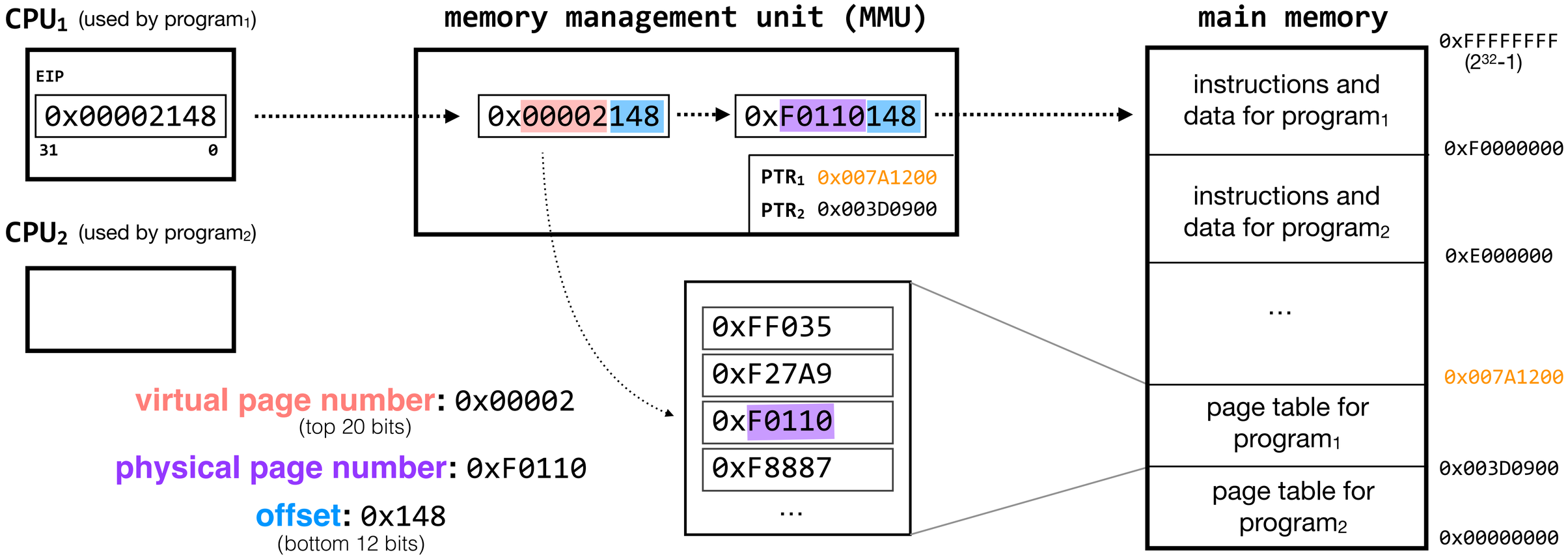

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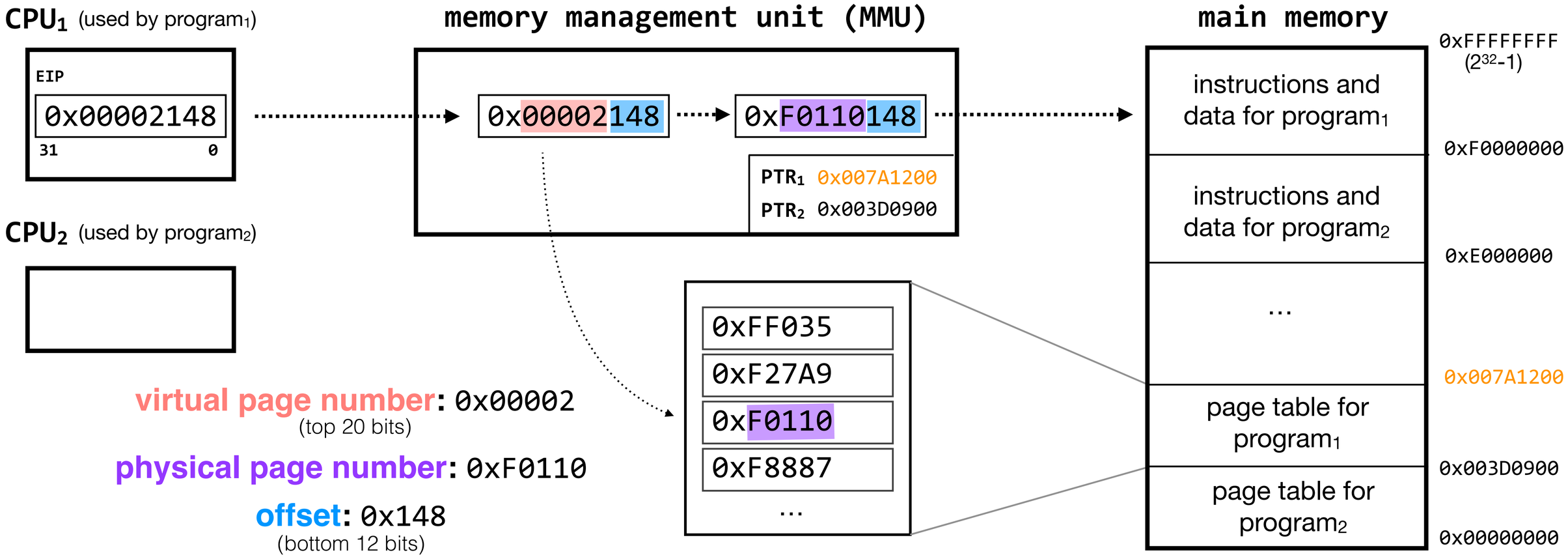

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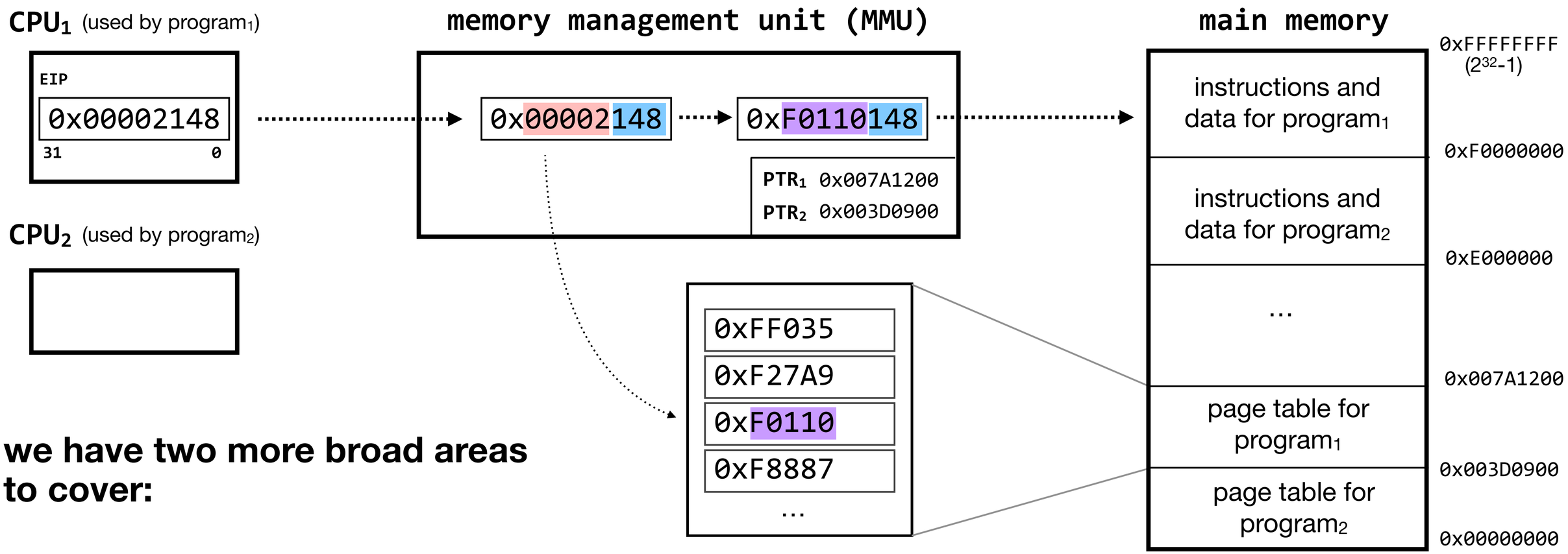
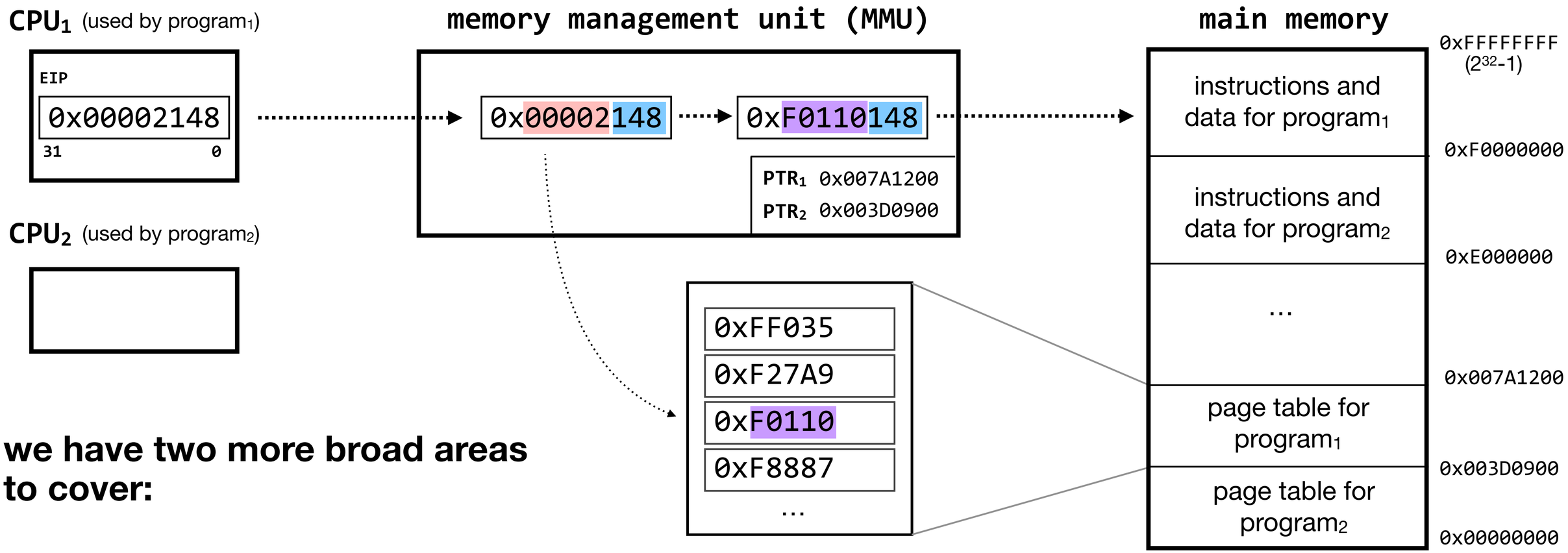
2^{20} virtual page numbers each mapping to a 32-bit page-table entry (PTE) → **4MB to store this table**

(why 32-bit PTEs, not 20-bit? hang on)



we have two more broad areas to cover:



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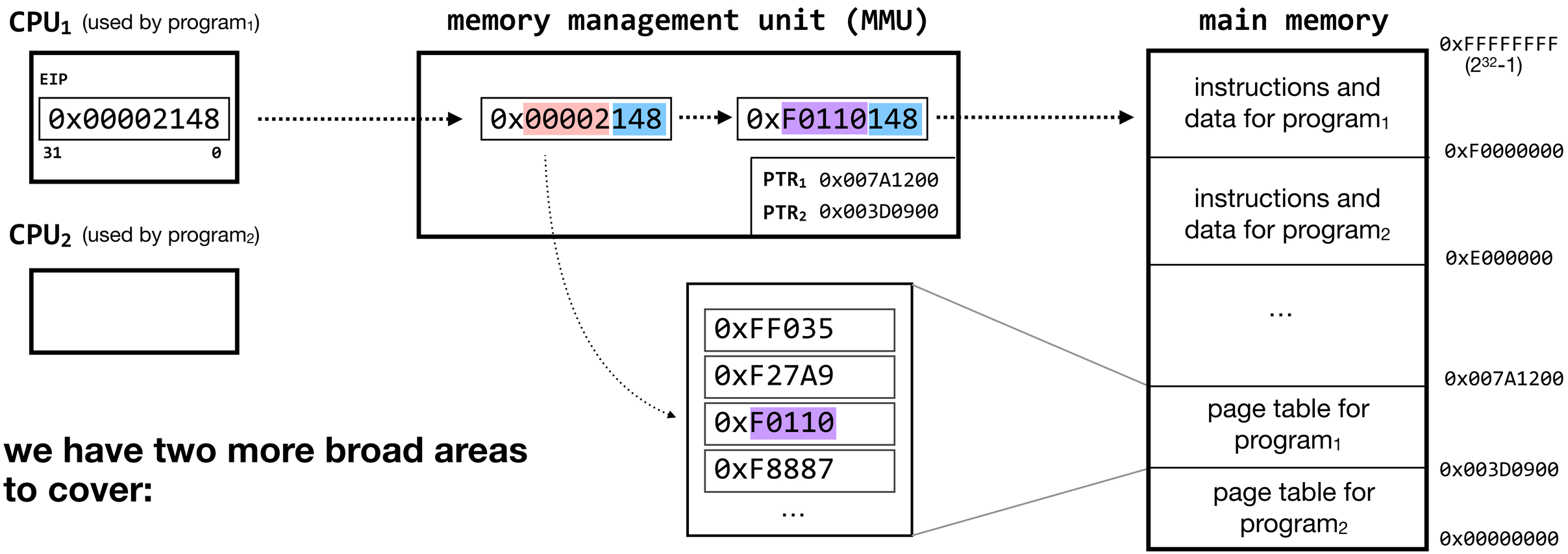
does virtual memory protect programs from accessing each other's memory?
(to answer this, we'll need to address some other issues first)



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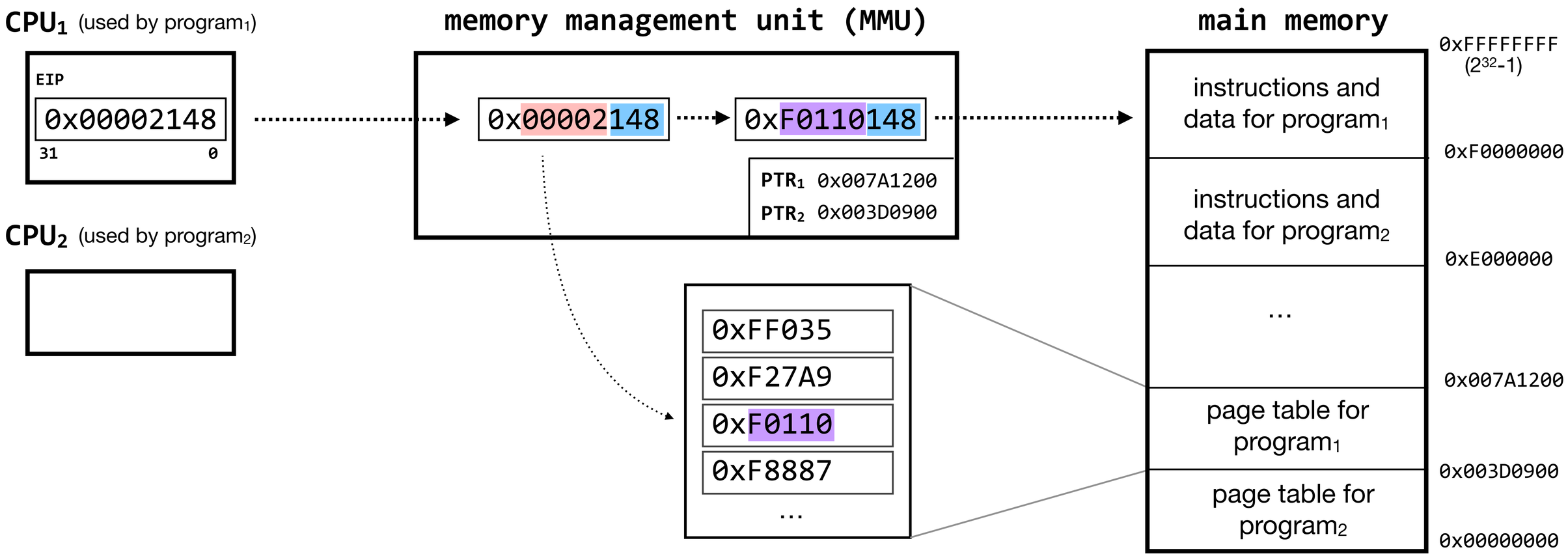
what performance issues matter here?

what happens if we don't have enough memory to store all of our programs' instructions and data?



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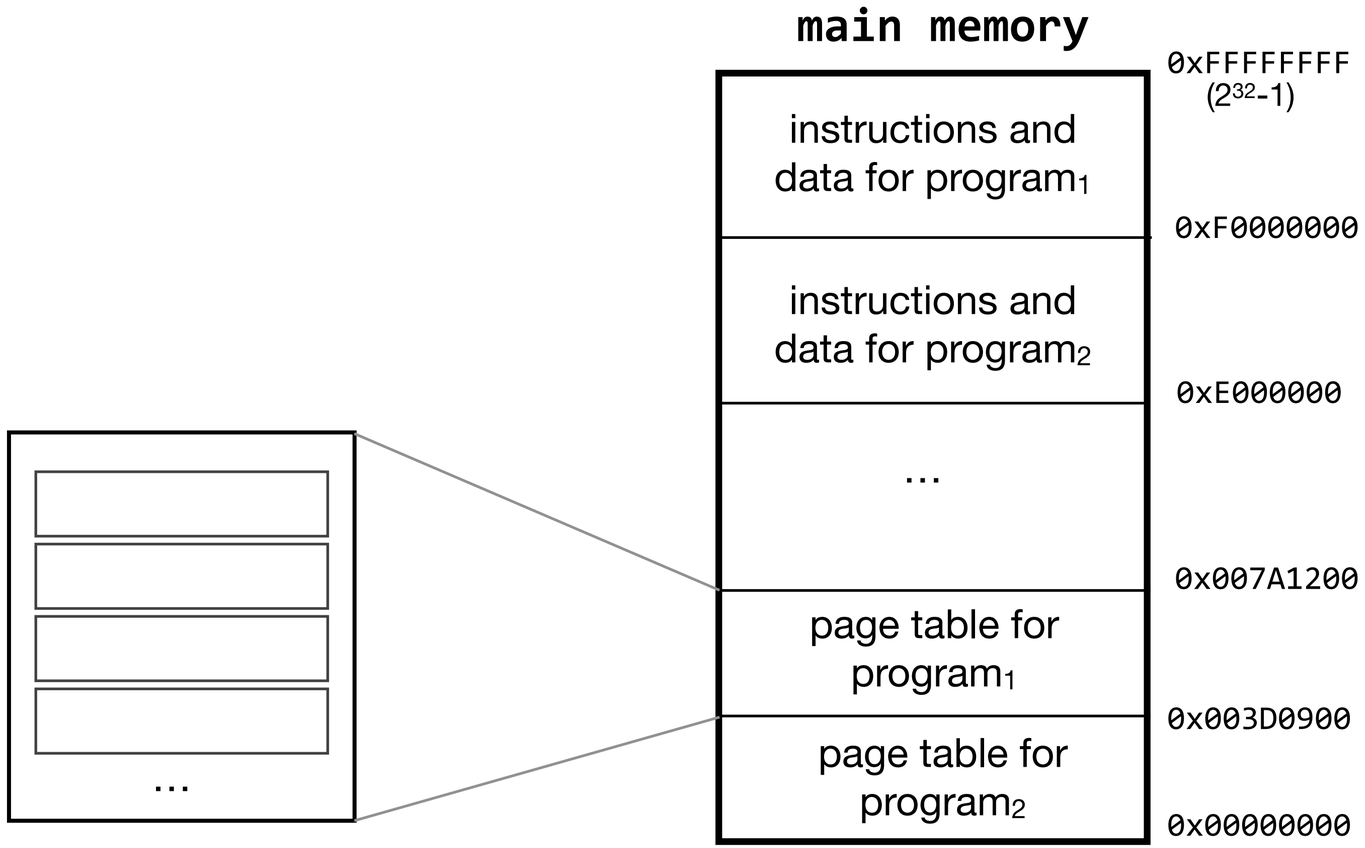

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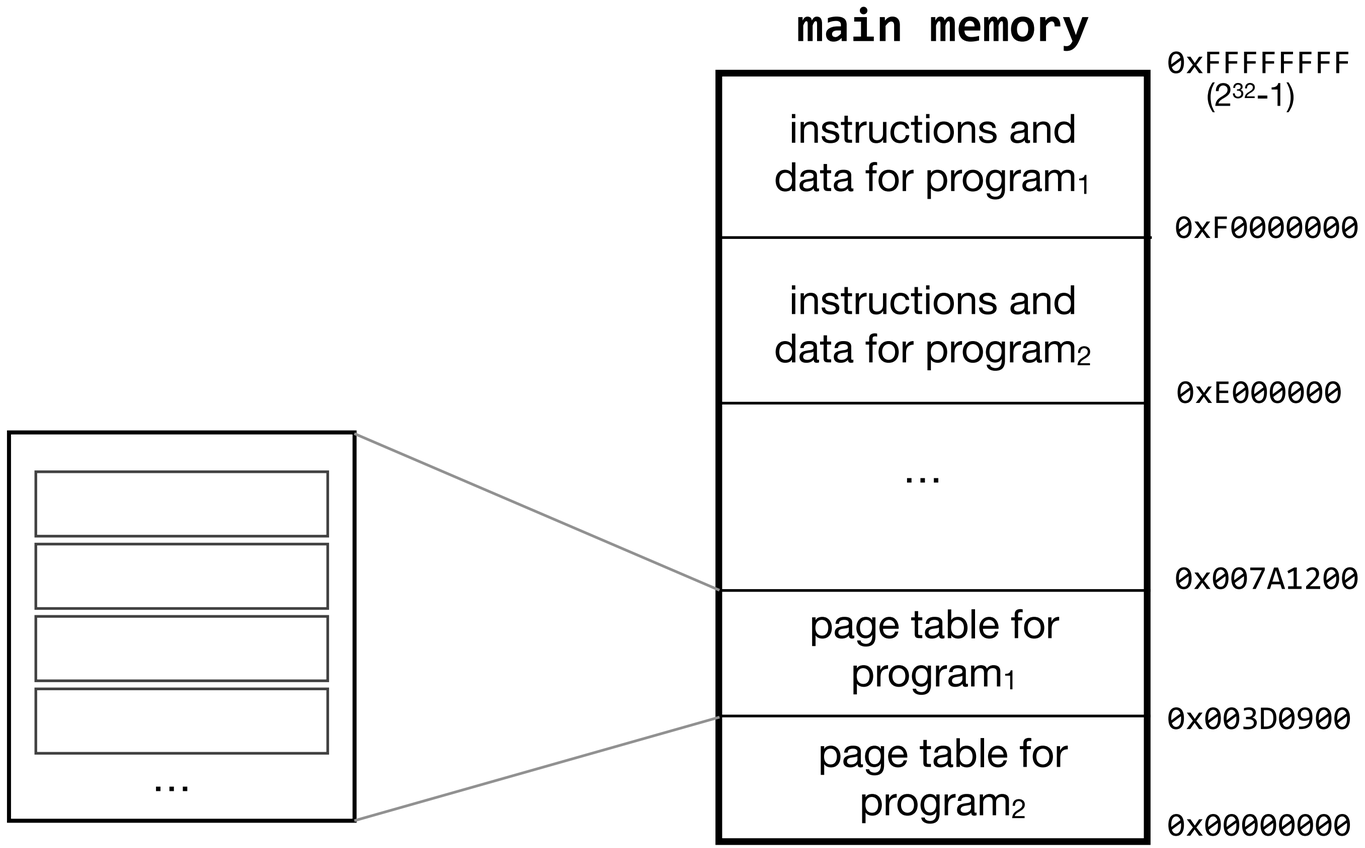

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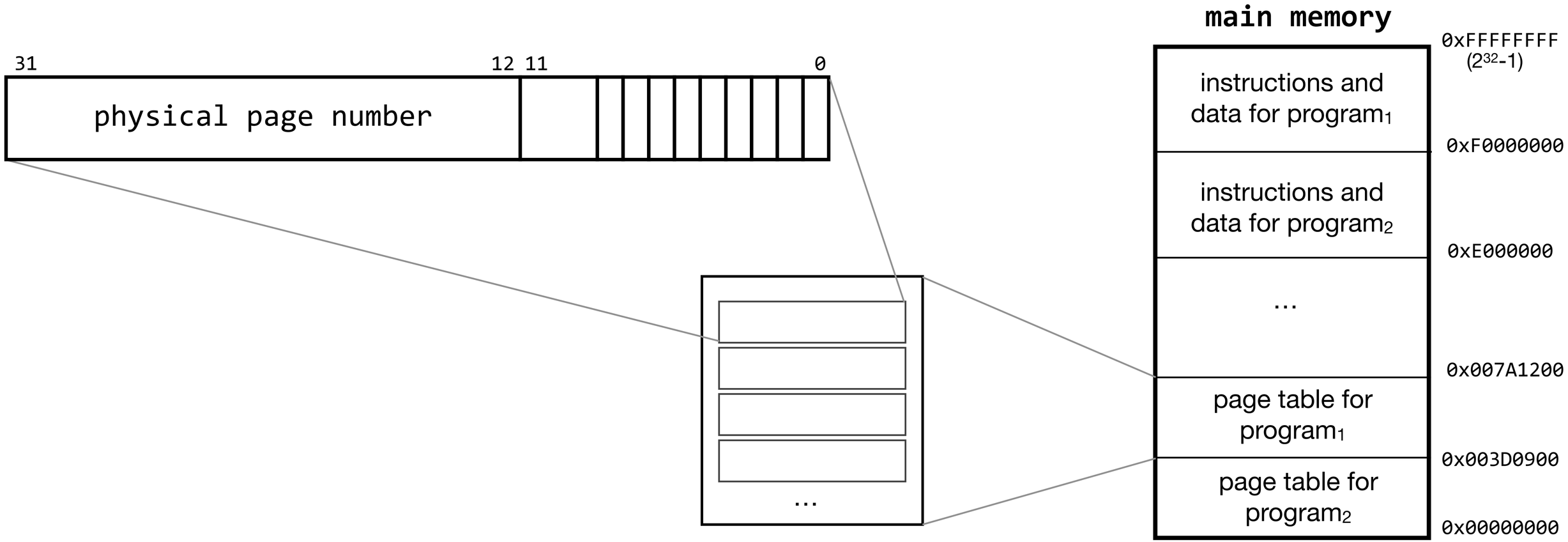

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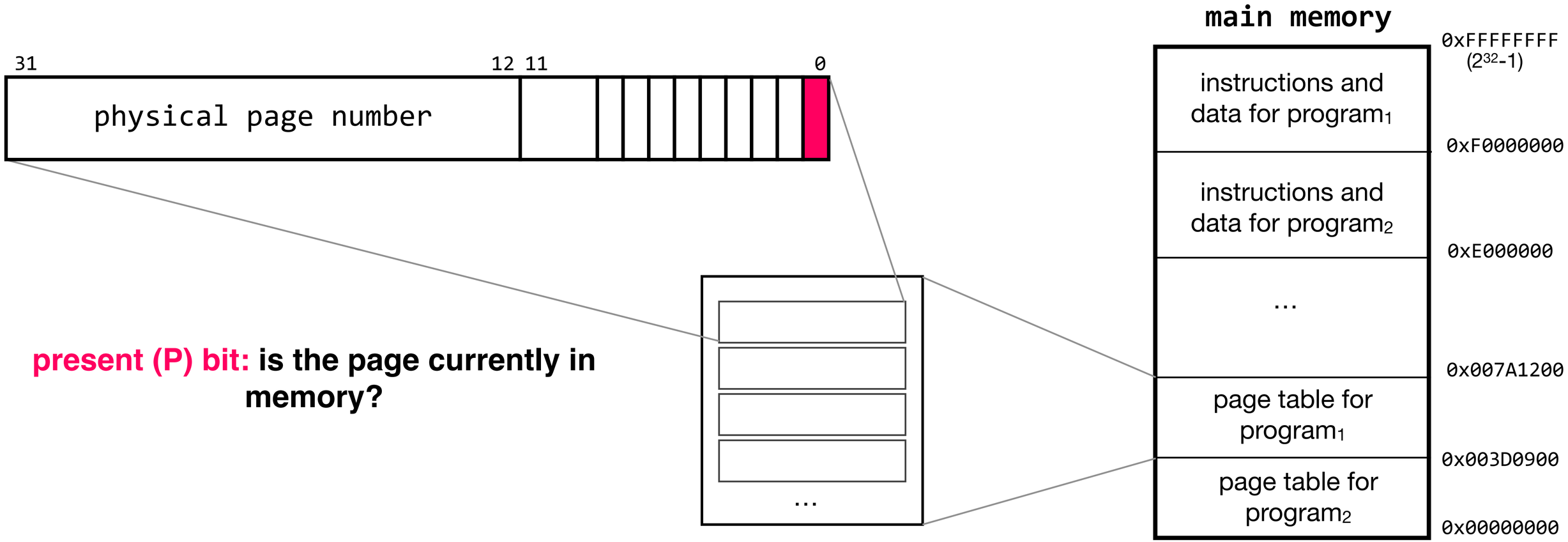

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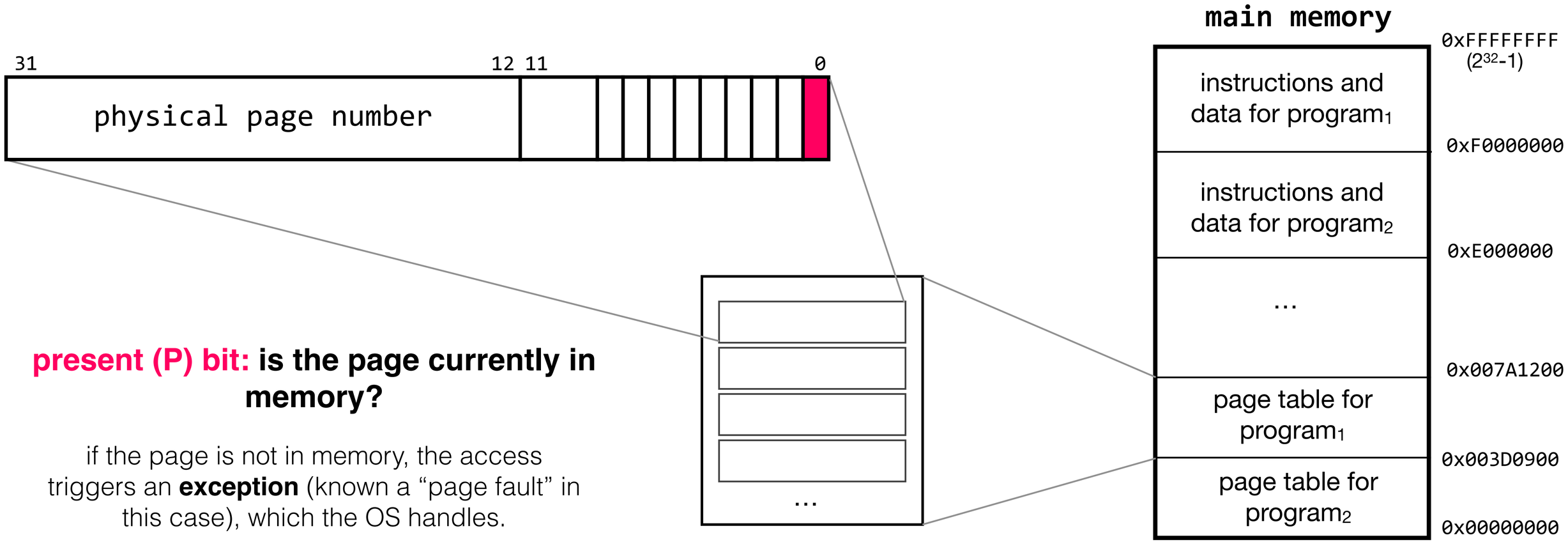

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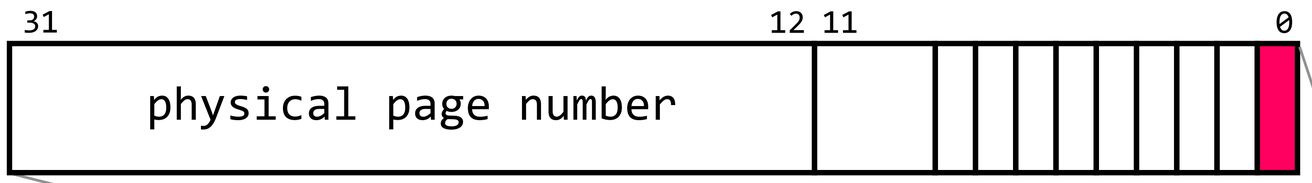

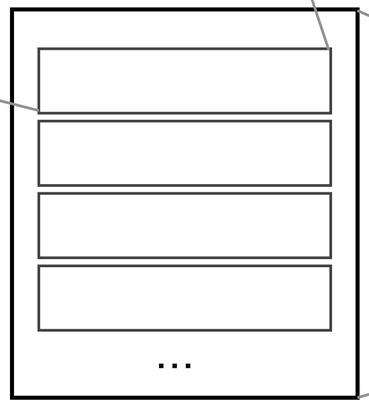

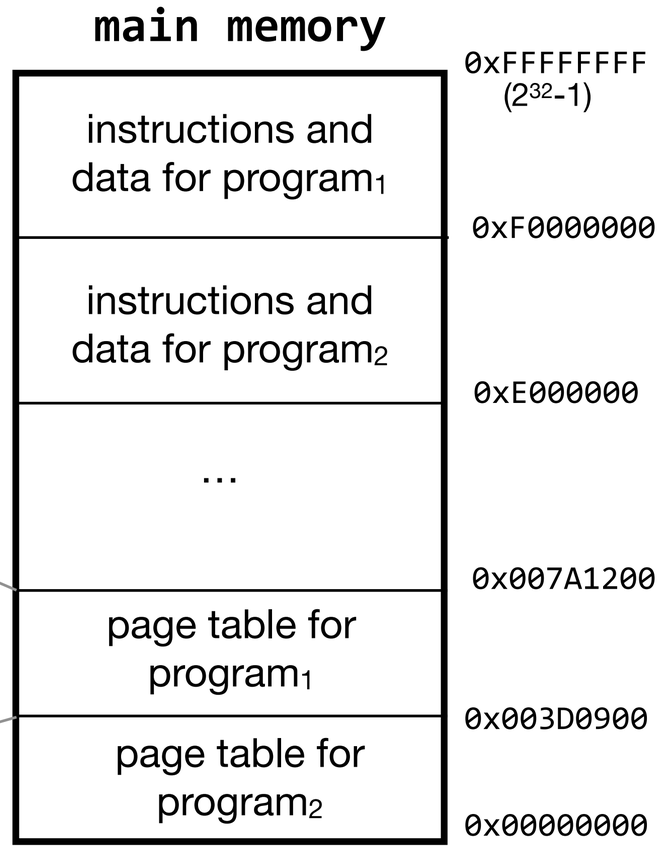

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this also answers the question of why PTEs are 32 bits, not 20: they store information beyond the page number

interlude: handling exceptions

(such as page faults)

this idea will remain relevant, as we are going to find that there are quite a few exceptions for the OS to handle

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```
// special instruction that calls the exception handler for exception x
exception(x):
  // switch from user mode to kernel mode
  // call the handler for this particular exception
  // switch from kernel mode to user mode
```

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// special instruction that calls the exception handler for exception x
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```

the processor stores a **user/kernel (U/K) bit**, which indicates whether it's operating in user mode or kernel mode. this bit helps the processor control access to certain kernel-specific actions

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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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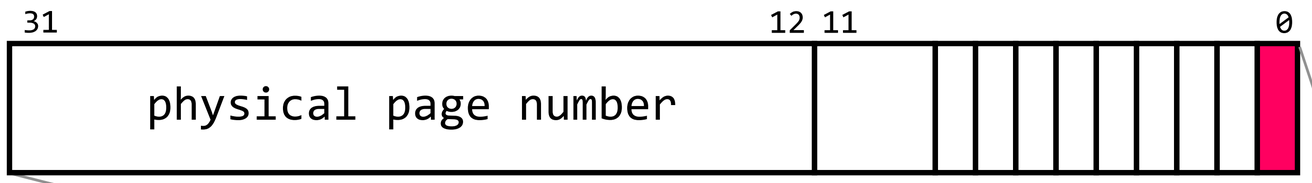

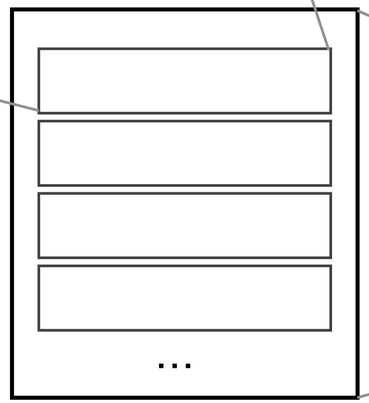

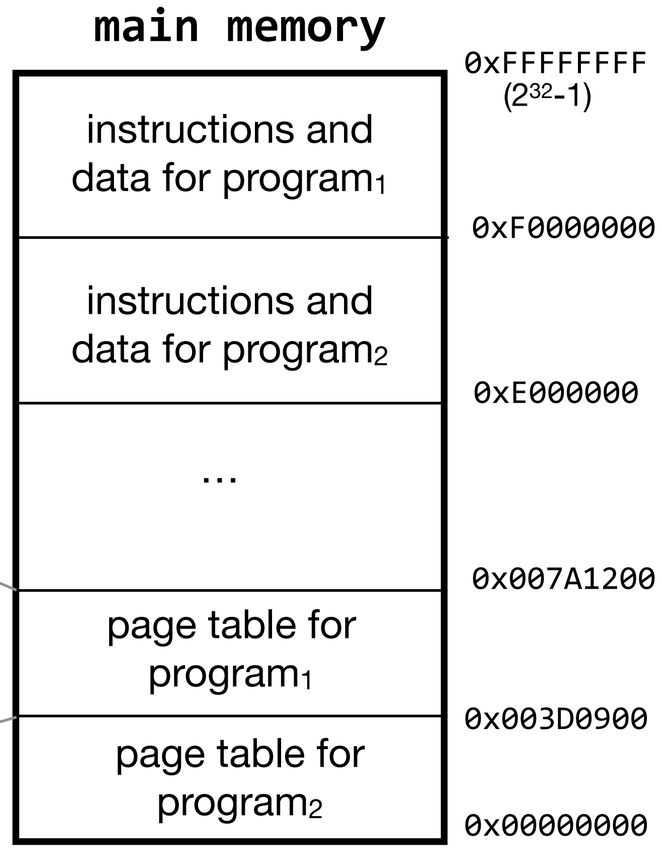

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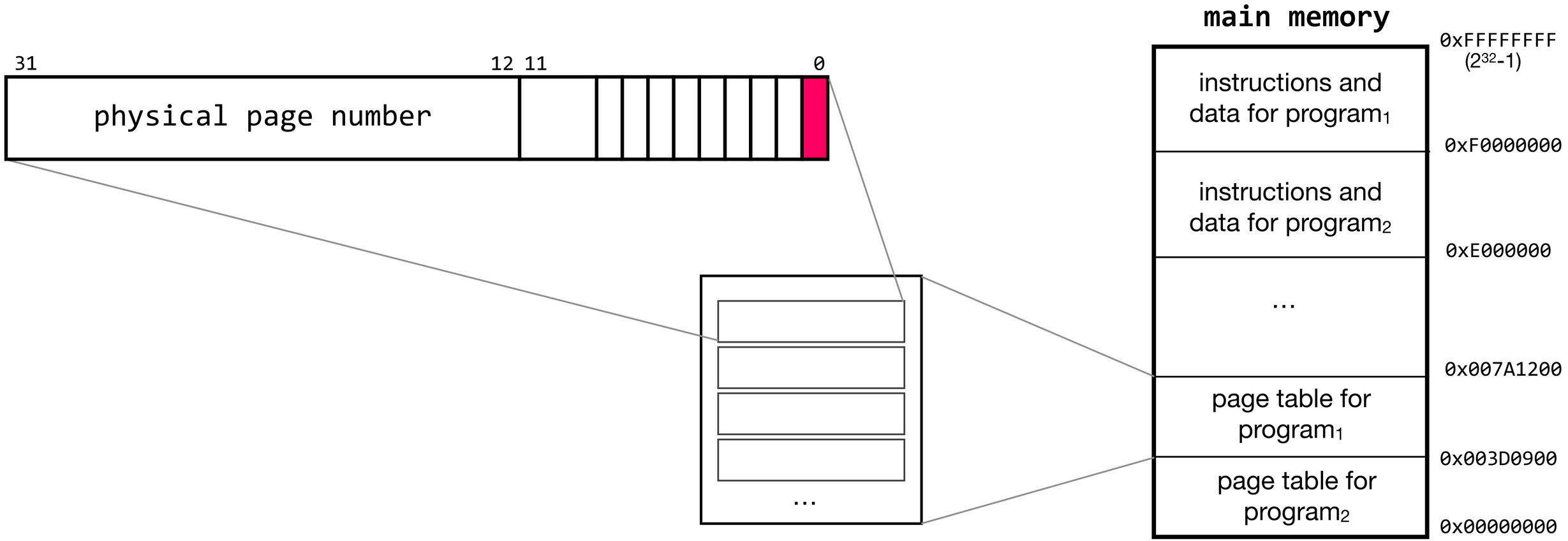
what happens if a program tries to write to memory that it doesn't have write-access to?



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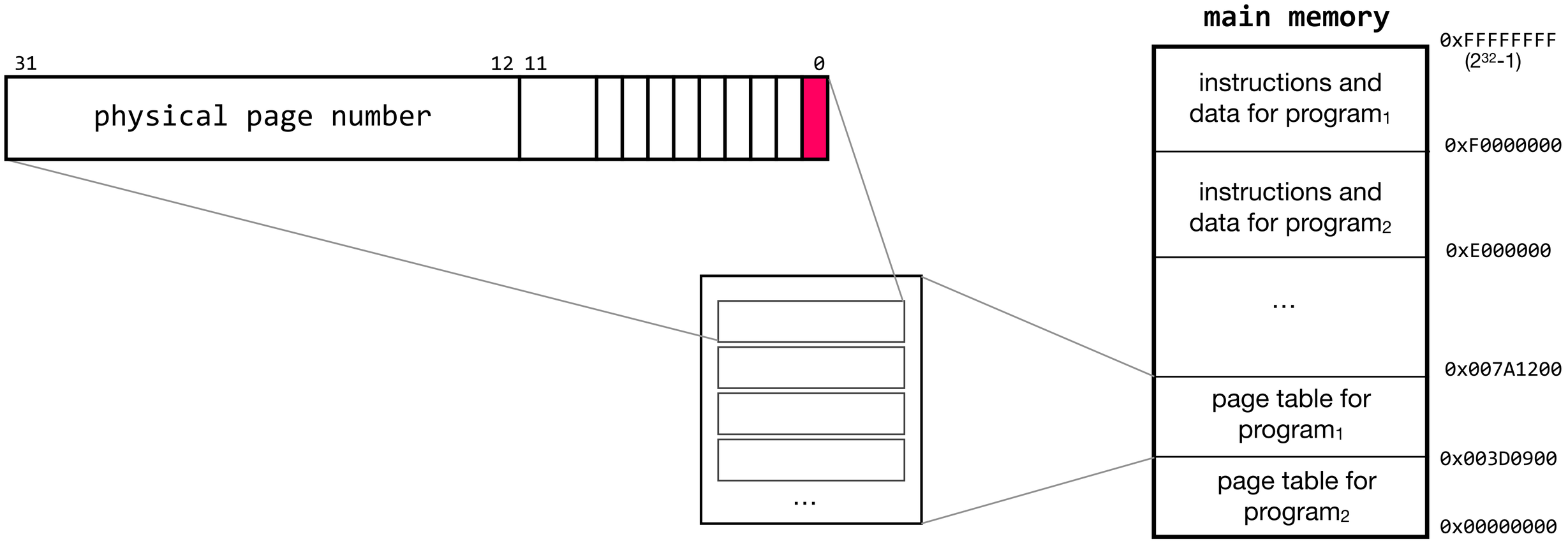

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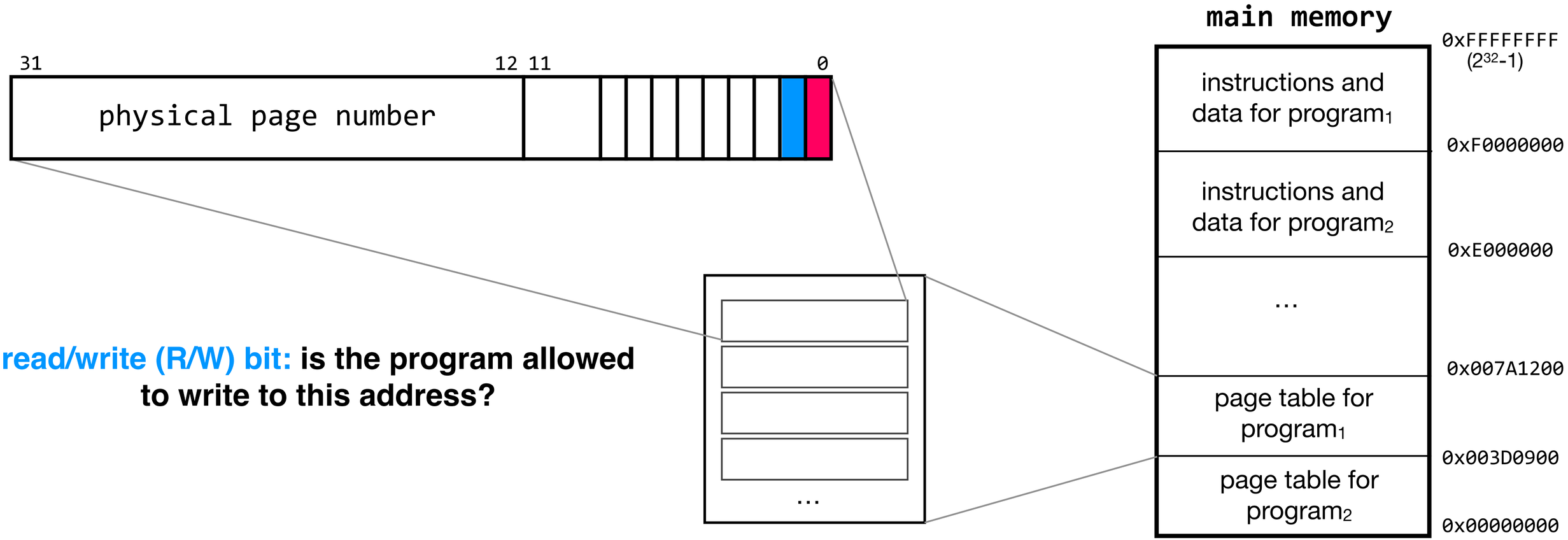

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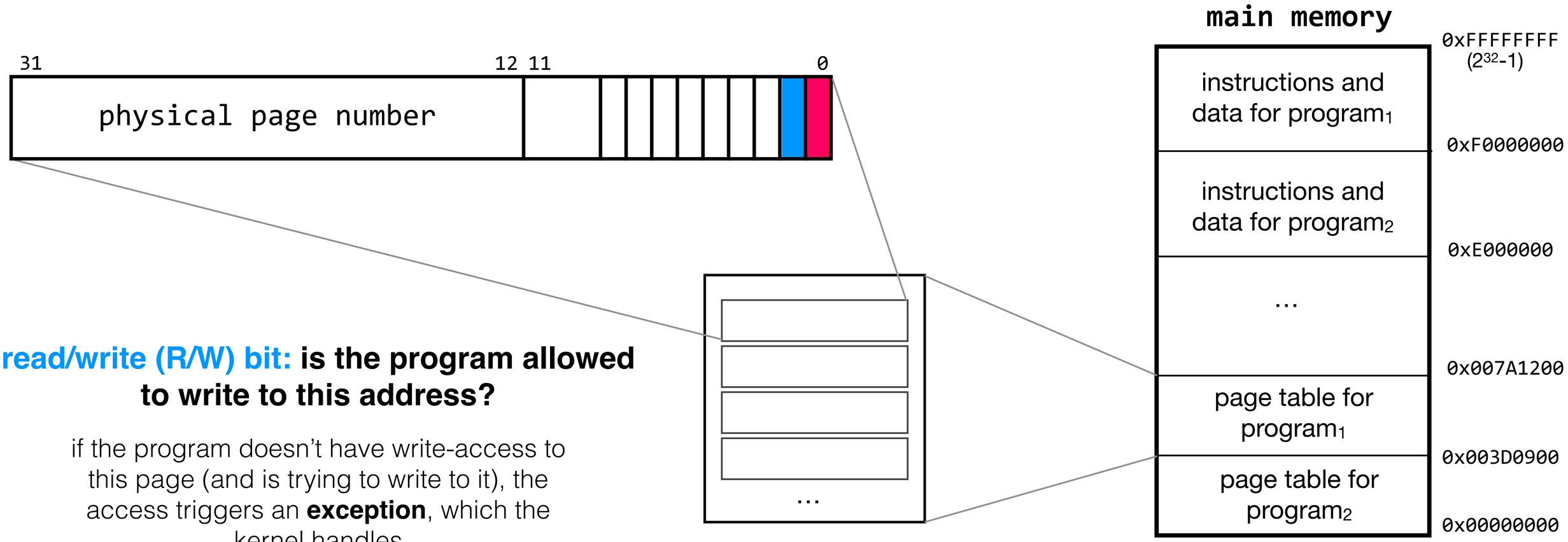

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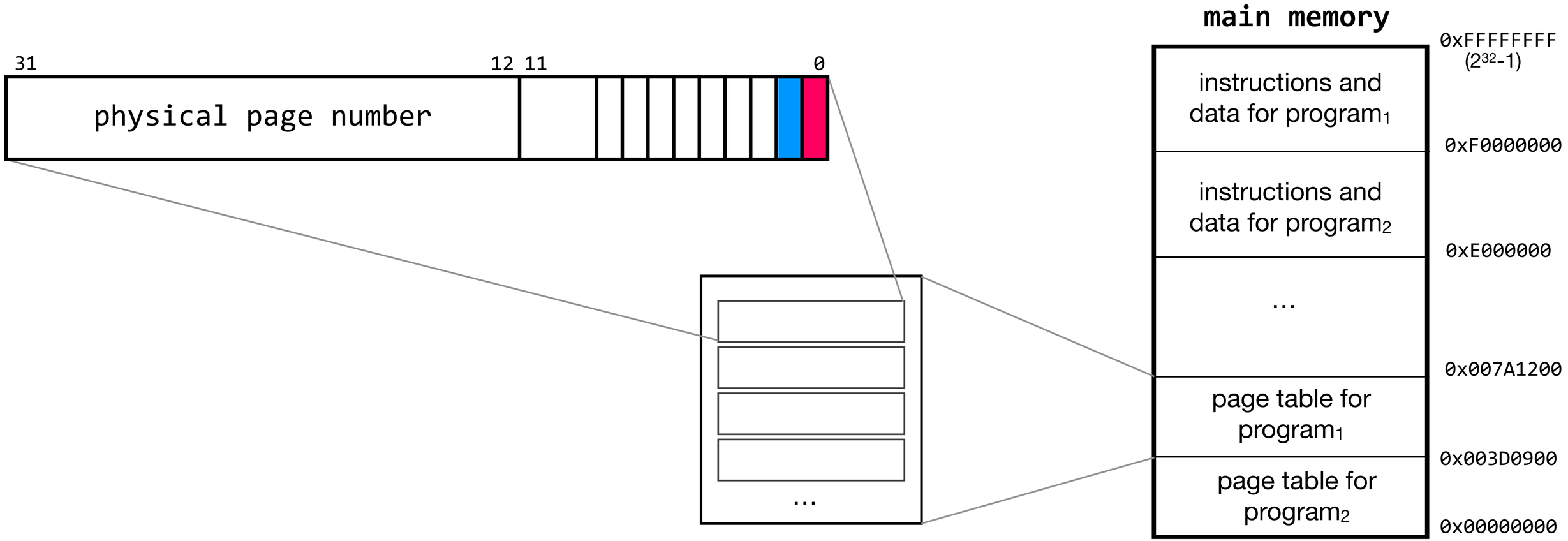
if the program doesn't have write-access to this page (and is trying to write to it), the access triggers an **exception**, which the kernel handles

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



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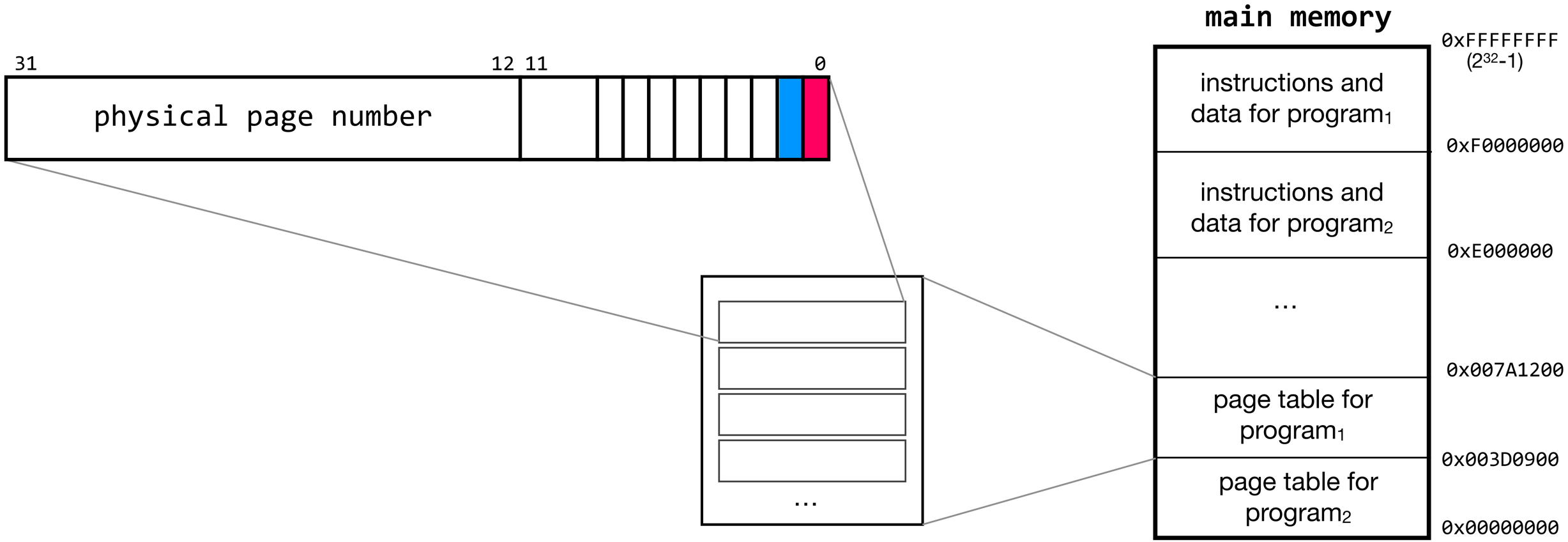
we need to enforce modularity between programs and the kernel, not just between programs



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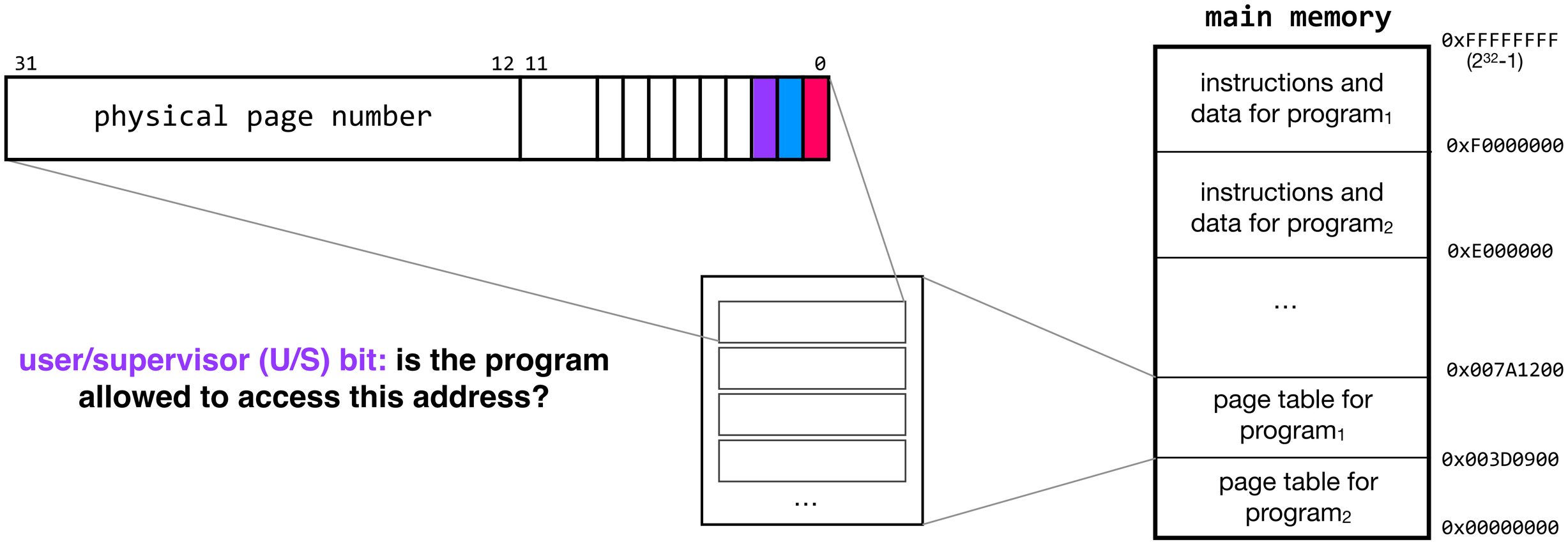

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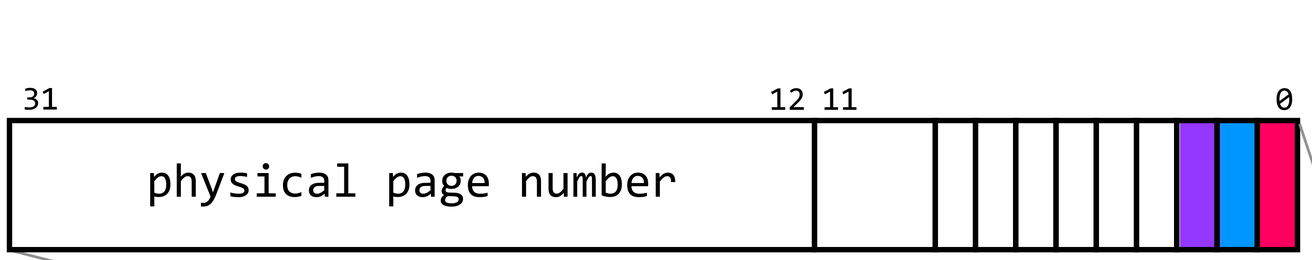

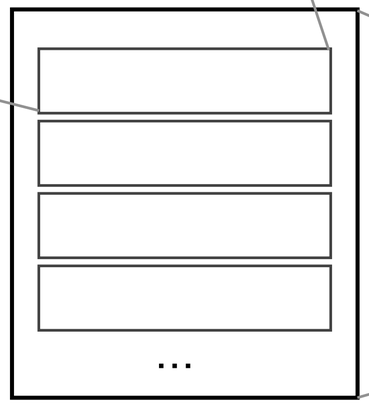

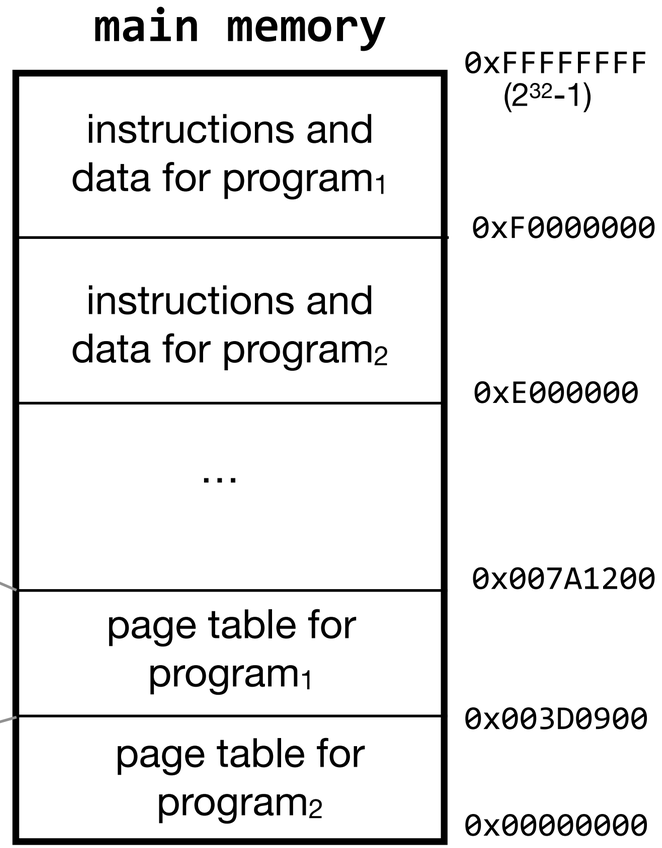

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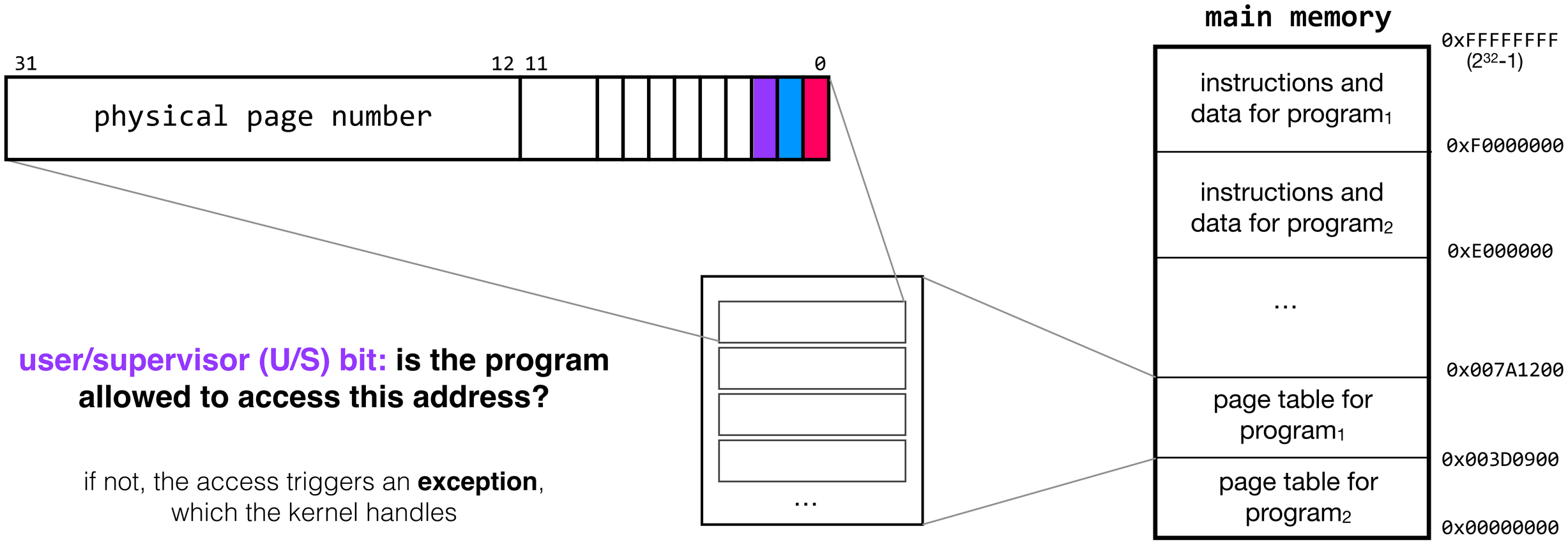

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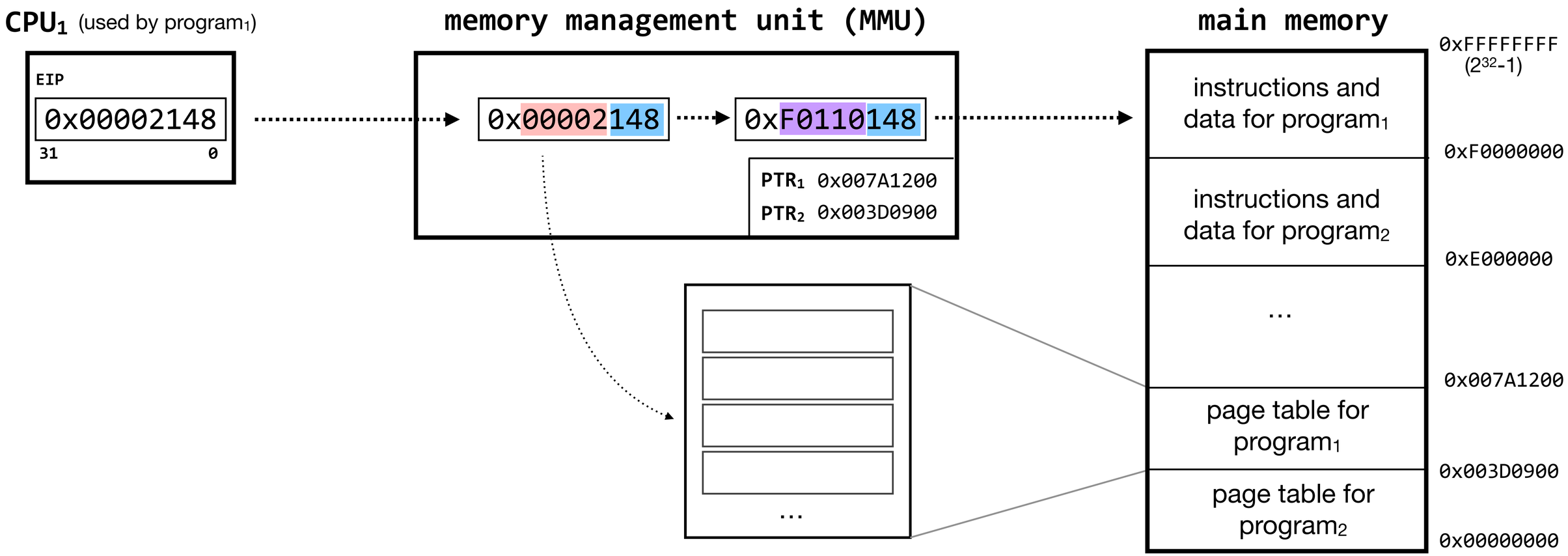
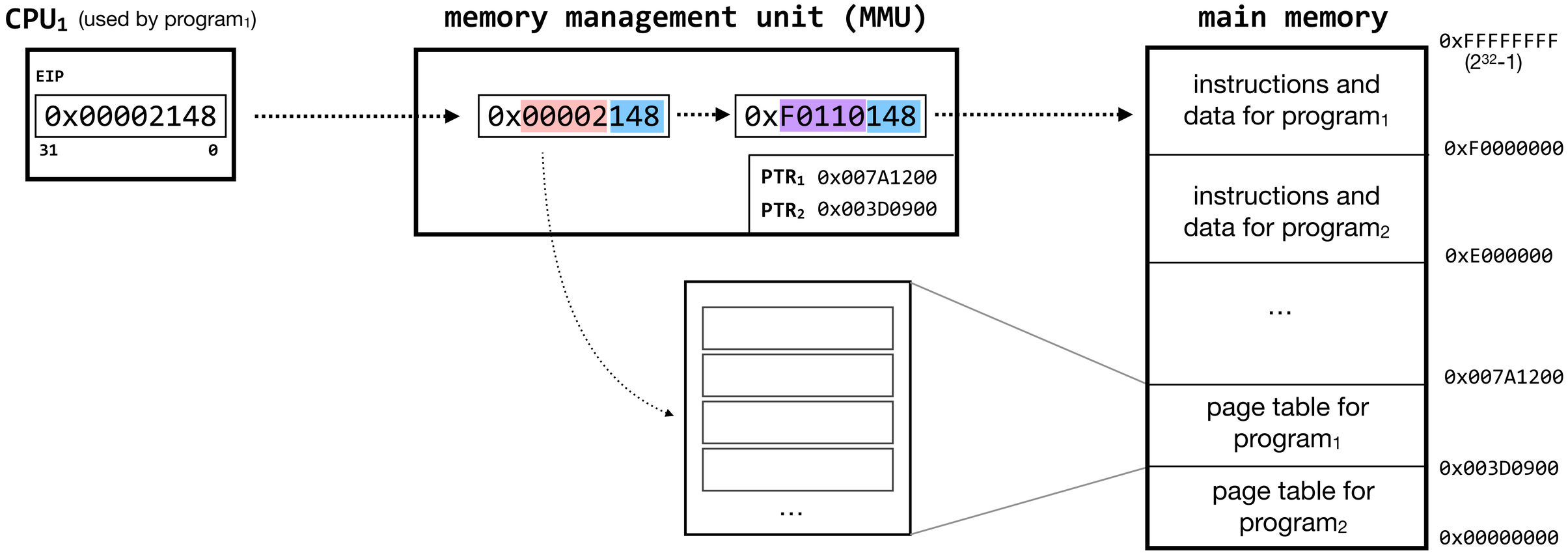
without this last piece, a determined program could still attempt to circumvent modularity by doing things such as modifying the page-table registers

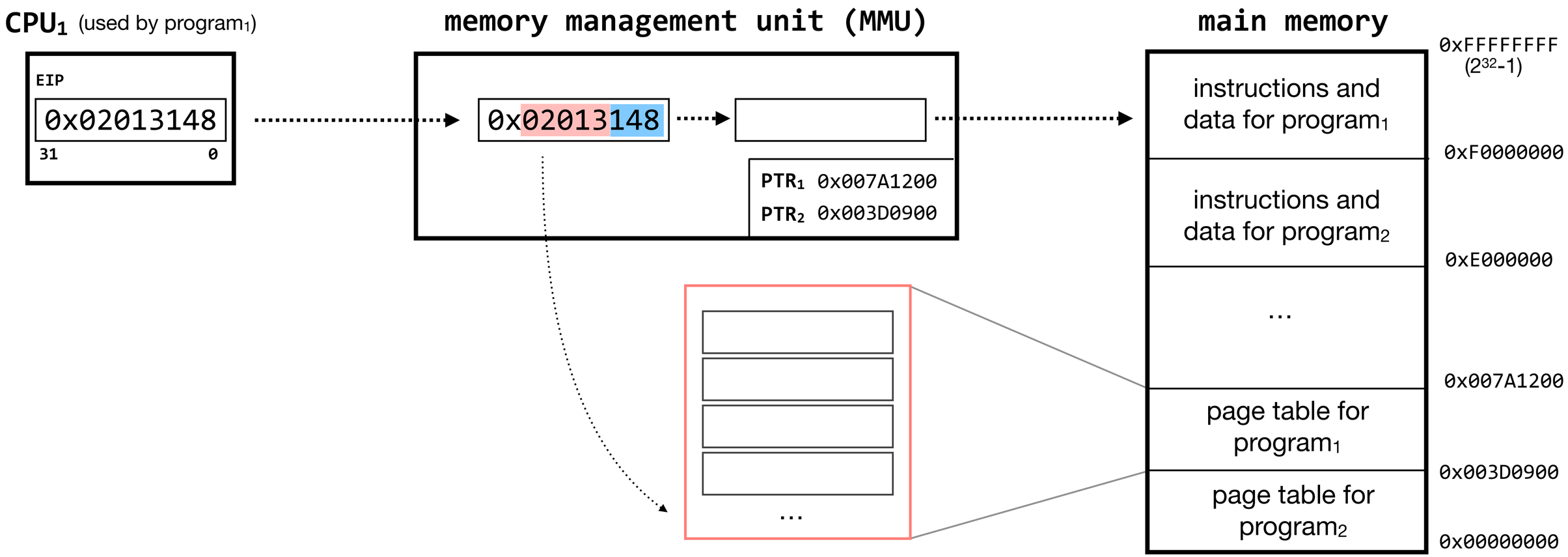

CPU1 (used by program1)
EIP
0x00002148
31
0
memory management unit (MMU)
0x00002148
0xF0110148
PTR1 0x007A1200
PTR2 0x003D0900
...
main memory
instructions and data for program1
instructions and data for program2
...
page table for program1
page table for program2
0xFFFFFFFF (2^32-1)
0xF0000000
0xE000000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

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 need to make a few memory accesses



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

hierarchical (or “multilevel”) page tables potentially use less space



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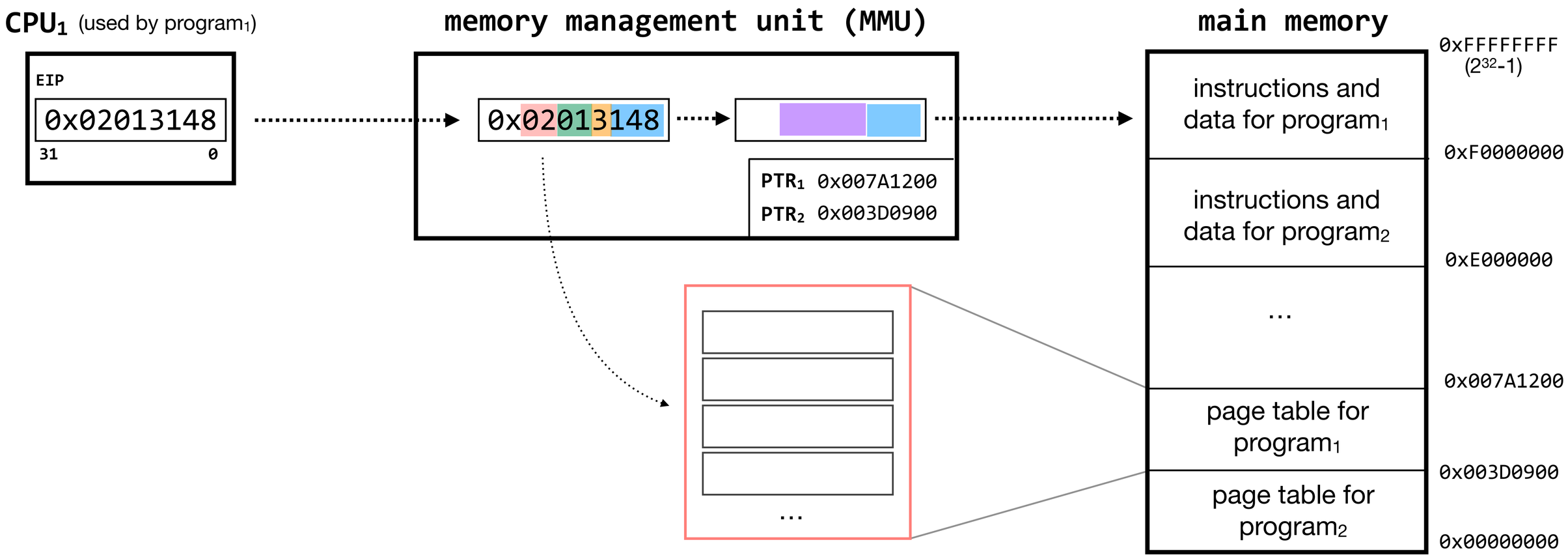

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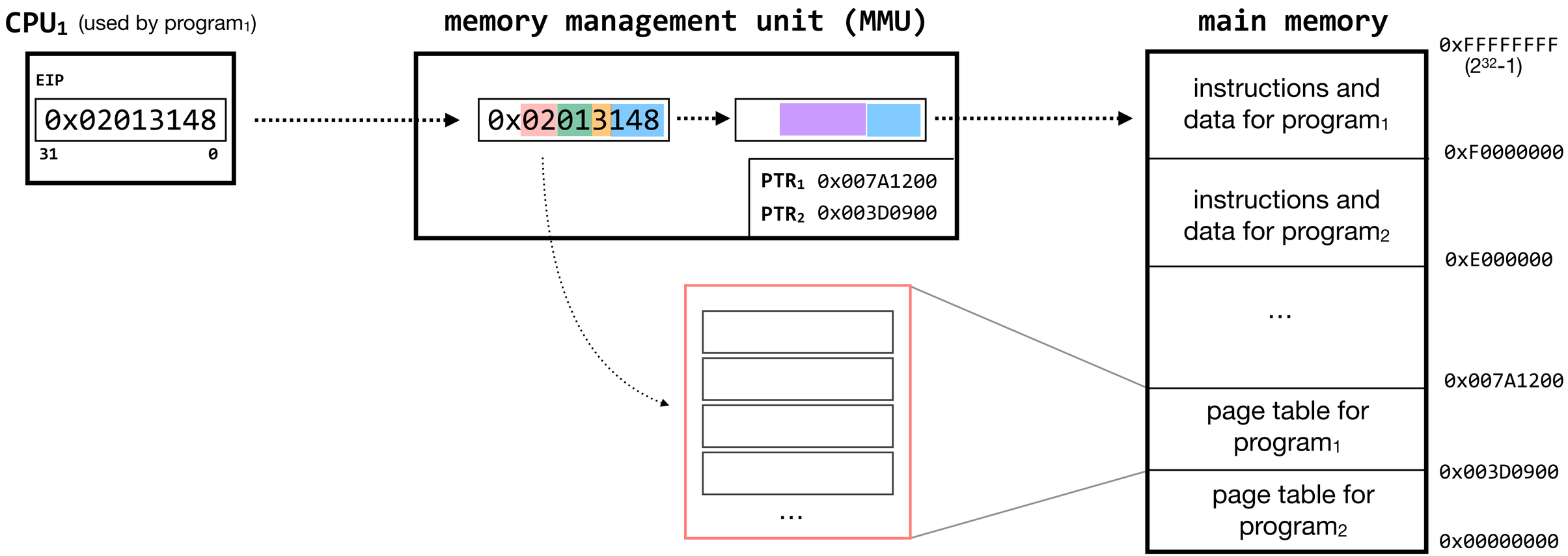

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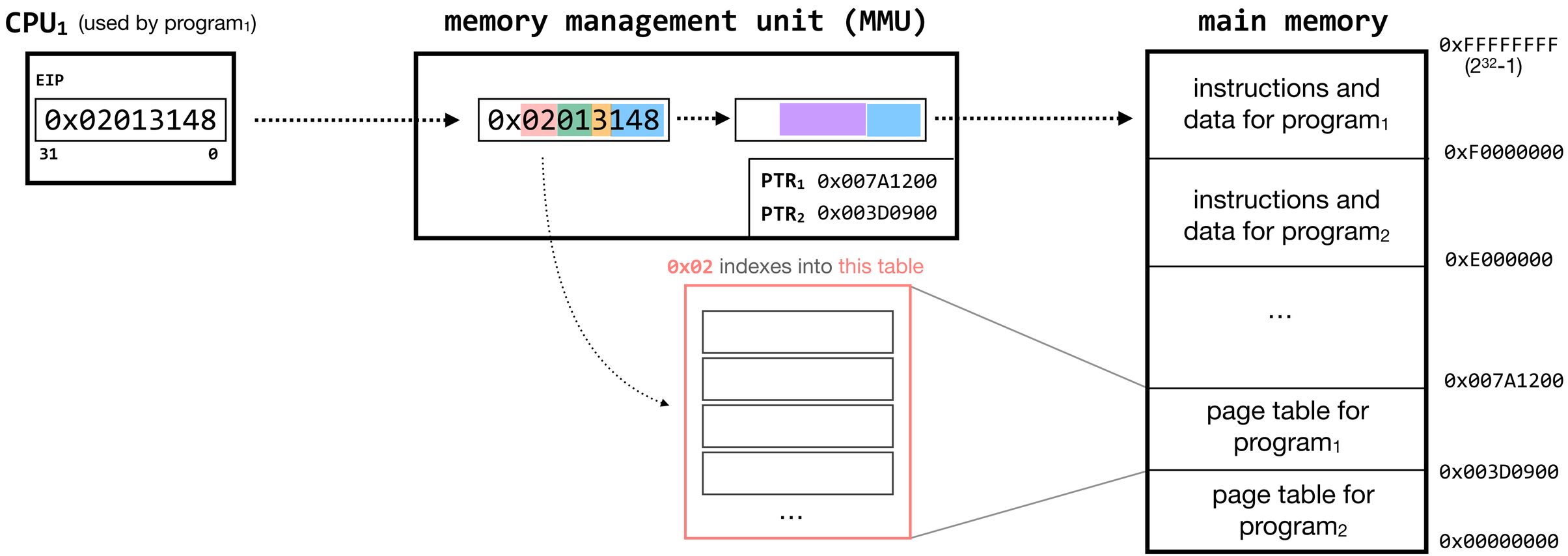

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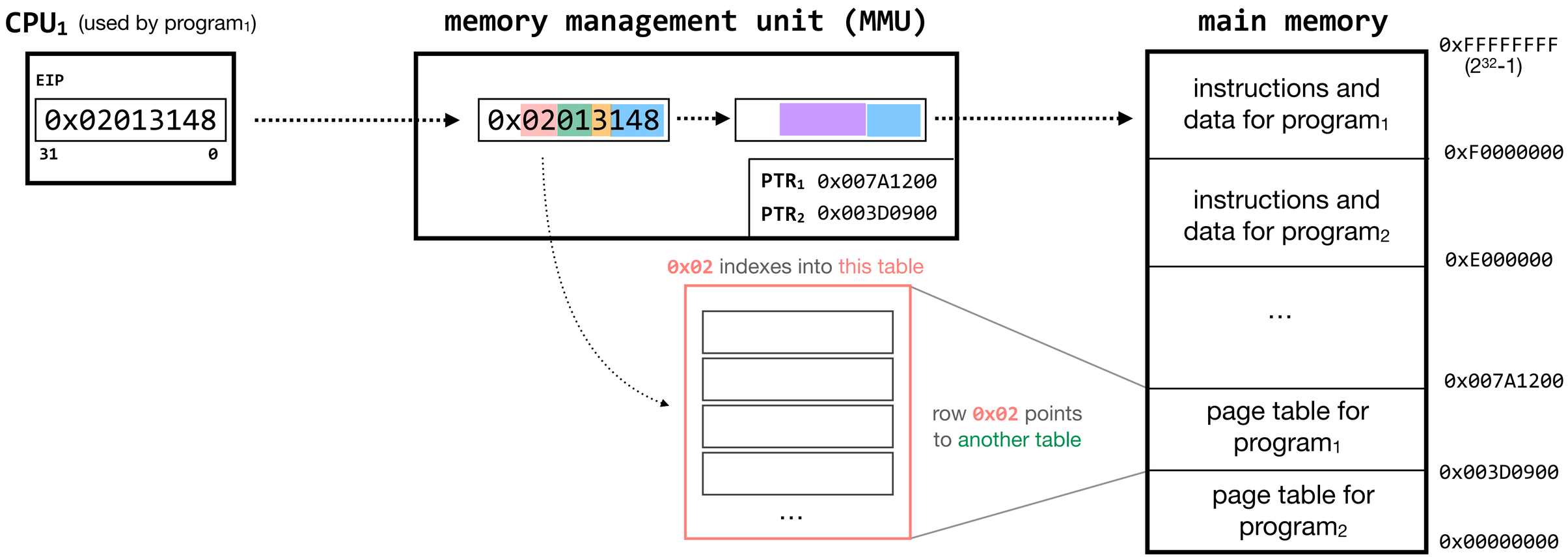

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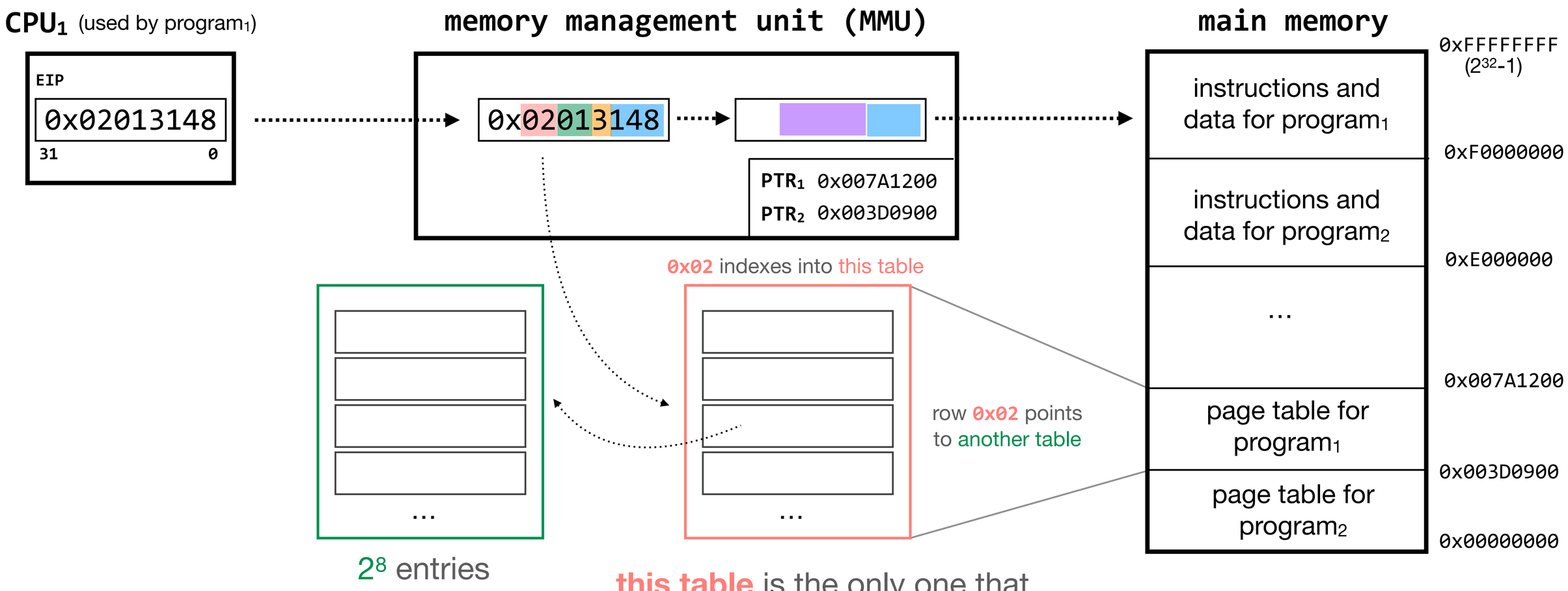

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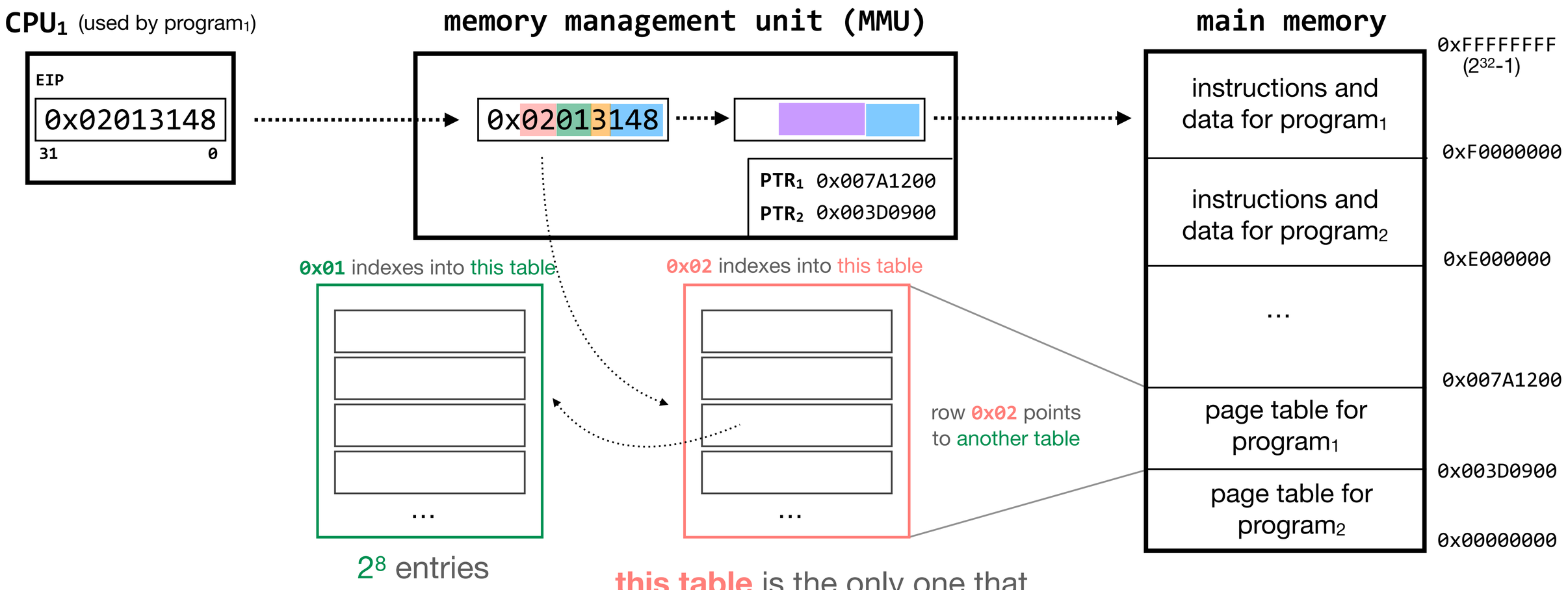

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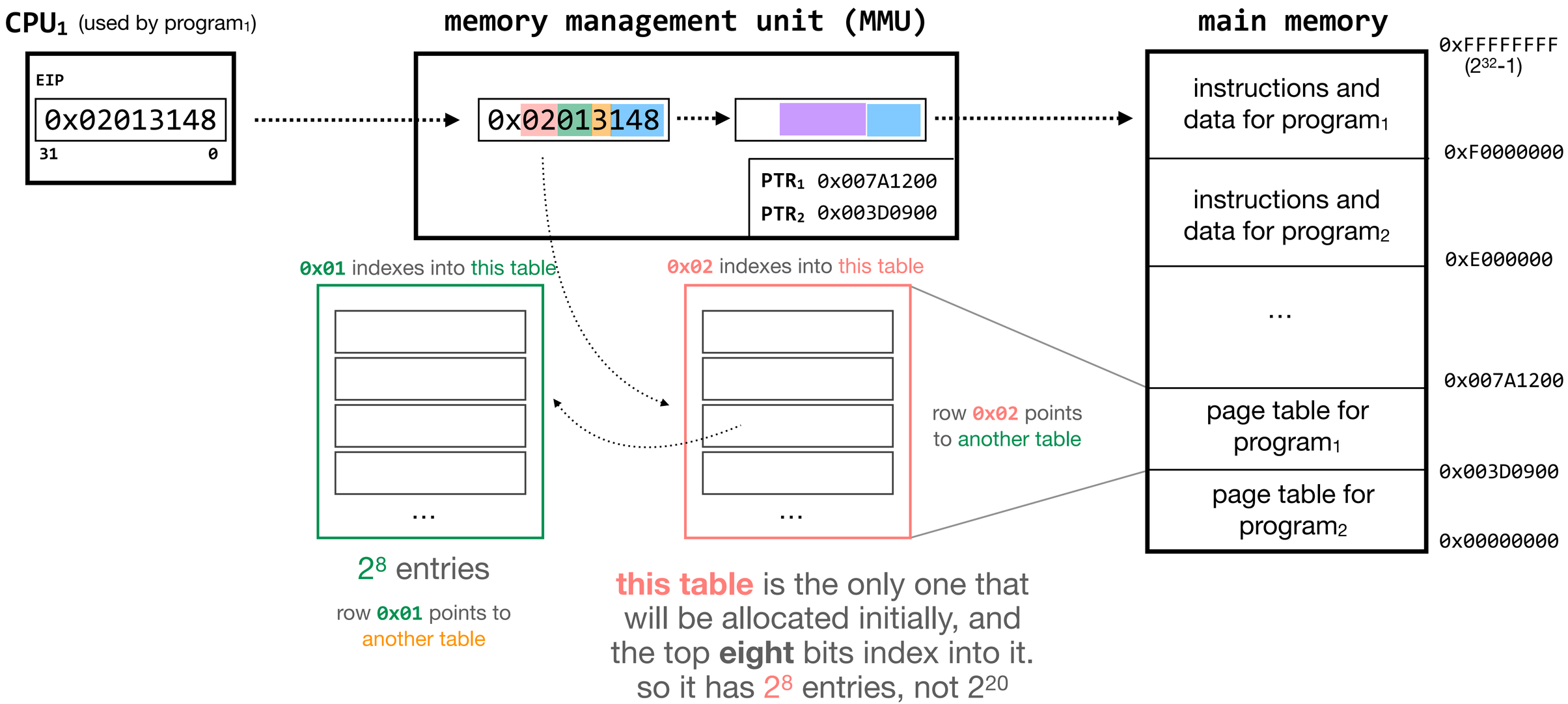

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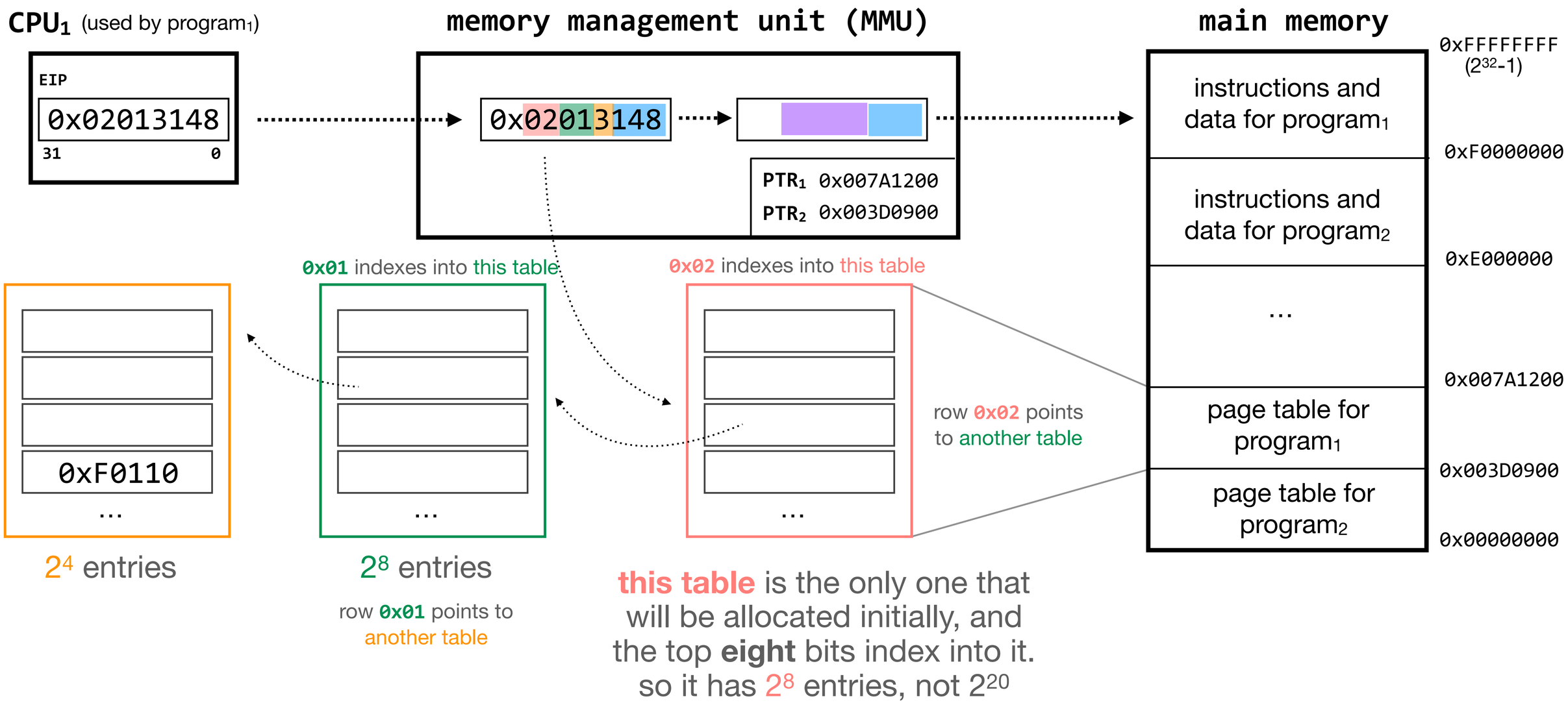

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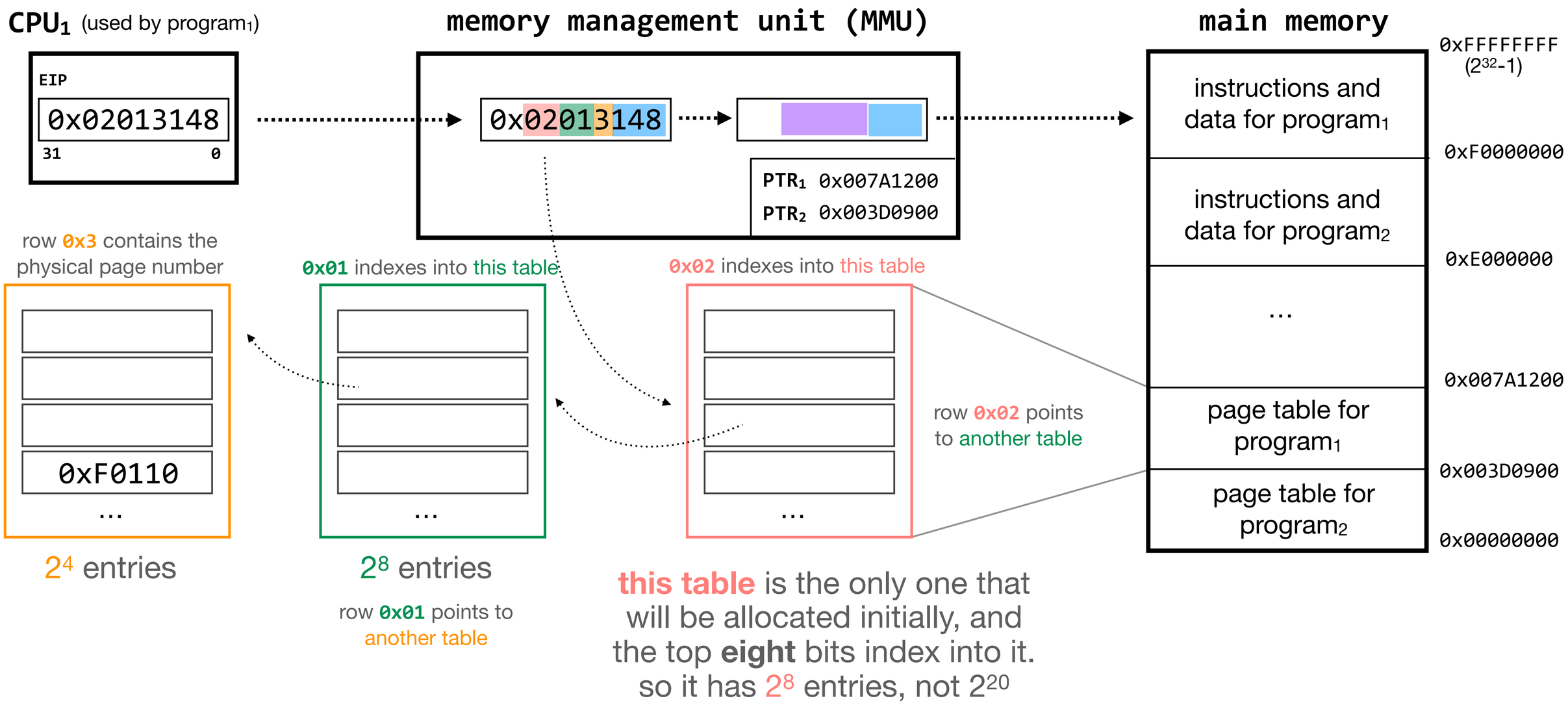

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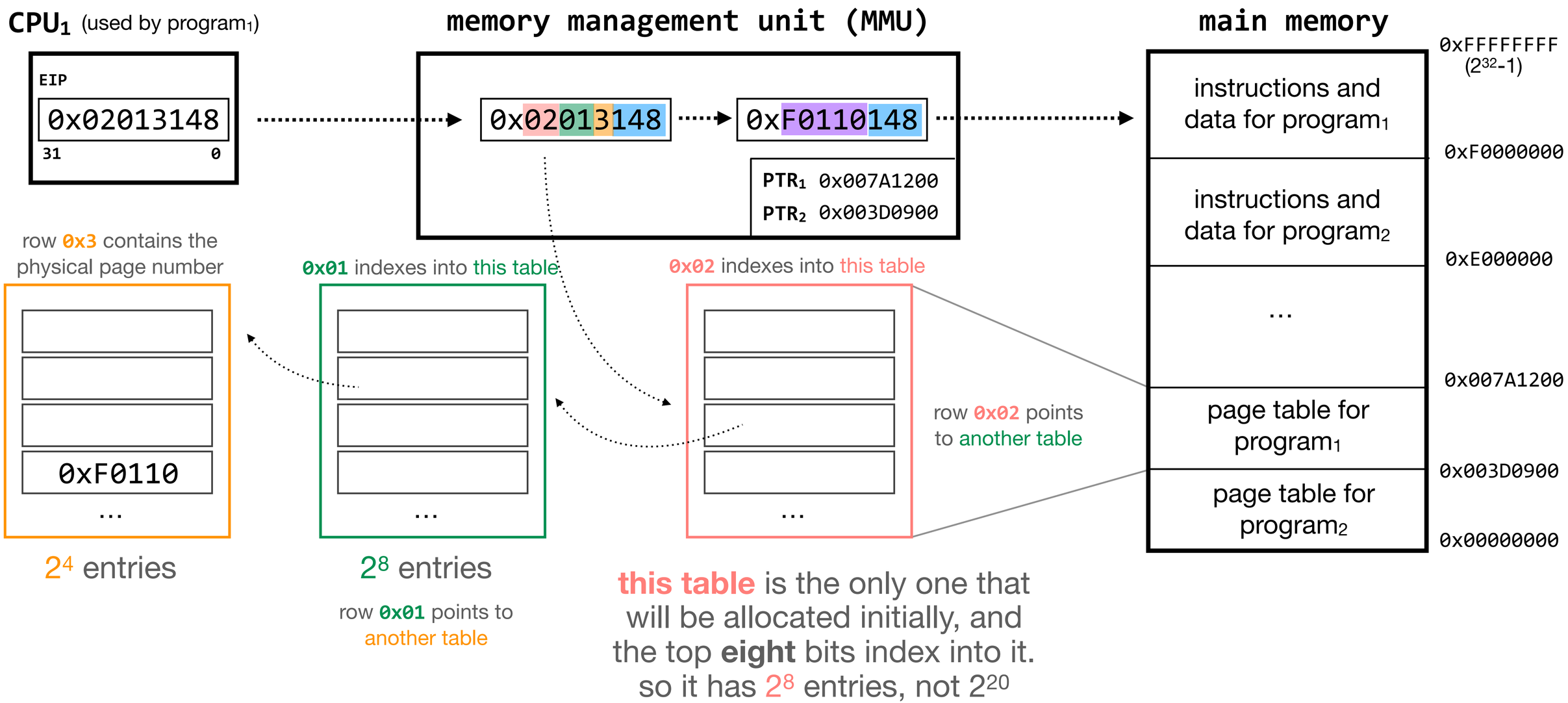

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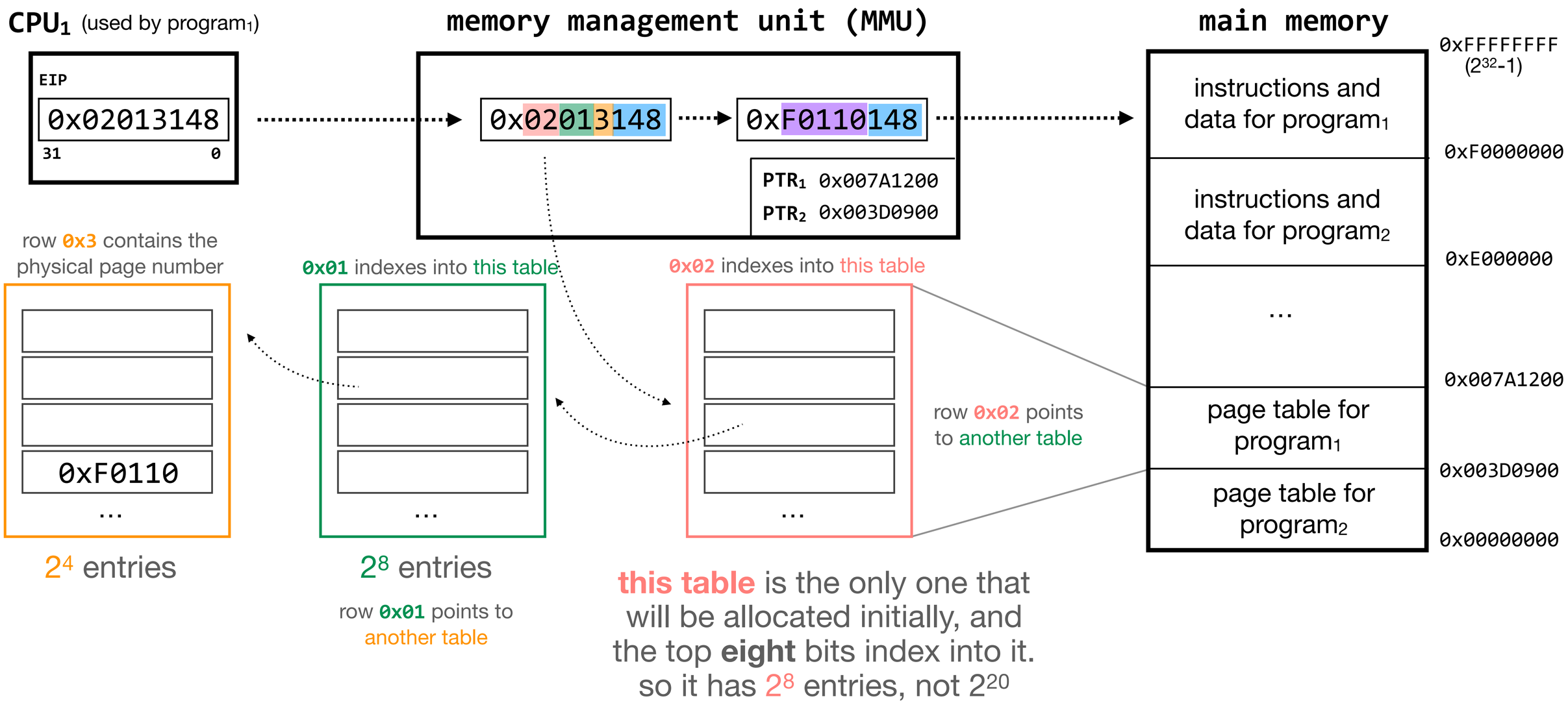

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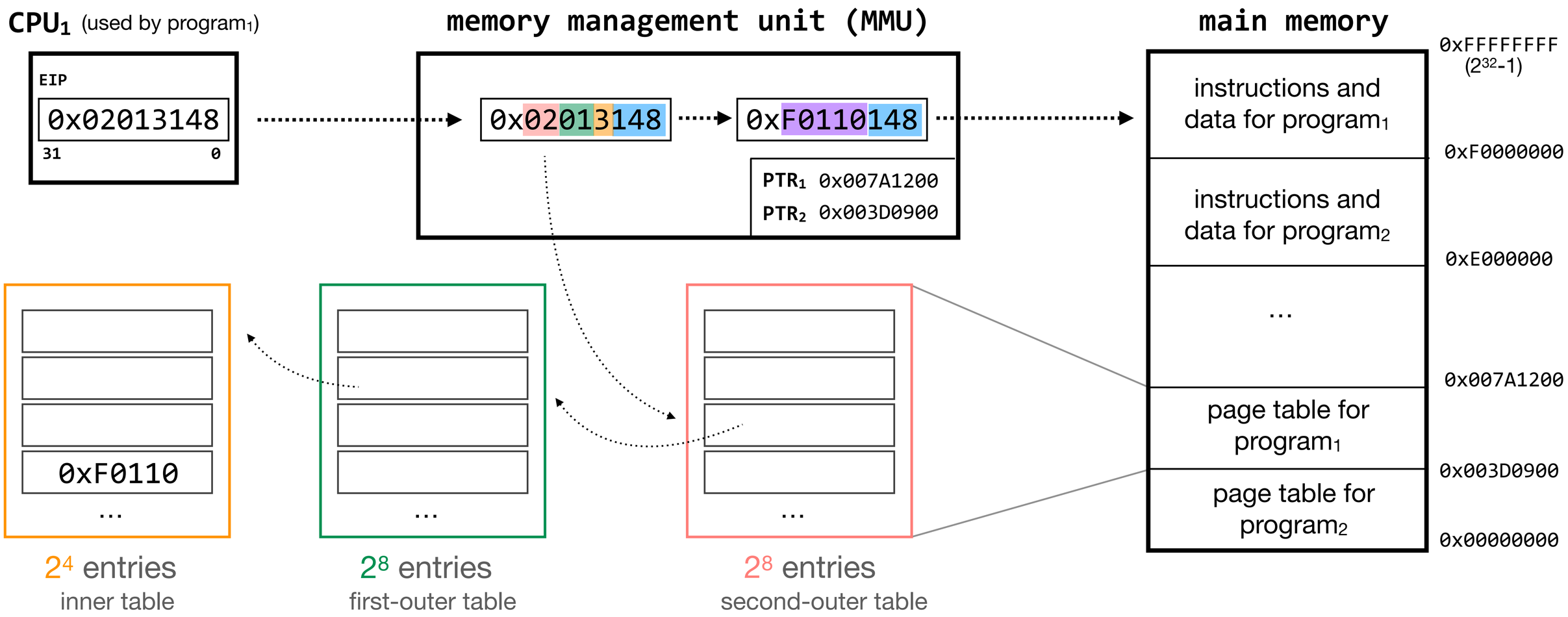

if the program never accesses a virtual memory address starting with 0x03 (say), no **first-outer table** will be allocated corresponding to row 0x03 in the **second-outer table**

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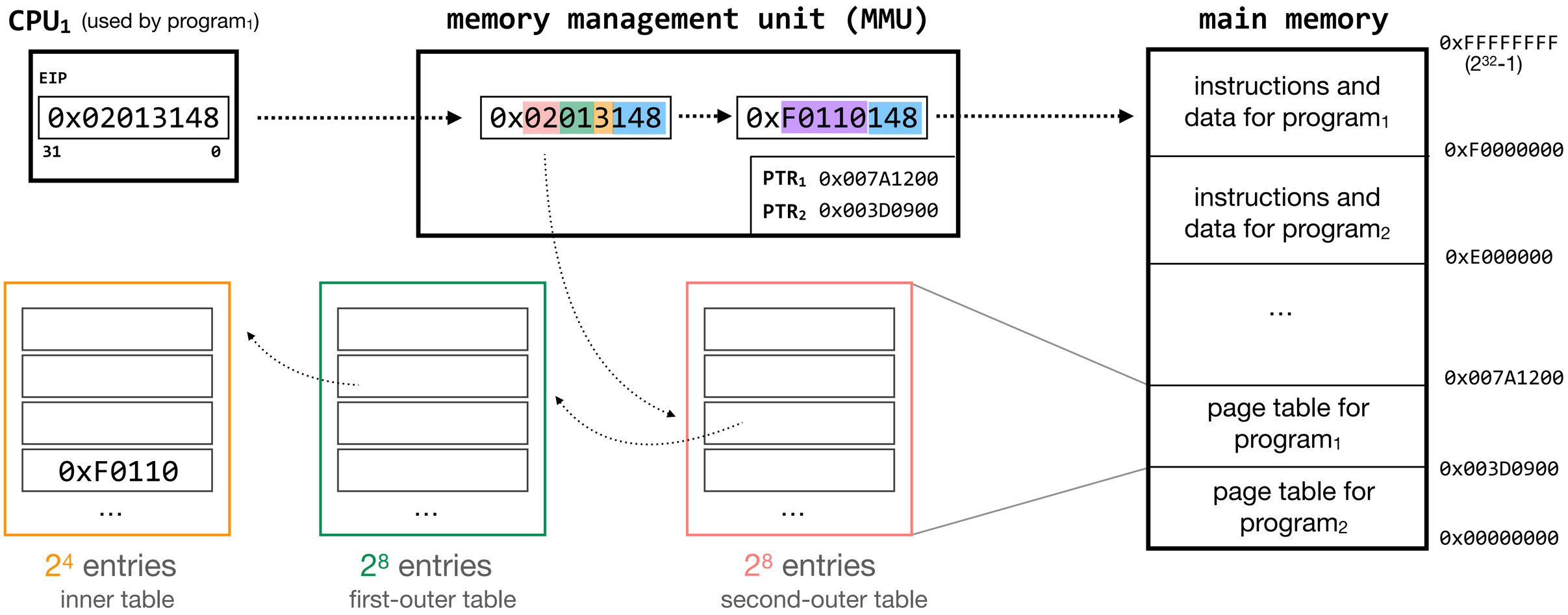
hierarchical (or “multilevel”) page tables potentially use less space, at the expense of more table look-ups and more exceptions (to allocate additional tables)



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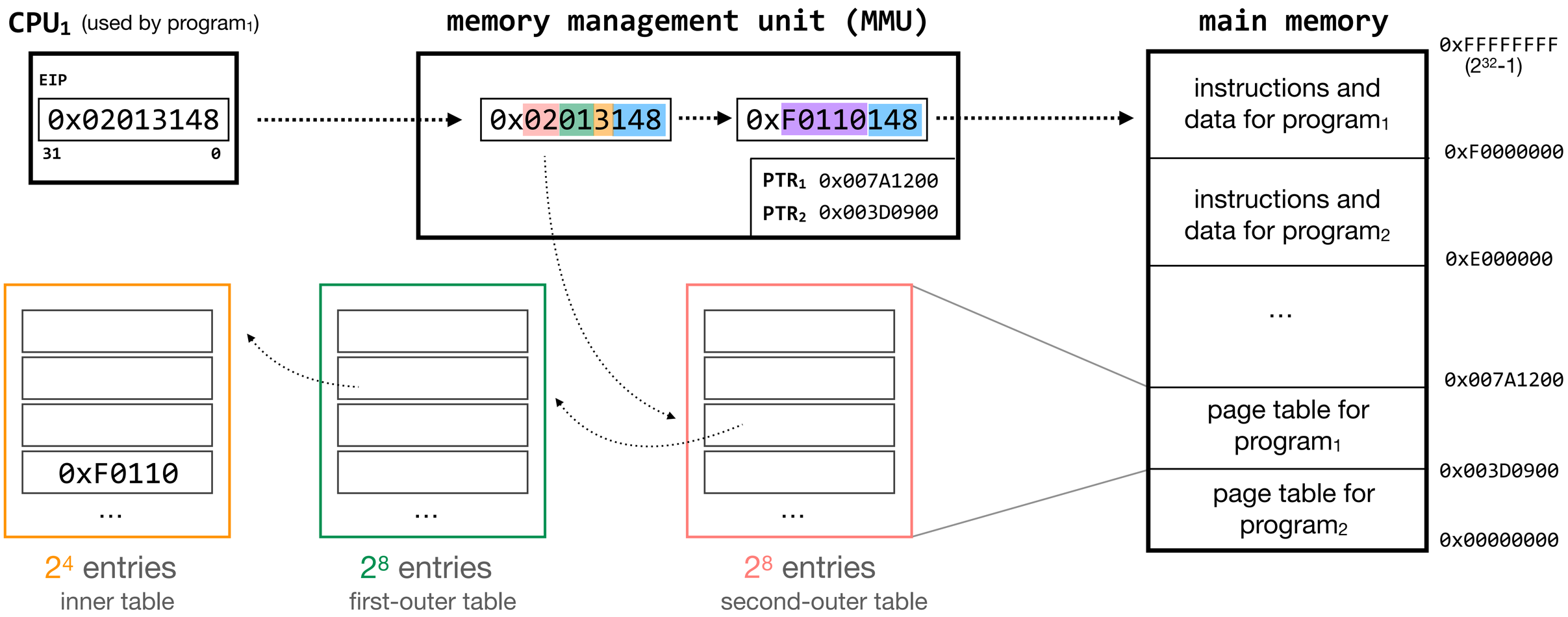
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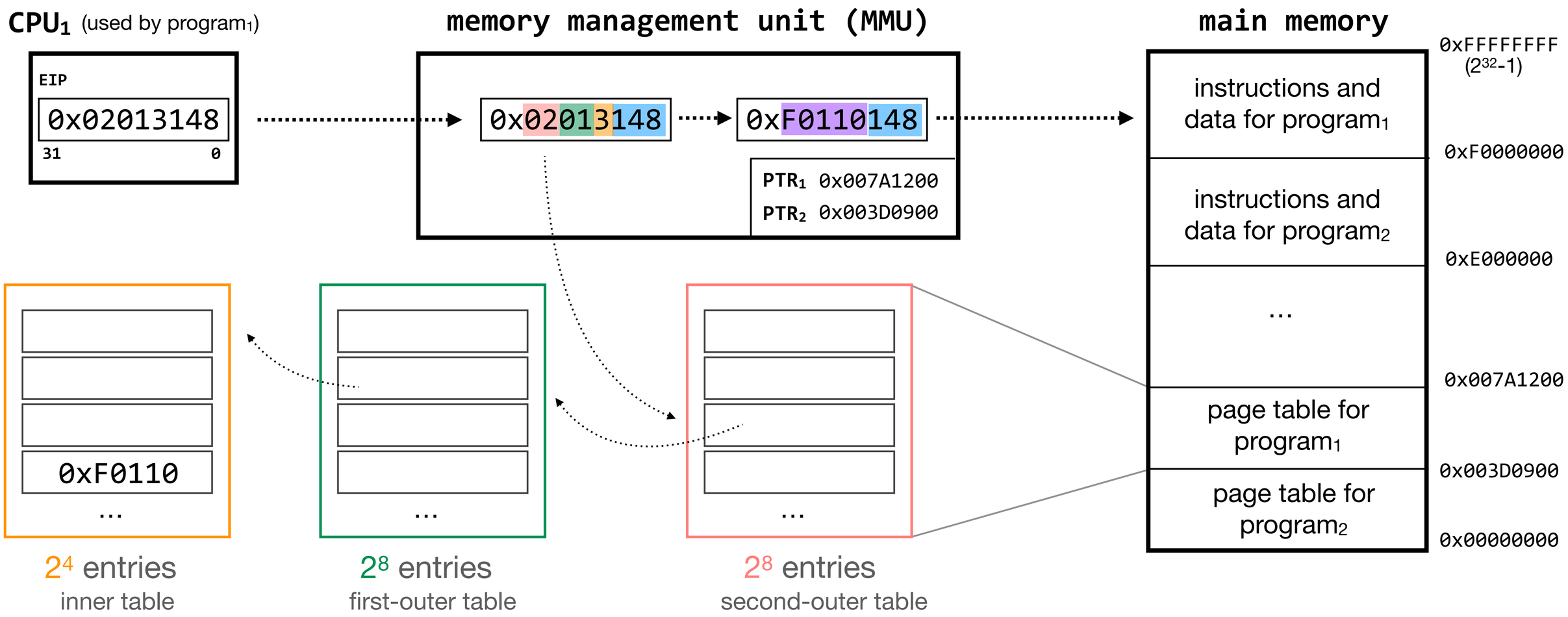
0xF0110148
PTR1 0x007A1200
PTR2 0x003D0900
main memory
0xFFFFFFFF
(2^32-1)
instructions and data for program1
0xF0000000
instructions and data for program2
0xE000000
...
0x007A1200
page table for program1
0x003D0900
page table for program2
0x00000000
0xF0110
...
...
...
2^4 entries
inner table
2^8 entries
first-outer table
2^8 entries
second-outer 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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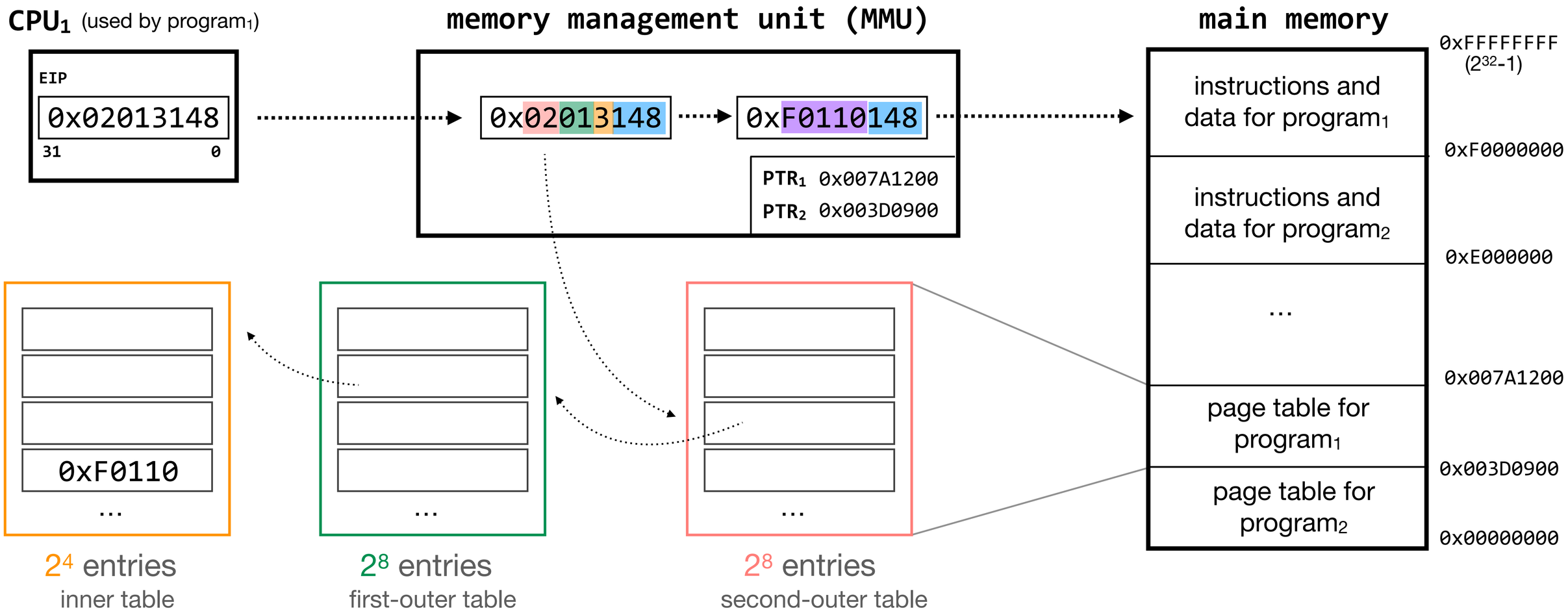

yes. caches are involved in a variety of places here, to (in theory) make common look-ups faster. you've also seen caching in the context of DNS, now.

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)

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)

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