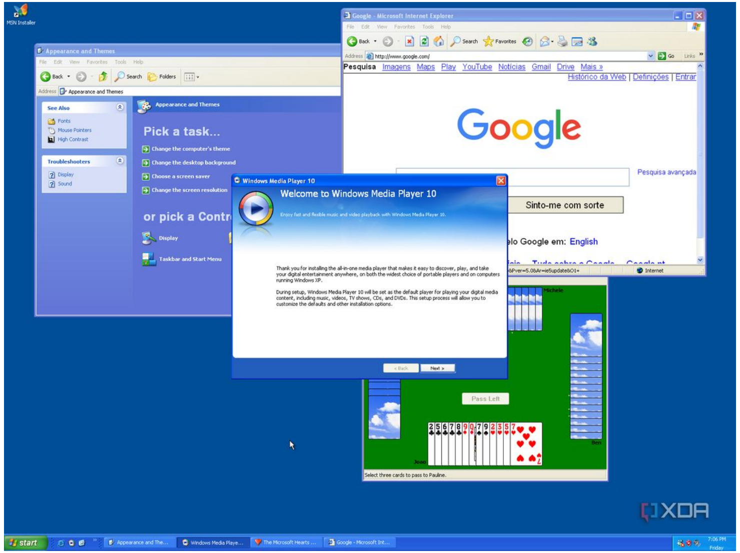


Lecture 33

Virtual Memory I

CS 61C, Fall 2024 @ UC Berkeley

Slides credit: Dan Garcia, Borivoje Nikolic, Lisa Yan, Peyrin Kao

Slides template credit: Josh Hug, Lisa Yan

For Today: Pretend Caches Don't Exist

Today's topic is **virtual memory**.

- It's easier to understand if we temporarily forget that caches exist.
- For today, imagine that there are no caches.
  All loads/stores directly access memory.

Next time, we'll see how caches interact with virtual memory.

My personal opinion: Virtual memory is very similar to caches, but trying to compare them immediately will confuse you even further.

I suggest trying to understand VM first, forgetting about caches. Then, compare them only after you're comfortable with VM.

For this reason, these slides will never mention caches until the end.

Running Multiple Programs

Lecture 33, CS 61C, Fall 2024

Our Memory Model So Far

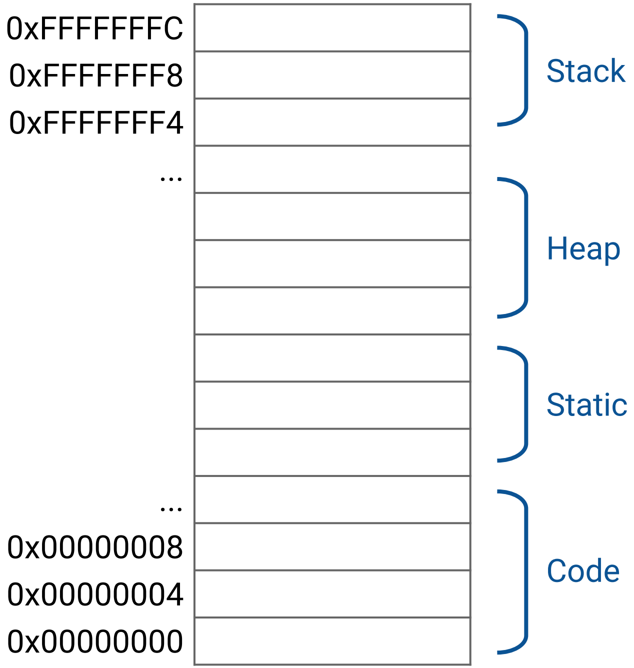
Our model so far: Each program has its own dedicated memory.

32-bit system: Array of 2^{32} bytes, addressed from 0x00000000 to 0xFFFFFFFF.

classify.s

```
add s0 t5 t6
sw s0 0(a0)
lw s1 4(a1)
...
```

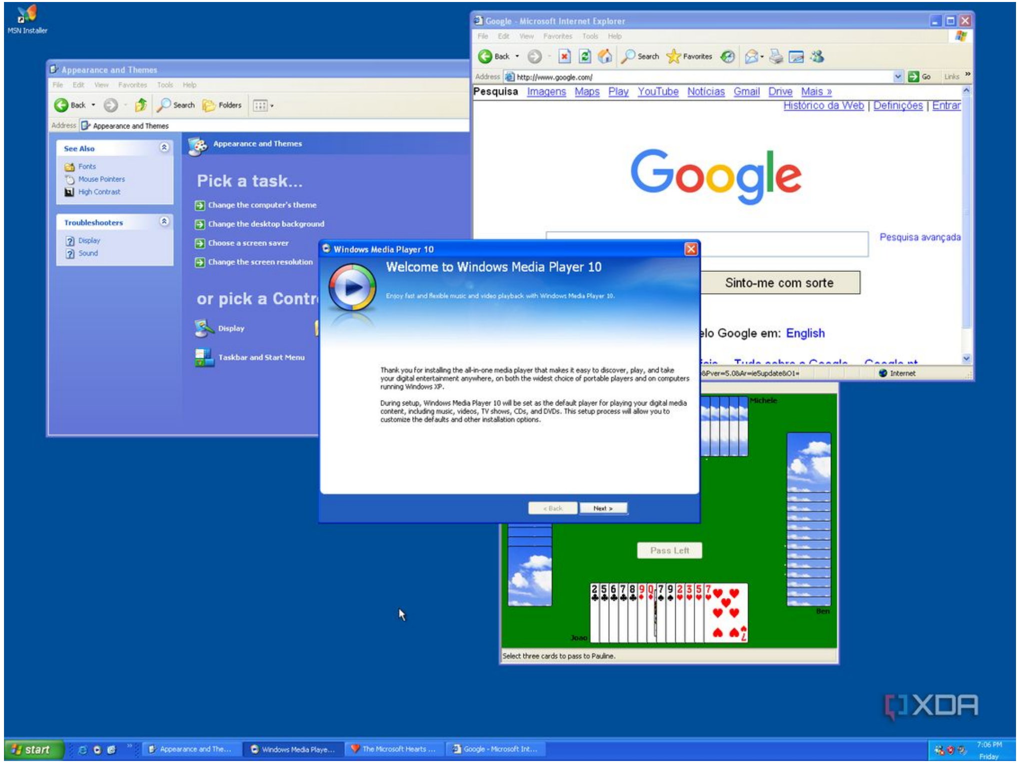
When your program loads or stores, it accesses memory.



A Real Computer

When I run Venus, it only executes one program, and then stops.

Our computer runs many programs simultaneously!

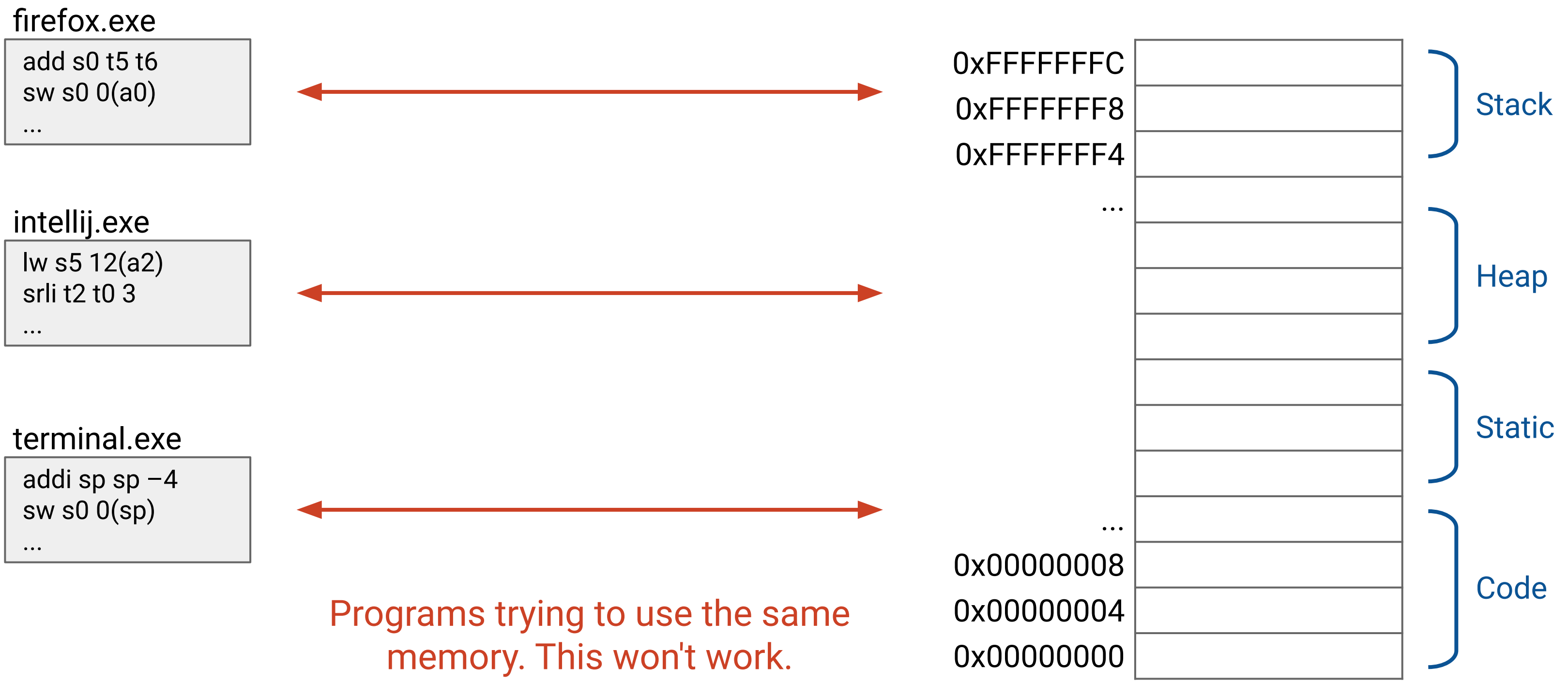


I miss Windows XP.

Today's Goal: Virtual Memory

If multiple programs try to access the same memory, we'd have problems.

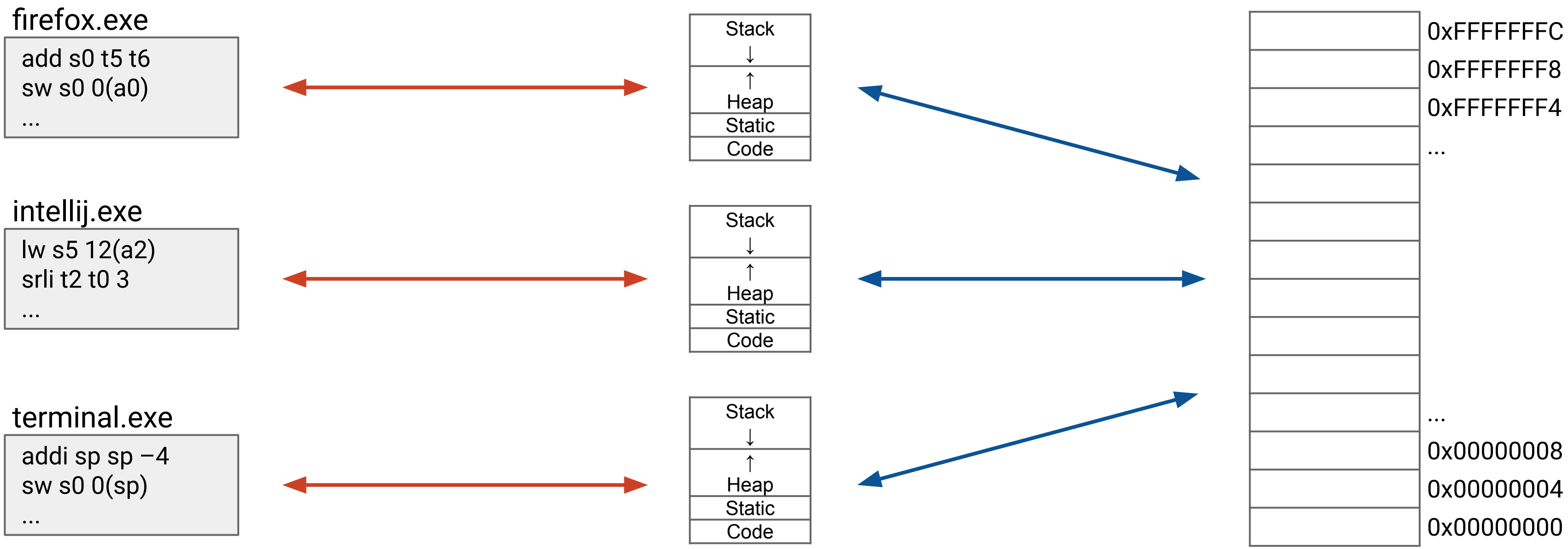
What if firefox.exe and terminal.exe both want to store data at the same address?



Today's Goal: Virtual Memory

Today's goal: Give each process the *illusion* of its own dedicated memory...

...even though everyone is sharing the same memory on the computer.



Programs think they're accessing their own dedicated memory...

...but they're really sharing the same address space.

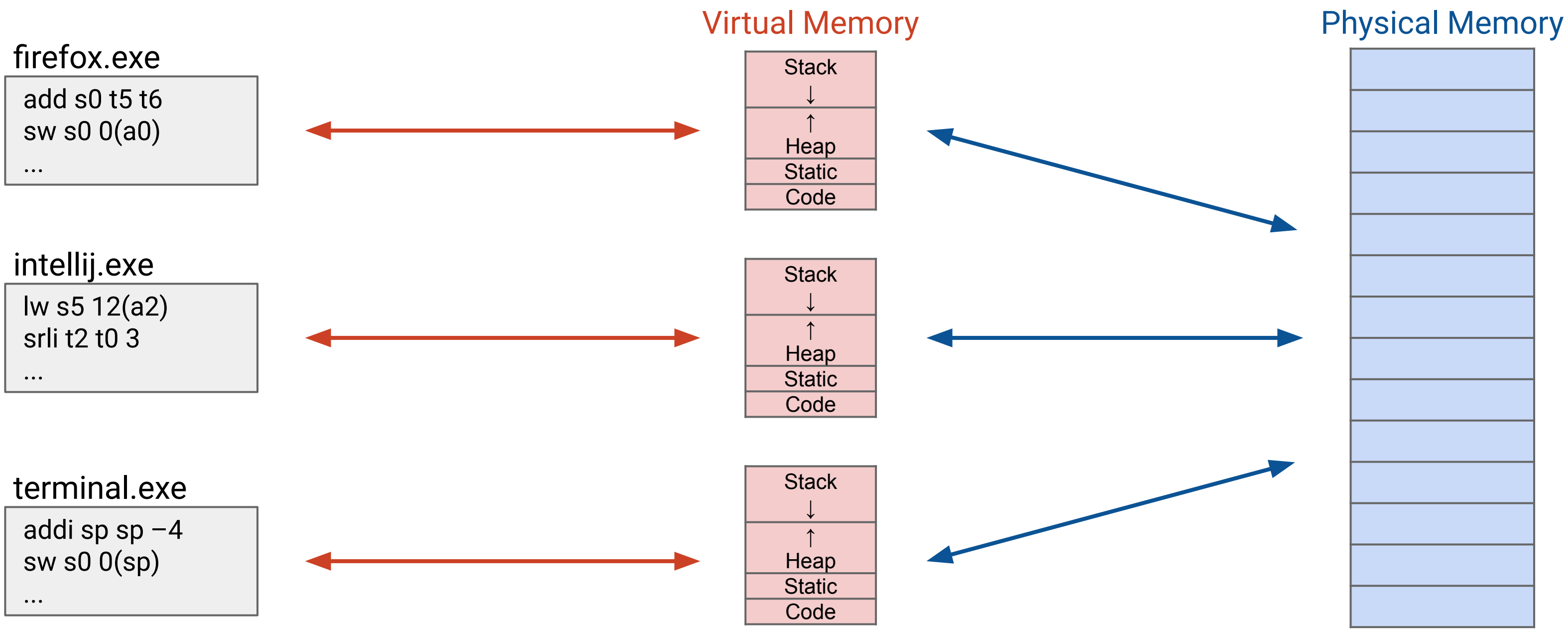
Virtual Addresses and Physical Addresses

Lecture 33, CS 61C, Fall 2024

Virtual and Physical Addresses

Virtual addresses: The addresses the program is thinking about.

Physical addresses: The addresses that actually map to physical memory locations.



Programs think about *virtual addresses.*

The OS translates to *physical addresses.*

Virtual and Physical Addresses

There are now two kinds of memory addresses:

Virtual addresses: The addresses the program is thinking about.

- Each program has its own dedicated virtual address space.

Physical addresses: The addresses that actually map to physical memory locations.

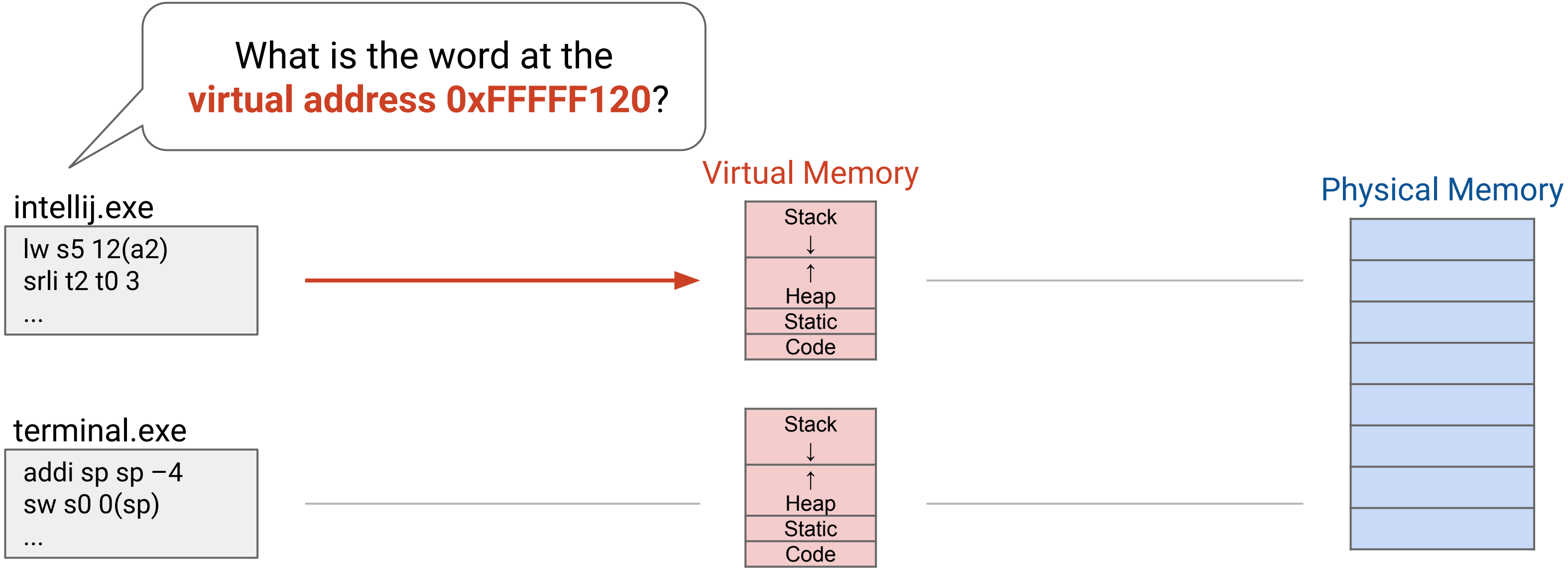
- Everyone shares the same physical address space.

The *memory manager* in the OS translates virtual addresses to physical addresses.

- Programs don't need to think about physical addresses!

Virtual Address Translation (Conceptual)

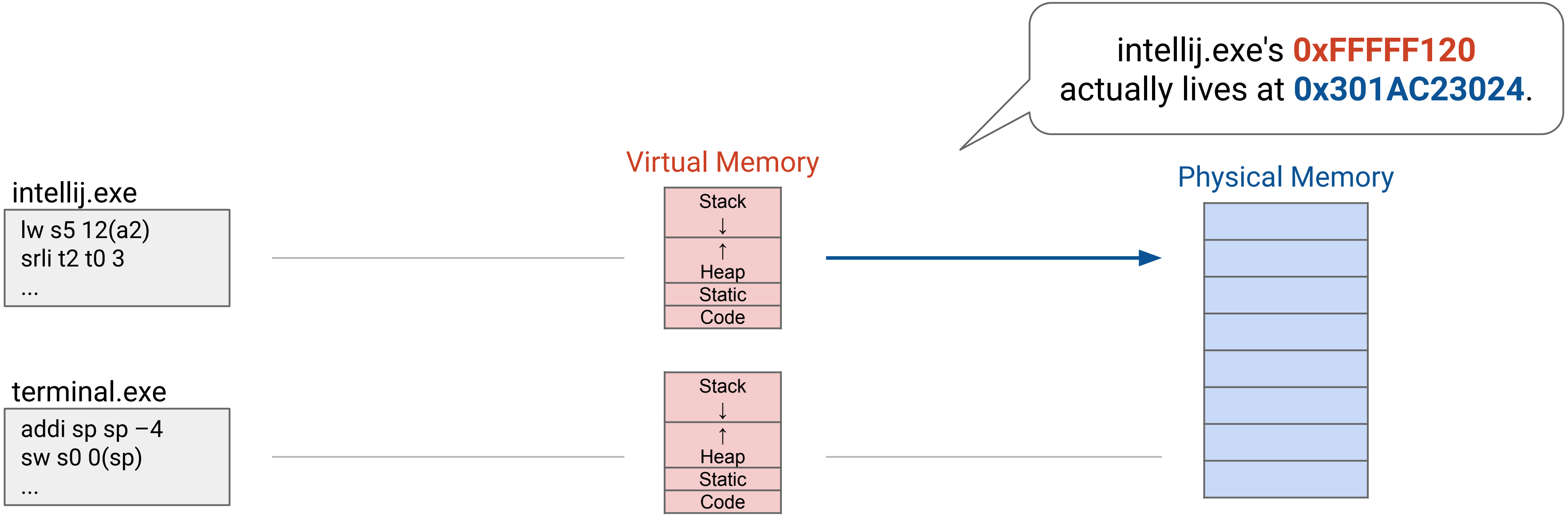
Step 1: The program wants to read/write from a **virtual address**.



Virtual Address Translation (Conceptual)

Steps 2–4: OS translates the **virtual address** to its corresponding **physical address**.

The OS can now fetch the data at that **physical address**.



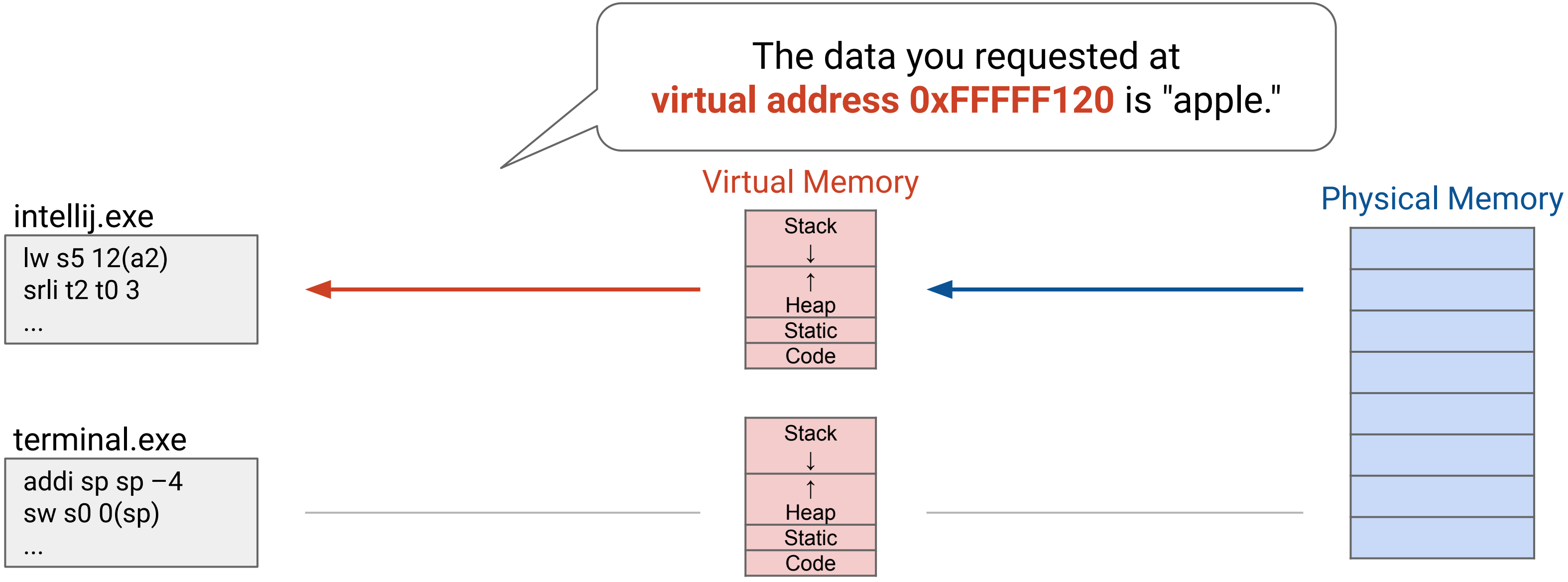
10-digit = 40-bit physical address because we assume computer has 2^{40} bits of physical memory. More on this later.

We will see why it's 3 steps (Steps 2–4) later.

Virtual Address Translation (Conceptual)

Step 5: The OS returns that data to the program.

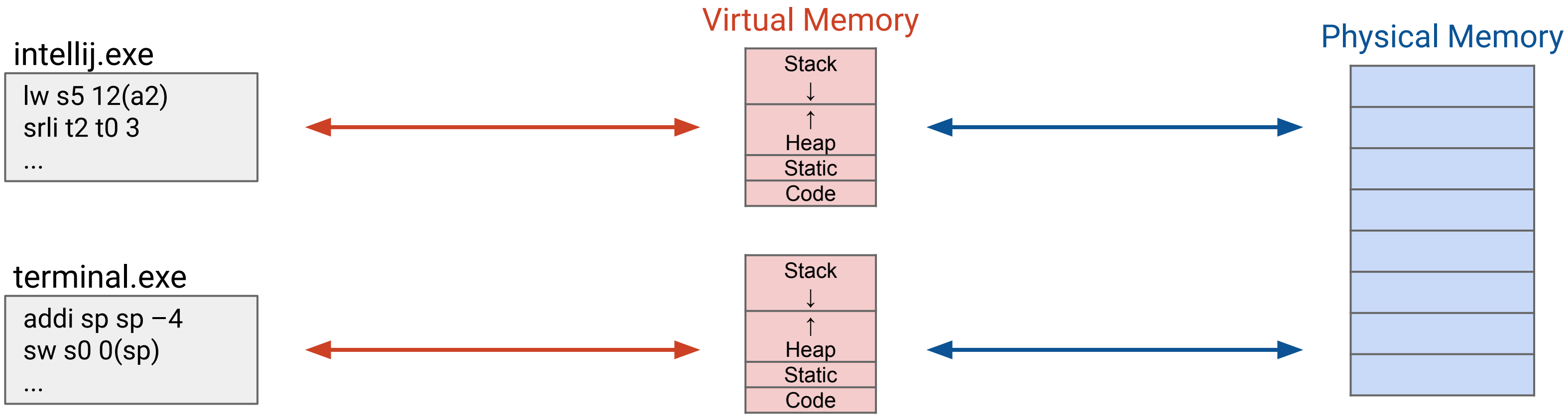
The program never thinks about physical addresses!



Programs Using the Same Virtual Address

Notice: Two programs could use the same virtual address.

- intellij.exe could store "apple" at virtual address **0xFFFFF120**.
- terminal.exe could store "potato" at virtual address **0xFFFFF120**.
- The OS stores "apple" and "potato" at two different physical addresses.



Page Tables

Lecture 33, CS 61C, Fall 2024

Mapping Virtual to Physical Addresses (Naive)

How do we remember the mapping of virtual addresses to physical addresses?

- Idea: Let's use a table!
- We need **one table for each program**.
  Because each program has its own virtual address space.

Naive approach: Map every virtual address to a corresponding physical address.

- Problem: These tables will be huge.

firefox.exe's Table (Naive)	
Virtual Address	**Physical Address**
...	...
0x00000400	0x60C25E65CE
0x00000401	0x1F96EC70D9
0x00000402	0xEC70DB7F19
0x00000403	0x69977241BB
...	...

intellij.exe's Table (Naive)	
Virtual Address	**Physical Address**
...	...
0x00000400	0xCD178731DD
0x00000401	0x128E05D21C
0x00000402	0x0C709FD626
0x00000403	0x937D13CF3E
...	...

Mapping Virtual to Physical Addresses with Pages

Better approach: Group all memory (virtual and physical) into **pages**.

- Example: Each page could be 4 KiB = 0x1000 addresses.

The table now maps **virtual pages** to **physical pages**.

- **Virtual page:** A chunk of memory in the virtual address space.
- **Physical page:** A chunk of memory in the physical address space.

firefox.exe's Table	
Virtual Page	**Physical Page**
...	...
0x**00004**000 to 0x00004FFF	0x**60C25E6**000 to 0x60C25E6FFF
0x**00005**000 to 0x00005FFF	0x**1F96EC7**000 to 0x1F96EC7FFF
0x**00006**000 to 0x00006FFF	0x**EC70DB7**000 to 0xEC70DB7FFF
0x**00007**000 to 0x00007FFF	0x**6997724**000 to 0x6997724FFF
...	...

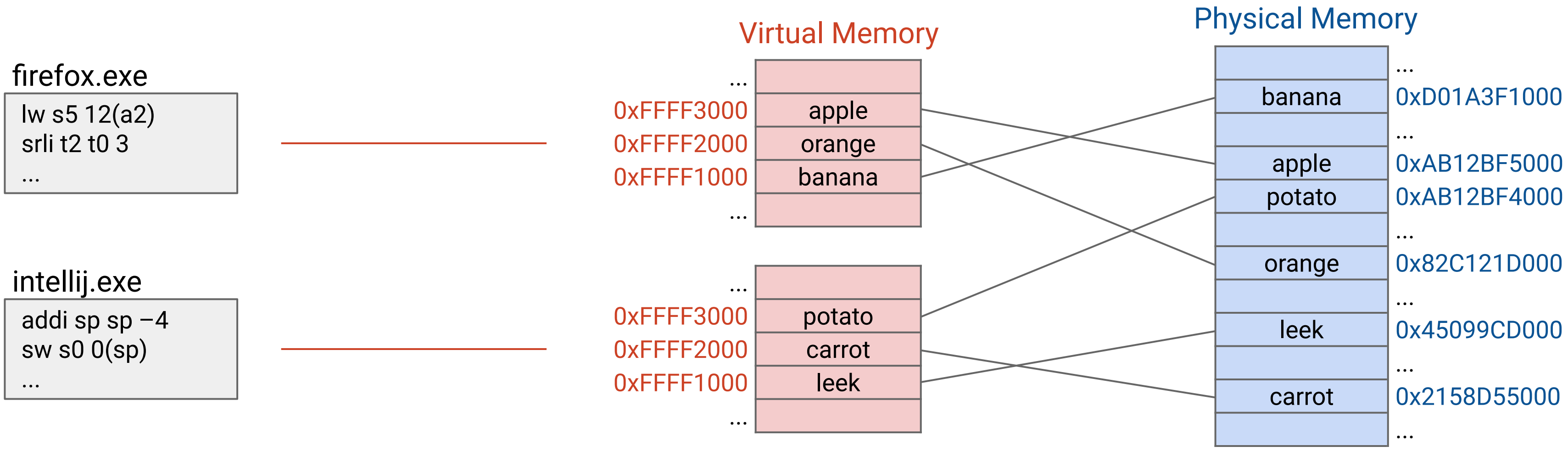
intellij.exe would have its own table (not pictured here).

Mapping Virtual to Physical Addresses with Pages

Same address translation as before.
We just grouped data into *pages*.

Note: Page size is the same in both physical and virtual worlds.

firefox.exe's Table	
Virtual Page	**Physical Page**
...	...
0x**FFFF1**000 to 0x00004FFF	0x**D01A3F1**000 to 0xD01A3FFFF
0x**FFFF2**000 to 0x00005FFF	0x**82C121D**000 to 0x82C121DFFF
0x**FFFF3**000 to 0x00006FFF	0x**AB12BF5**000 to 0xAB12BF5FFF
...	...



Each English word here represents arbitrary data in a fixed-size page, e.g. imagine "potato" and "leek" are both 0x1000 bytes.

Storing Page Tables – Page Numbers

The table maps **virtual pages** to **physical pages**.

firefox.exe's Table	
Virtual Page	**Physical Page**
...	...
0x**00004**000 to 0x00004FFF	0x**60C25E6**000 to 0x60C25E6FFF
0x**00005**000 to 0x00005FFF	0x**1F96EC7**000 to 0x1F96EC7FFF
0x**00006**000 to 0x00006FFF	0x**EC70DB7**000 to 0xEC70DB7FFF
0x**00007**000 to 0x00007FFF	0x**6997724**000 to 0x6997724FFF
...	...

We don't really need to store all this data.

- Instead of "0x00004000 to 0x00004FFF," just store "0x00004."
- Instead of "0x60C25E6000 to 0x60C25E6FFF," just store "0x60C25E6."
- We call these top bits the **page number**.

Storing Page Tables – Page Numbers

The table maps **virtual pages** to **physical pages**.

firefox.exe's Table	
Virtual Page Number (VPN)	**Physical Page Number (PPN)**
...	...
0x**00004**~~000 to 0x00004FFF~~	0x**60C25E6**~~000 to 0x60C25E6FFF~~
0x**00005**~~000 to 0x00005FFF~~	0x**1F96EC7**~~000 to 0x1F96EC7FFF~~
0x**00006**~~000 to 0x00006FFF~~	0x**EC70DB7**~~000 to 0xEC70DB7FFF~~
0x**00007**~~000 to 0x00007FFF~~	0x**6997724**~~000 to 0x6997724FFF~~
...	...

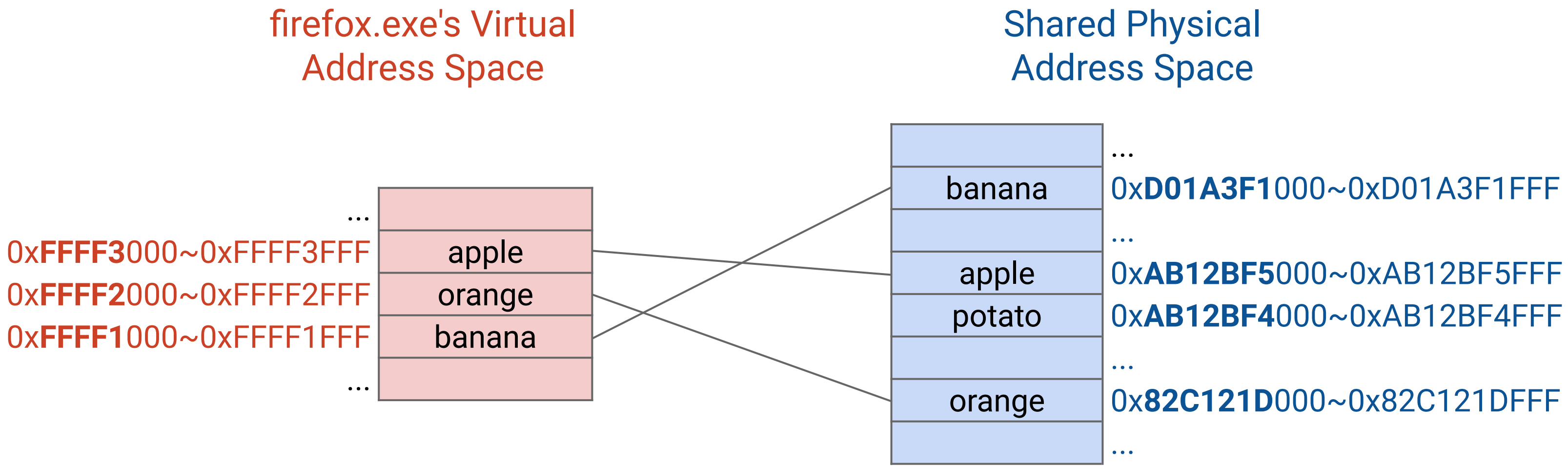
We don't really need to store all this data.

- Instead of "0x00004000 to 0x00004FFF," just store "0x00004."
- Instead of "0x60C25E6000 to 0x60C25E6FFF," just store "0x60C25E6."
- We call these top bits the **page number**.

Storing Page Tables – Page Numbers

We can interpret the top bits of an address as a **page number**.

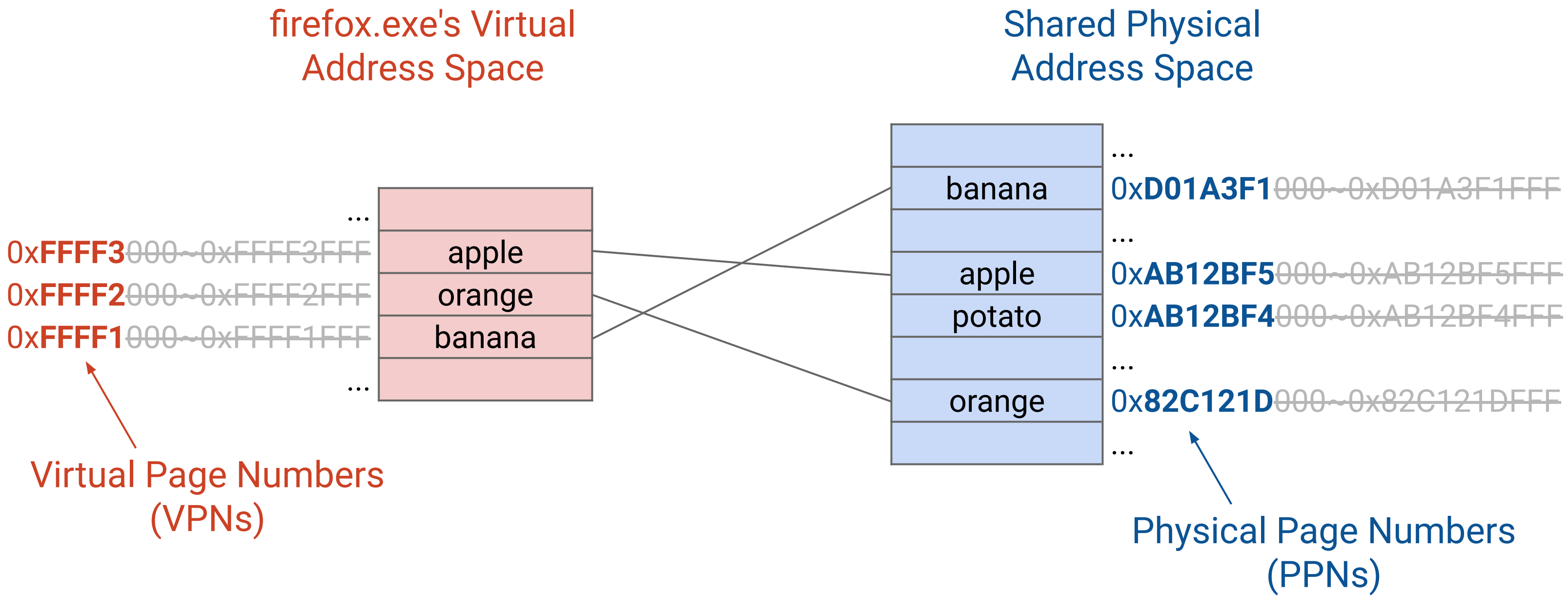
- Virtual page 0x**00004** has addresses 0x**00004**000 to 0x**00004**FFF.
- Physical page 0x**60C25E6** has addresses 0x**60C25E6**000 to 0x**60C25E6**FFF.



Storing Page Tables – Page Numbers

We can interpret the top bits of an address as a **page number**.

- Virtual page 0x**00004** has addresses 0x**00004**000 to 0x**00004**FFF.
- Physical page 0x**60C25E6** has addresses 0x**60C25E6**000 to 0x**60C25E6**FFF.



Address Translation with Page Tables

The thing we just built is called the **page table**.

- Maps virtual page numbers (VPNs) to physical page numbers (PPNs).
- Remember: Every program needs its own page table.
- Notice: Page tables do not store actual program data! They only store addresses.

firefox.exe's Page Table	
Virtual Page Number (VPN)	**Physical Page Number (PPN)**
...	...
0x00004	0x60C25E6
0x00005	0x1F96EC7
0x00006	0xEC70DB7
0x00007	0x6997724
...	...

Address Translation with Page Tables

Performing address translation with a page table:

Step 2: Split virtual address into VPN and offset.

Step 3: Translate VPN to PPN using table. ← We call this a *page table walk*.

Step 4: Concatenate PPN and offset.

firefox.exe's Page Table	
Virtual Page Number (VPN)	**Physical Page Number (PPN)**
...	...
0x00004	0x60C25E6
0x00005	0x1F96EC7
0x00006	0xEC70DB7
0x00007	0x6997724
...	...

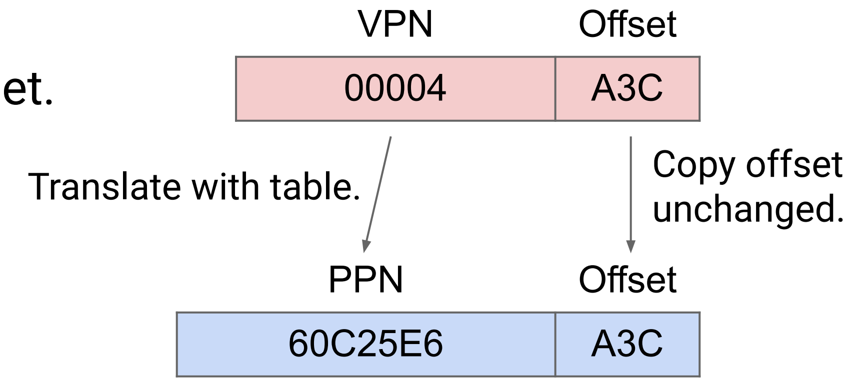
Address Translation with Page Tables

Example: Virtual address **0x00004A3C** translates to physical address **0x60C25E6A3C**.

Step 2: Split virtual address into VPN and offset.

Step 3: Translate VPN to PPN using table.

Step 4: Concatenate PPN and offset.



firefox.exe's Page Table	
Virtual Page Number (VPN)	**Physical Page Number (PPN)**
...	...
0x00004	0x60C25E6
0x00005	0x1F96EC7
0x00006	0xEC70DB7
0x00007	0x6997724
...	...

Storing Page Tables – VPN as Index

Notice: The VPN column just says 0, 1, 2, 3, 4, 5, etc.

- Optimization: There's no need to store the VPN column.

The page table can be stored as an *array* of PPNs.

- The VPN can be used to *index* into the array to find the corresponding VPN.
- Example: To translate VPN 0x00005, get the 5th PPN in the table.
- Example: To translate VPN 0x721CD, get the 0x721CD'th PPN in the table.

firefox.exe's Page Table	
Virtual Page Number (VPN)	**Physical Page Number (PPN)**
...	...
0x00004	0x60C25E6
0x00005	0x1F96EC7
0x00006	0xEC70DB7
...	...

firefox.exe's Page Table (Optimized)
Physical Page Number (PPN)
...
0x60C25E6
0x1F96EC7
0xEC70DB7
...

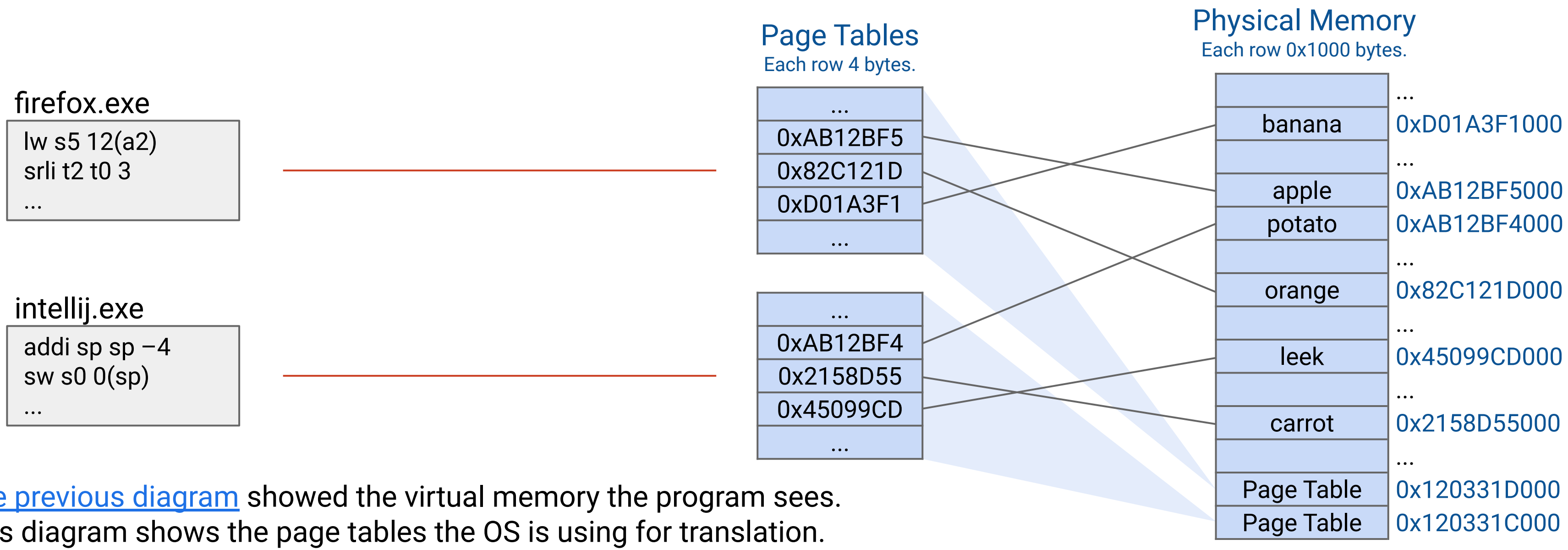
The slides will sometimes show unoptimized page tables for clarity.

Page Tables Live in Memory

Just like any other data, **page tables live in physical memory**.

This means that every load/store requires *two* memory accesses:

- First, access the page table to learn the physical address.
- Then, access the actual data at that physical address.



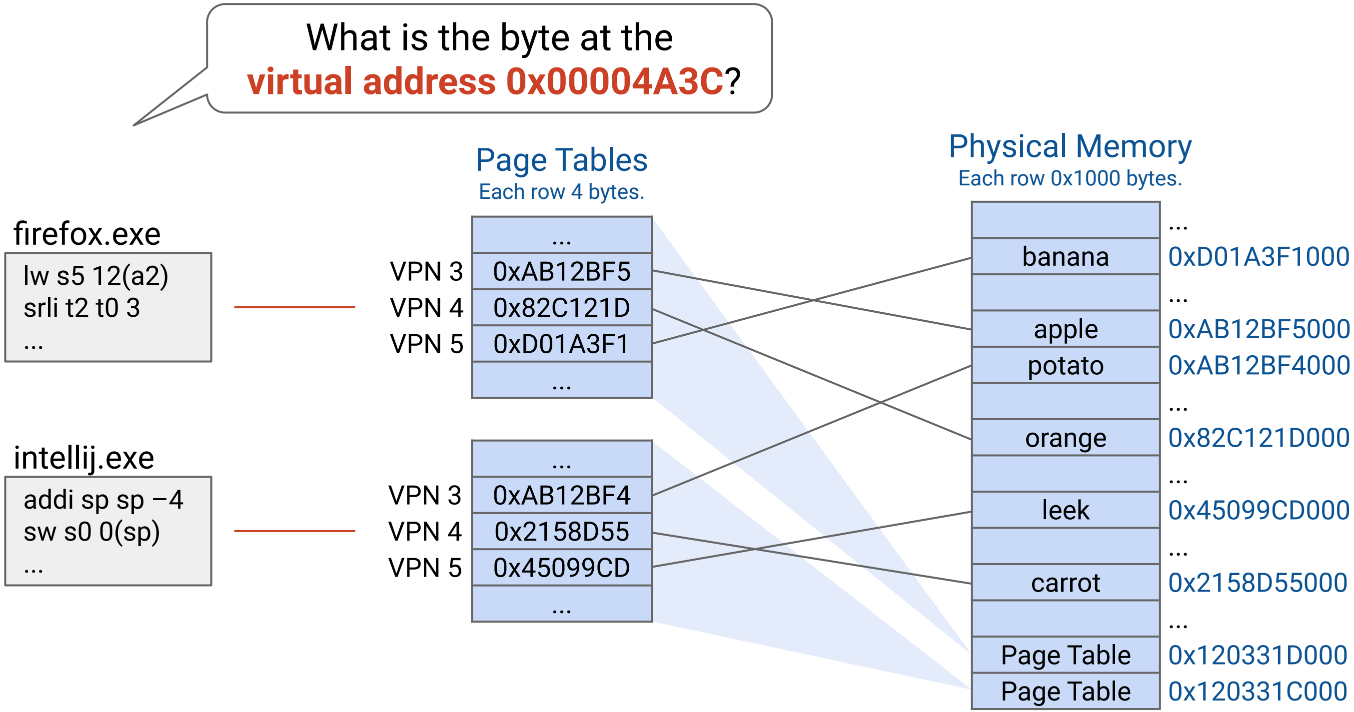
The previous diagram showed the virtual memory the program sees.
This diagram shows the page tables the OS is using for translation.

Memory Access Example

Lecture 33, CS 61C, Fall 2024

Memory Access Example

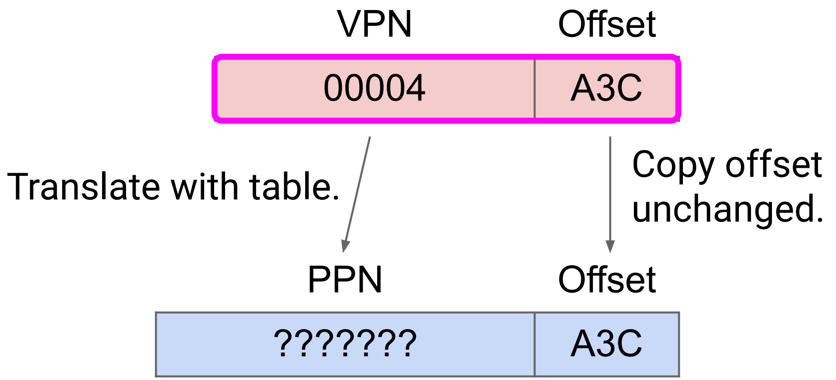
Step 1: The program wants to access memory at a given virtual address.

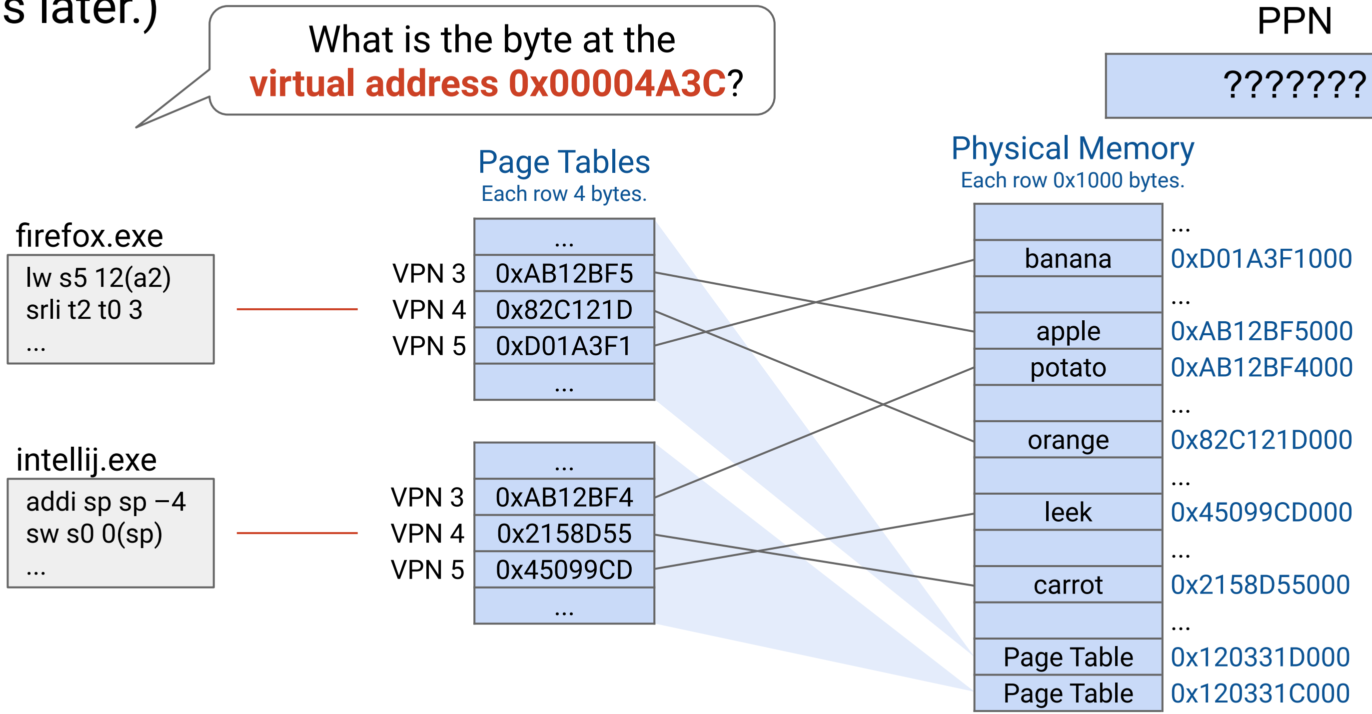


Memory Access Example

Step 2: Extract VPN and offset.

Use parameters to decide number of VPN bits and number of offset bits. (More on this later.)



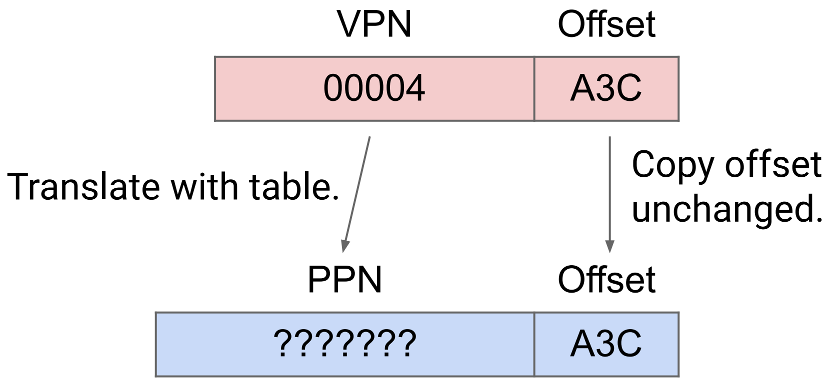


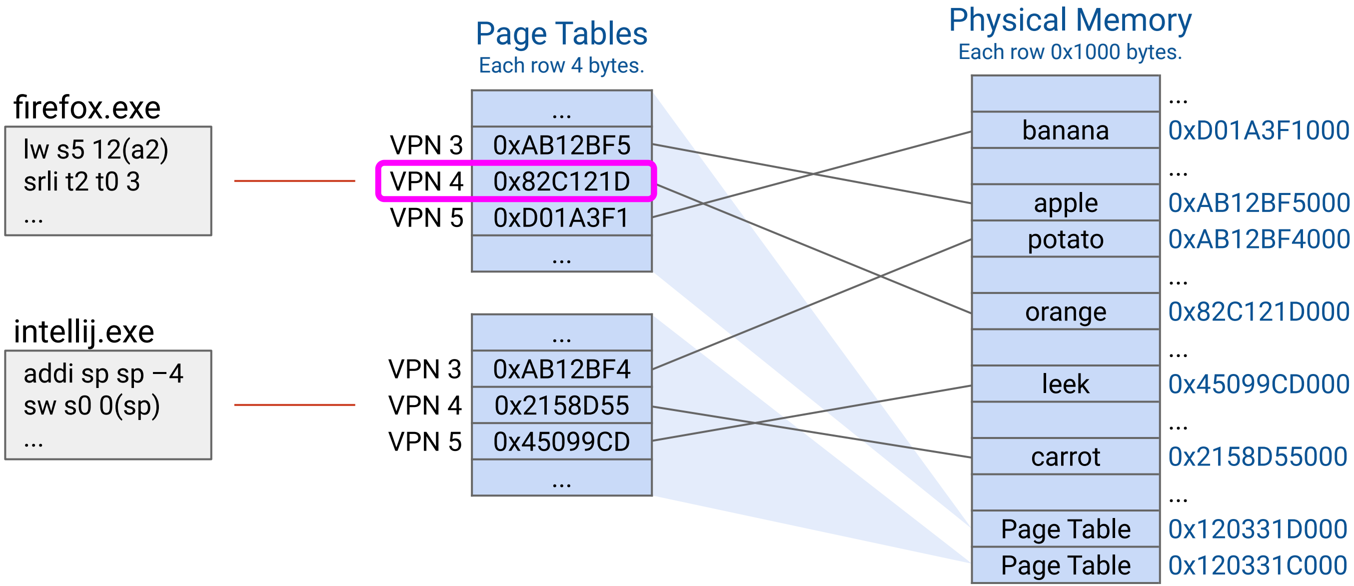
Memory Access Example

Step 3: Translate VPN to PPN using table.

Look up the VPN'th index in the table to find the corresponding PPN.

VPN is 4, so look up 4th PPN in the table.

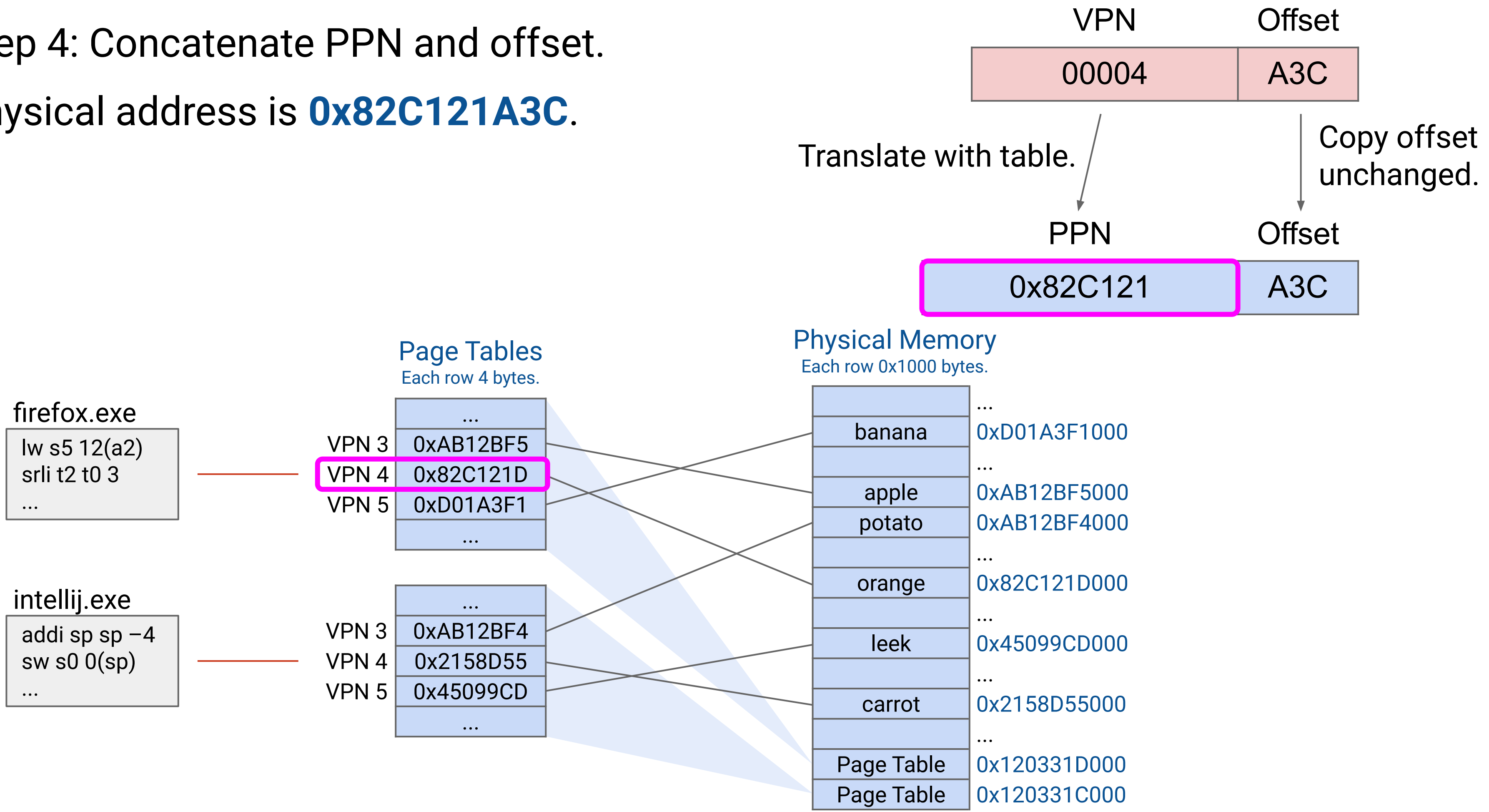




Memory Access Example

Step 4: Concatenate PPN and offset.

Physical address is **0x82C121A3C**.



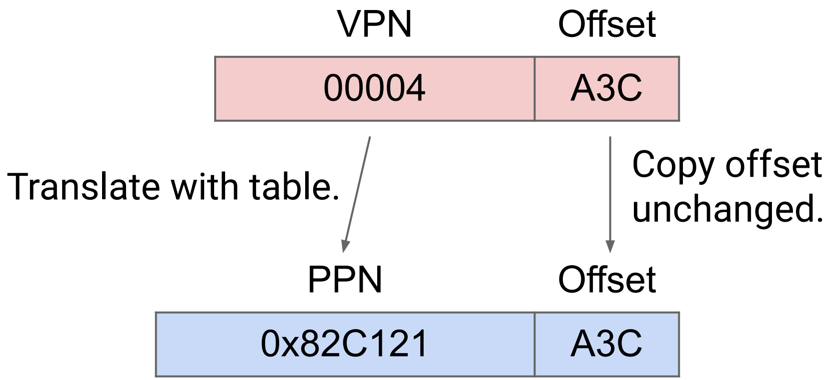
Memory Access Example

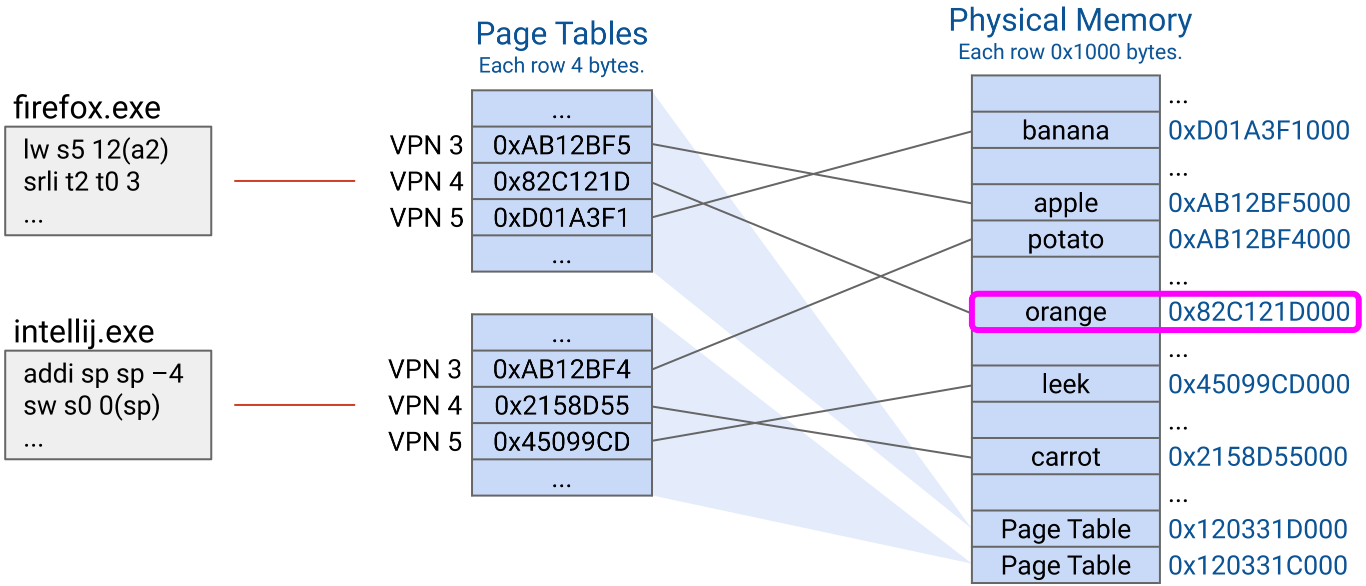
Step 5: Return data to the program.

Requested page says "orange."

Return the 0xA3C'th byte on that page.

(Remember, we used "orange" to represent a page's worth of arbitrary data.)





Virtual Memory Parameters

Lecture 33, CS 61C, Fall 2024

Virtual Memory Parameters

There are certain "knobs" you can turn in a system.

These parameters determine what addresses look like.

Parameter to change:	This parameter affects:
Page size	# of offset bits.
Virtual memory size	# of bits in virtual address.
Physical memory size	# of bits in physical address.

→ Take $\log_2(\text{size})$ to determine # of bits.

Take $2^{\text{\# of bits}}$ to determine size. ←

Virtual Memory Parameters

There are certain "knobs" you can turn in a system.

These parameters determine what addresses look like.

Parameter to change:	This parameter affects:
Page size	# of offset bits.
Virtual memory size	# of bits in virtual address.
Physical memory size	# of bits in physical address.

These determine the **number of VPN bits**.

VPN bits = Virtual address bits – Offset bits.

You can think of page number as "leftover bits" after removing the offset bits.

Virtual Memory Parameters

There are certain "knobs" you can turn in a system.

These parameters determine what addresses look like.

Parameter to change:	**This parameter affects:**
Page size	# of offset bits.
Virtual memory size	# of bits in virtual address.
Physical memory size	# of bits in physical address.

These determine the **number of PPN bits**.

PPN bits = Physical address bits – Offset bits.

You can think of page number as "leftover bits" after removing the offset bits.

Virtual Memory Parameters – Example

Parameter to change:	This parameter affects:
Page size	# of offset bits.
Virtual memory size	# of bits in virtual address.
Physical memory size	# of bits in physical address.

# of PPN bits

# of VPN bits

$2^{\#\text{ of bits}} \longleftarrow \qquad \longrightarrow \log_2(\text{size})$

Example parameters:

4 KiB pages	?-bit offset
4 GiB of virtual memory	?-bit virtual addresses
1 TiB of physical memory	?-bit physical addresses

?-bit PPN

?-bit VPN

$2^{\#\text{ of bits}} \longleftarrow \qquad \longrightarrow \log_2(\text{size})$

Virtual Memory Parameters – Example

Parameter to change:	This parameter affects:
Page size	# of offset bits.
Virtual memory size	# of bits in virtual address.
Physical memory size	# of bits in physical address.

# of PPN bits

# of VPN bits

$2^{\text{\# of bits}}$ ← → $\log_2(\text{size})$

Example parameters:

4 KiB pages	12-bit offset
4 GiB of virtual memory	32-bit virtual addresses
1 TiB of physical memory	40-bit physical addresses

28-bit PPN

20-bit VPN

$2^{\text{\# of bits}}$ ← → $\log_2(\text{size})$

Page Table Size

The approximate size of the page table can be computed from the other parameters.

$$\text{Size of page table} = \# \text{ of PTEs} \times \text{Size per PTE}$$

$2^{\# \text{ of VPN bits}}$

Because we need one entry per VPN, and this is the number of VPNs.

# of PPN bits*

Because each entry is just a PPN value.

*Additional status bits (e.g. valid bit, dirty bit) might increase size per PTE.
More on this later.

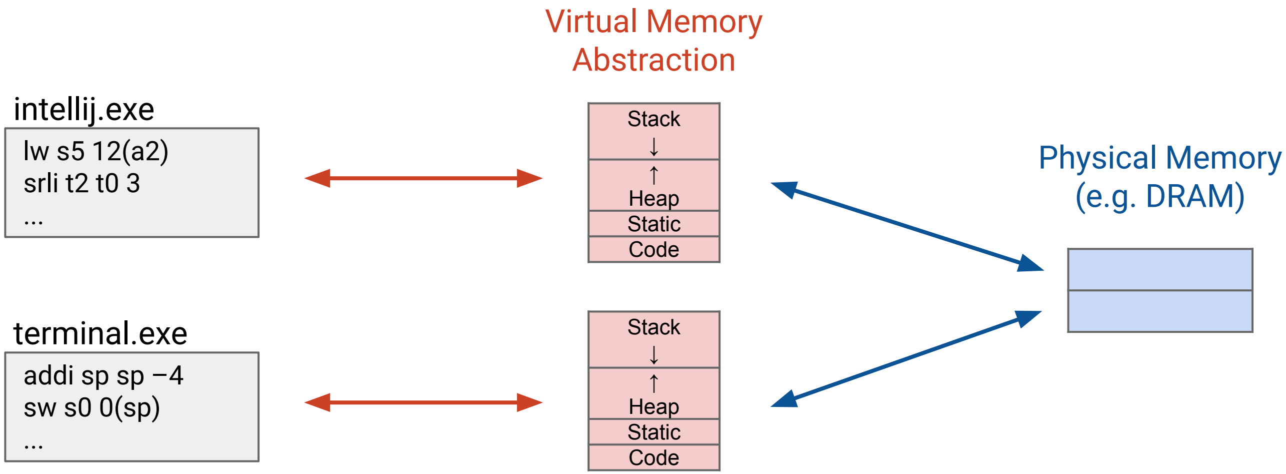
Memory Paging

Lecture 33, CS 61C, Fall 2024

Problem: Exceeding Physical Memory

What if we don't have enough physical memory?

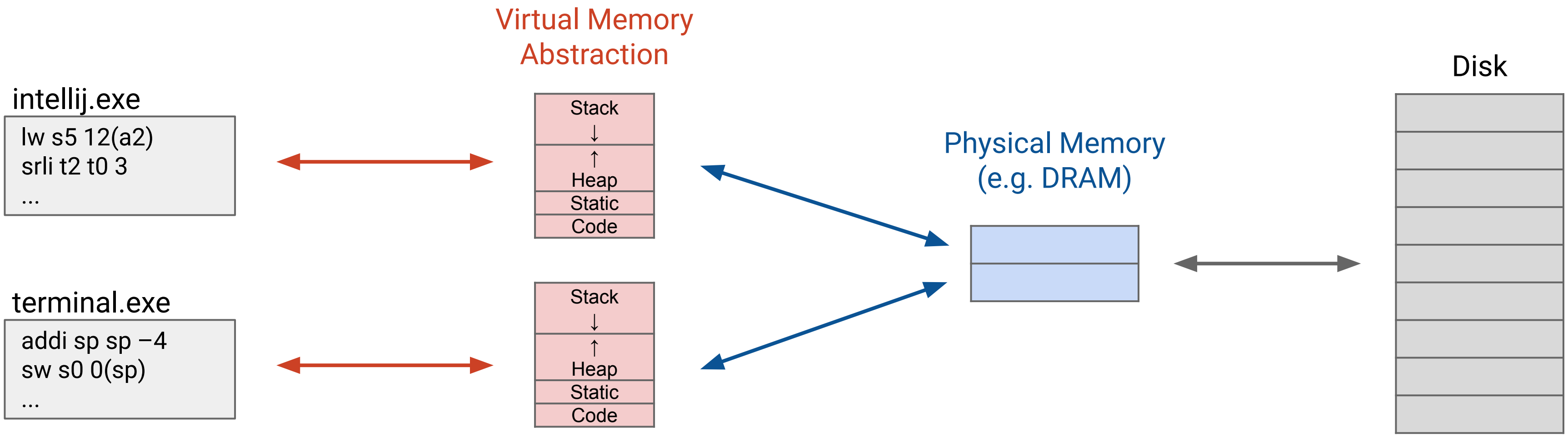
- Example: Virtual memory size > physical memory size.
- Example: Lots of programs. Not enough physical pages to support all programs.



Solution: Additional Storage on Disk

What if we don't have enough physical memory?

- Solution: Store additional pages on the *disk*. (Or some other secondary storage, e.g. tape, DVD.)
- Only store a subset of pages in memory.
- Gives the illusion of a larger physical memory.



Page Tables with Pages on Disk

Now, a page table entry (PTE) might say "this page is on disk," instead of PPN.

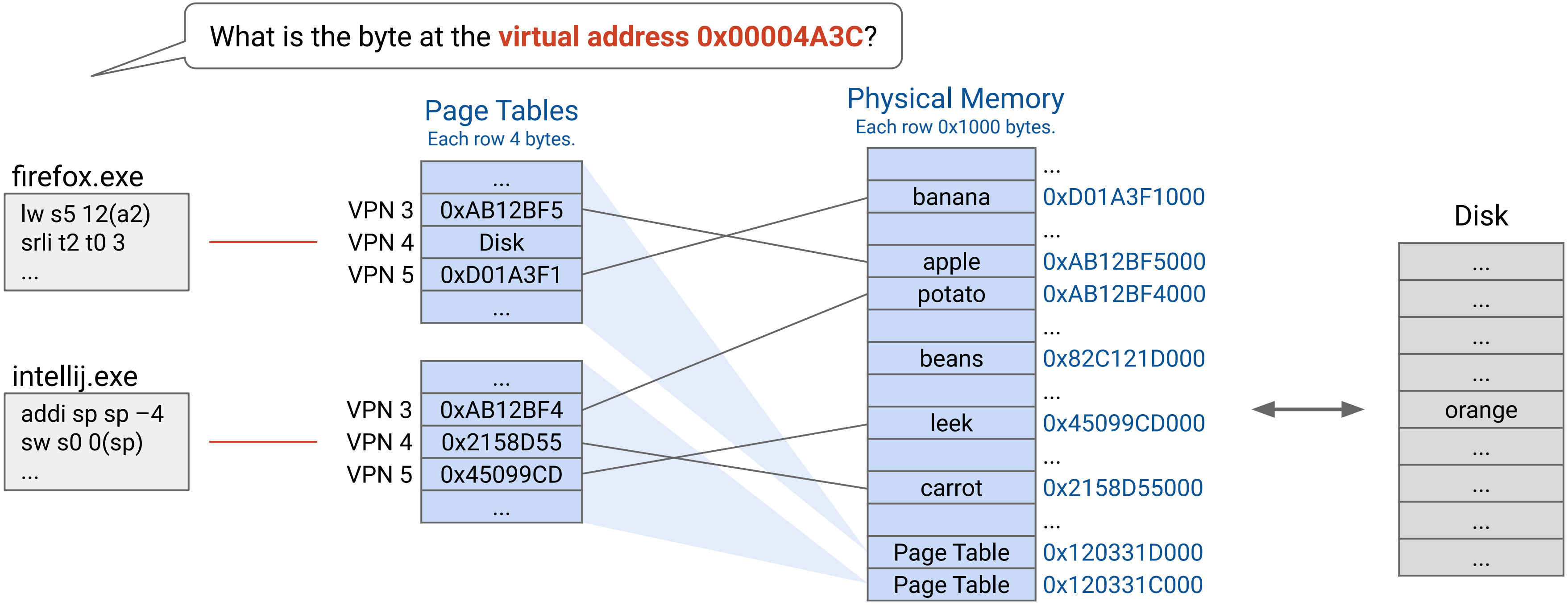
If a program tries to access a page that's not in memory, we get a **page fault**.

- The OS looks at the page table, and realizes the page is on disk.
- The OS loads the requested page from disk into memory.
  This might *evict* another page, kicking it out of memory.
- The OS updates the page table with the location (PPN) of the newly-loaded page.
- The OS returns the requested data to the program.

firefox.exe's Page Table	
VPN	**PPN**
...	...
0x00004	0x60C25E6
0x00005	Disk
0x00006	0xEC70DB7
...	...

Page Fault

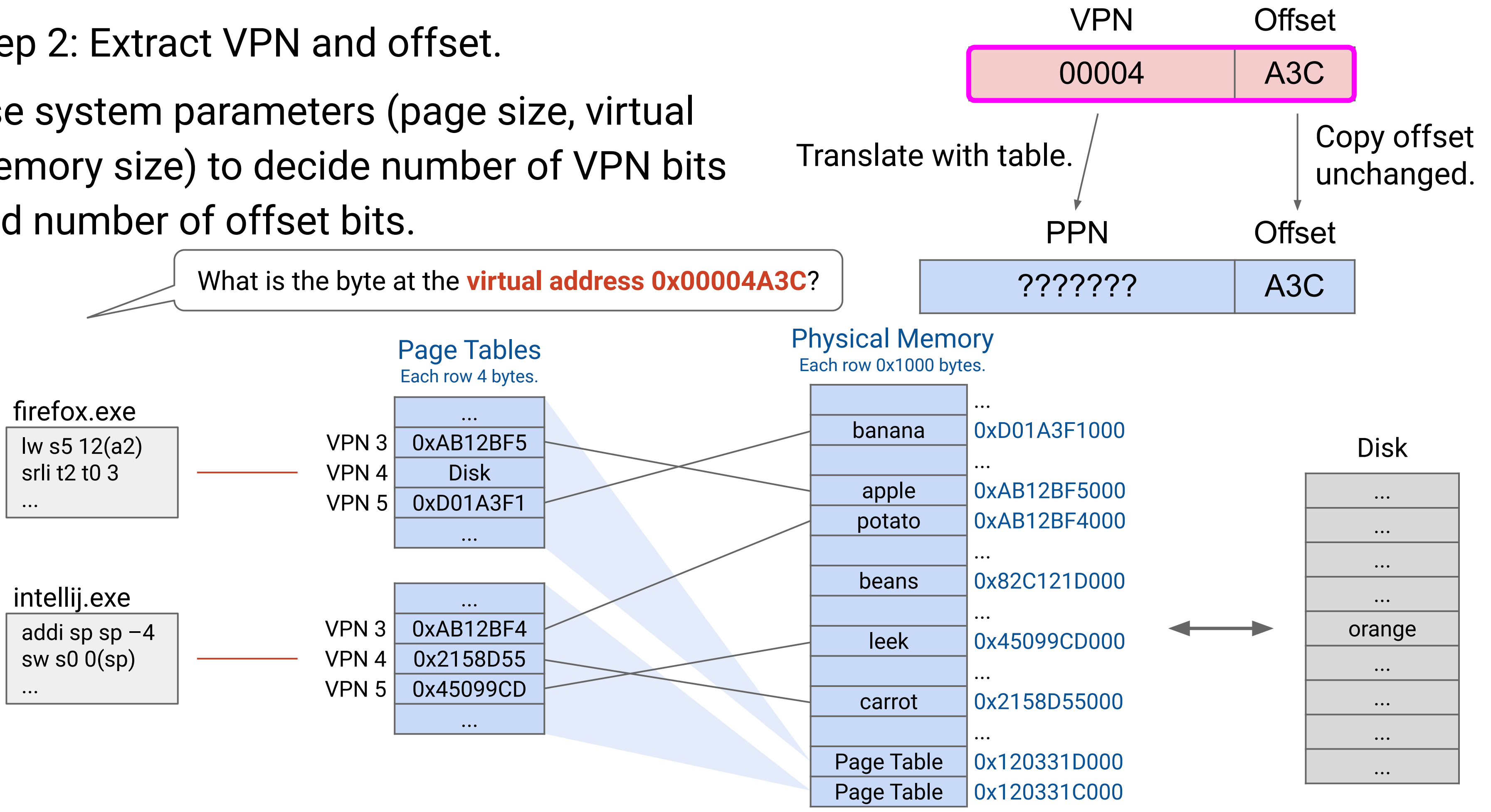
Step 1: The program wants to access memory at a given virtual address.



Page Fault

Step 2: Extract VPN and offset.

Use system parameters (page size, virtual memory size) to decide number of VPN bits and number of offset bits.

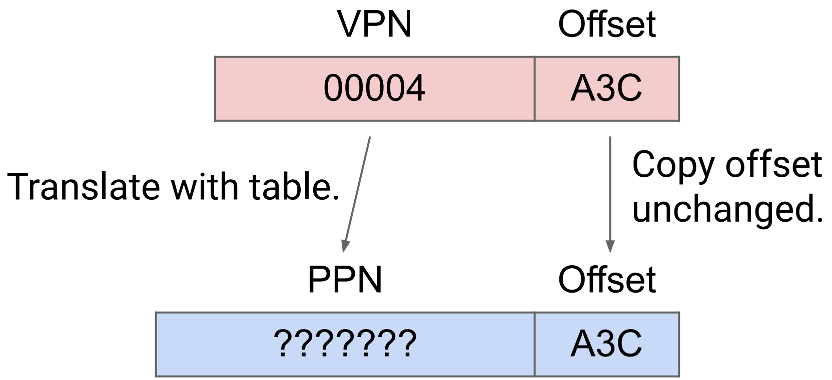


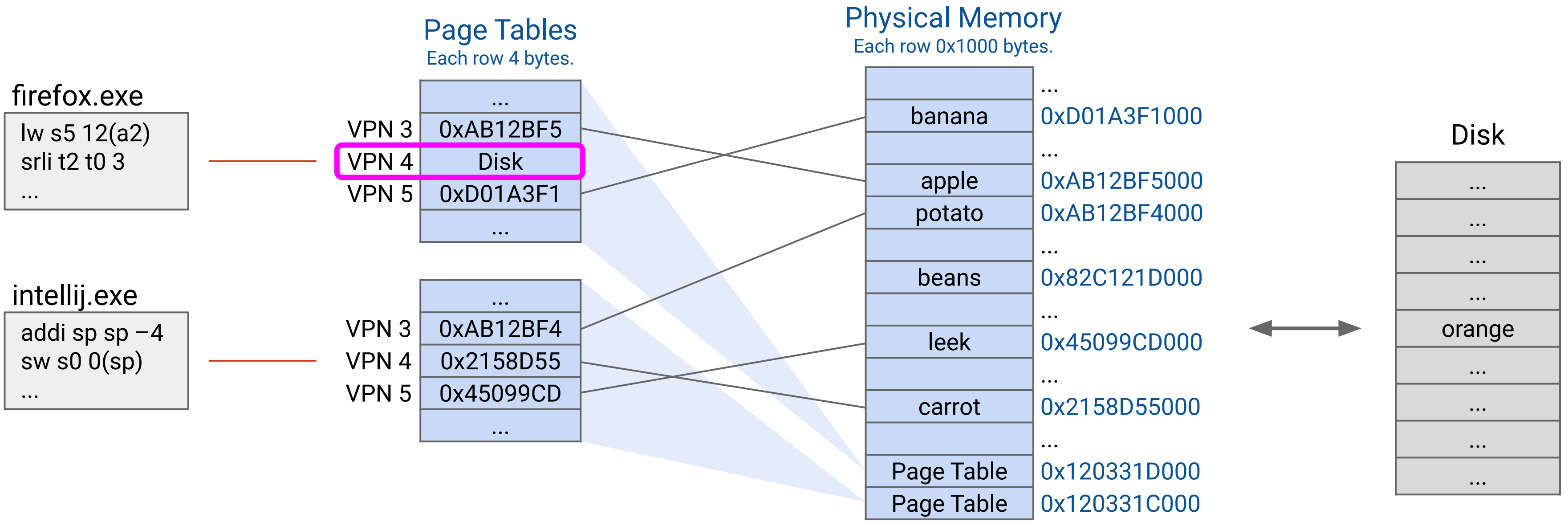
Page Fault

Step 3: Translate VPN to PPN using table.

Look up the VPN'th index in the table to find the corresponding PPN.

In this case, the entry says Disk, so we have a page fault!



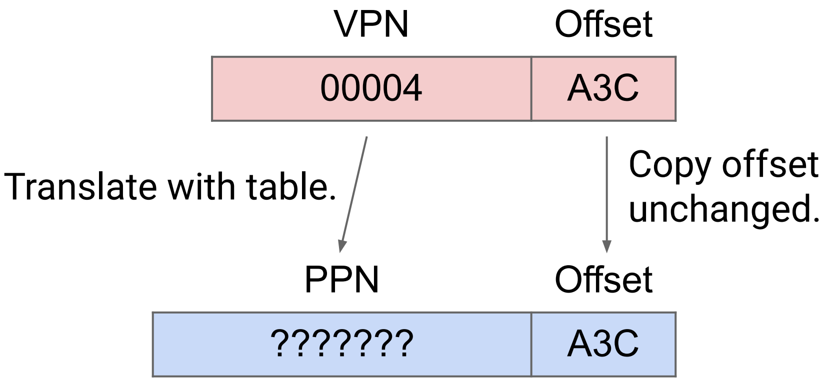


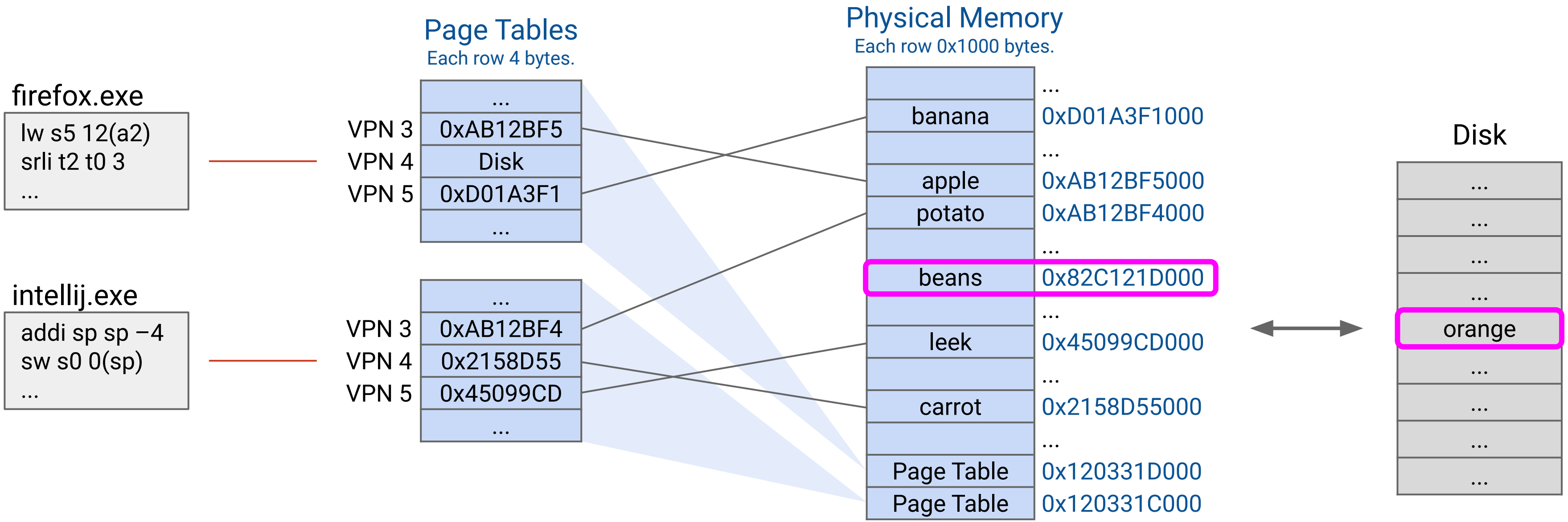
Page Fault

Page fault!

Step 3.1: Load the page from disk into memory.

This might *evict* another page, kicking it out of memory.



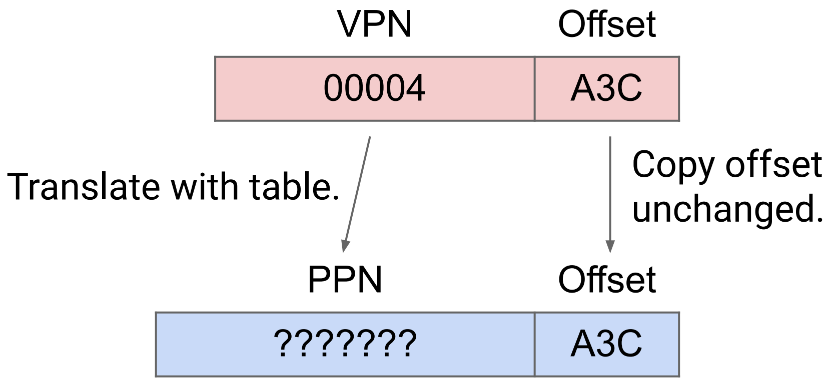


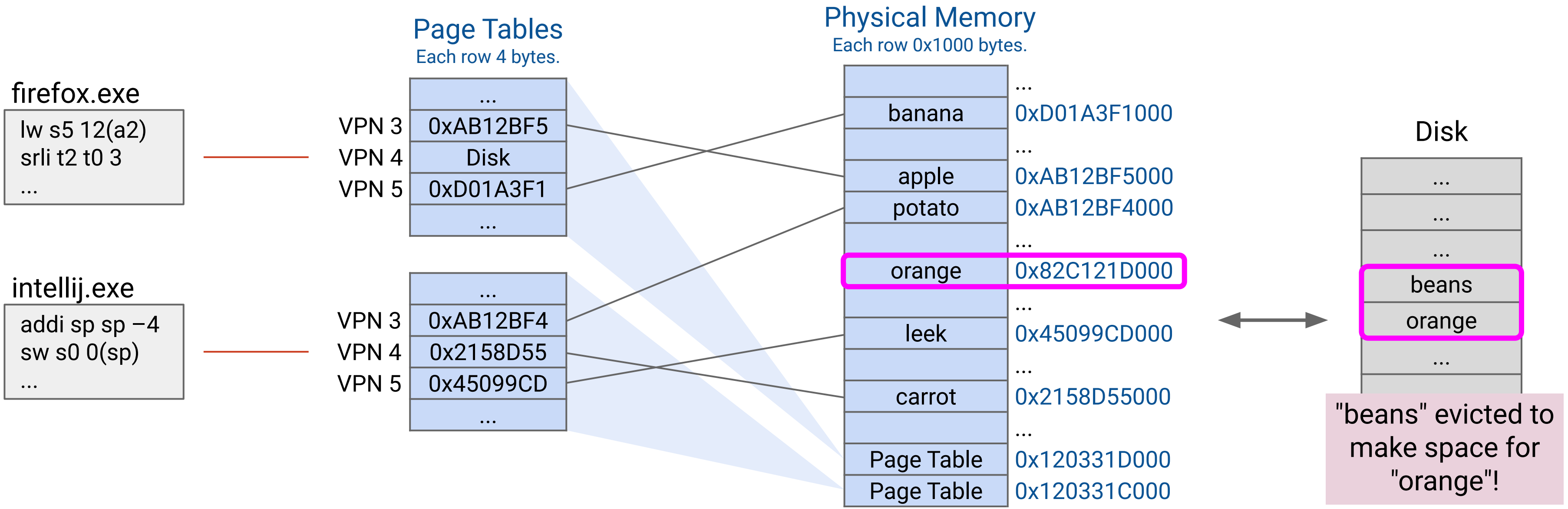
Page Fault

Page fault!

Step 3.1: Load the page from disk into memory.

This might *evict* another page, kicking it out of memory.



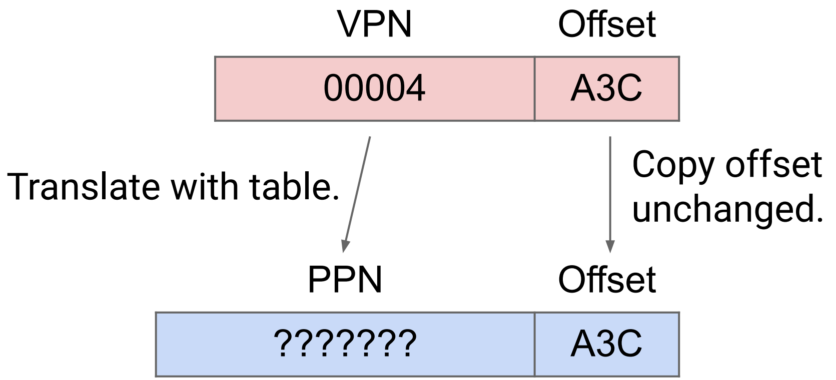


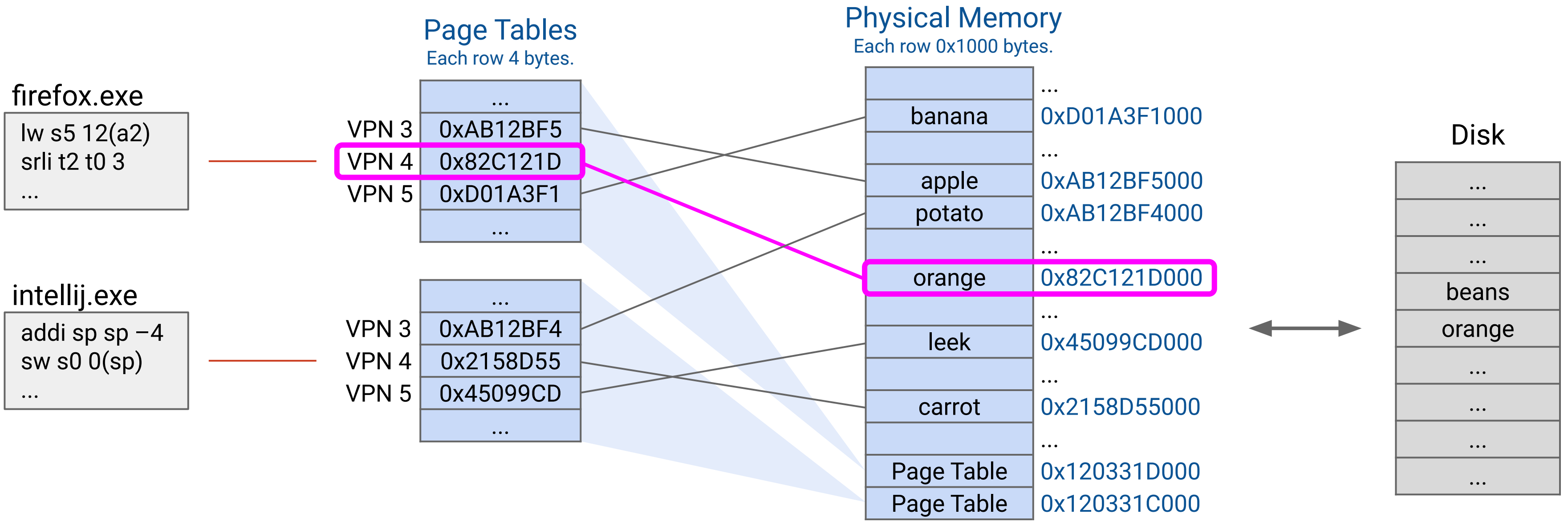
Page Fault

Page fault!

Step 3.2: Update the page table with the location (PPN) of the newly-loaded page.

Page fault resolved. Back to the usual steps.

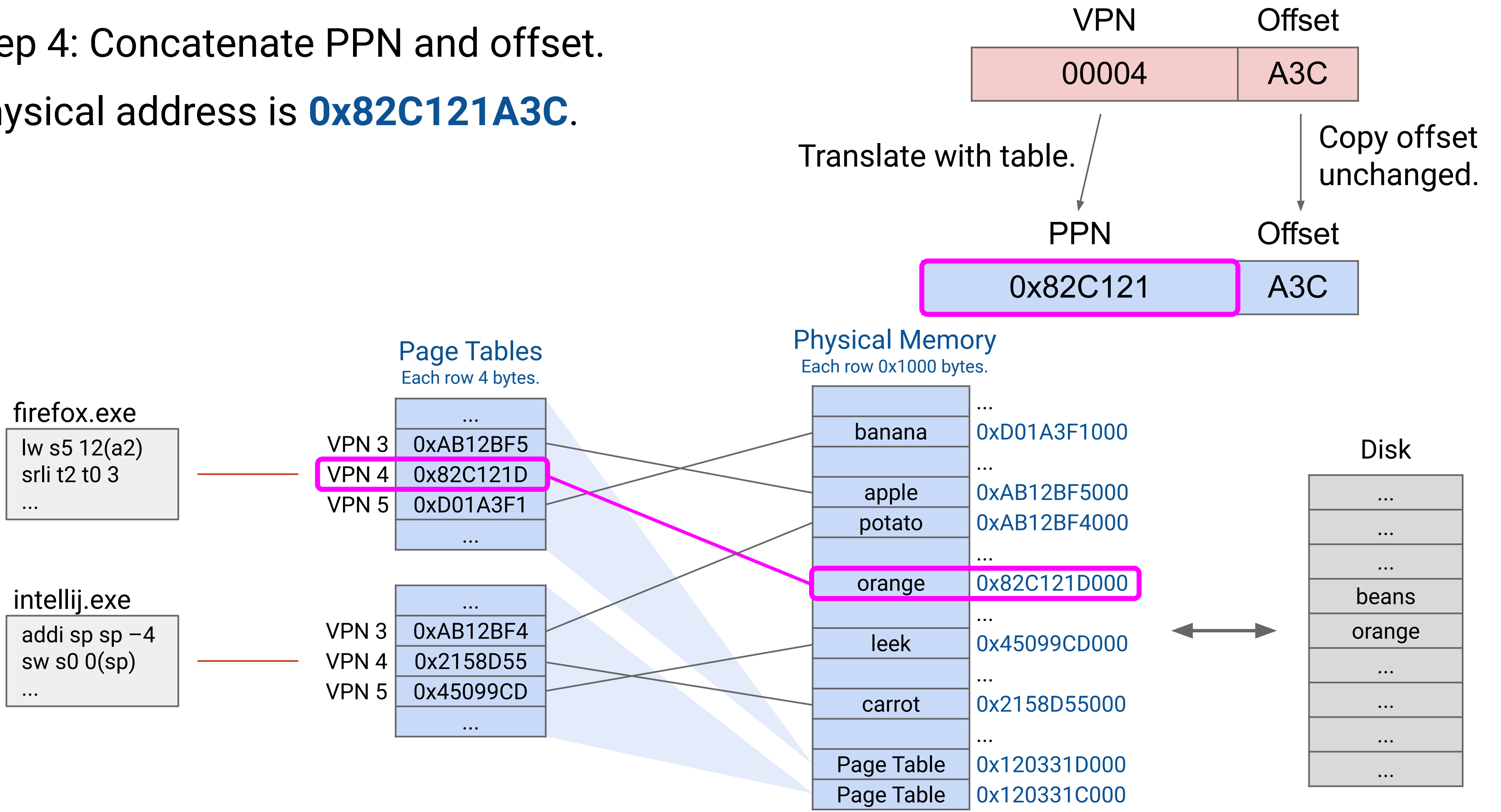




Page Fault

Step 4: Concatenate PPN and offset.

Physical address is **0x82C121A3C**.



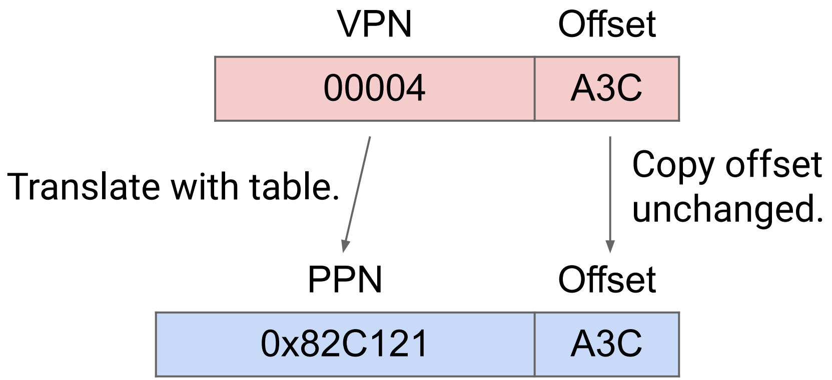
Page Fault

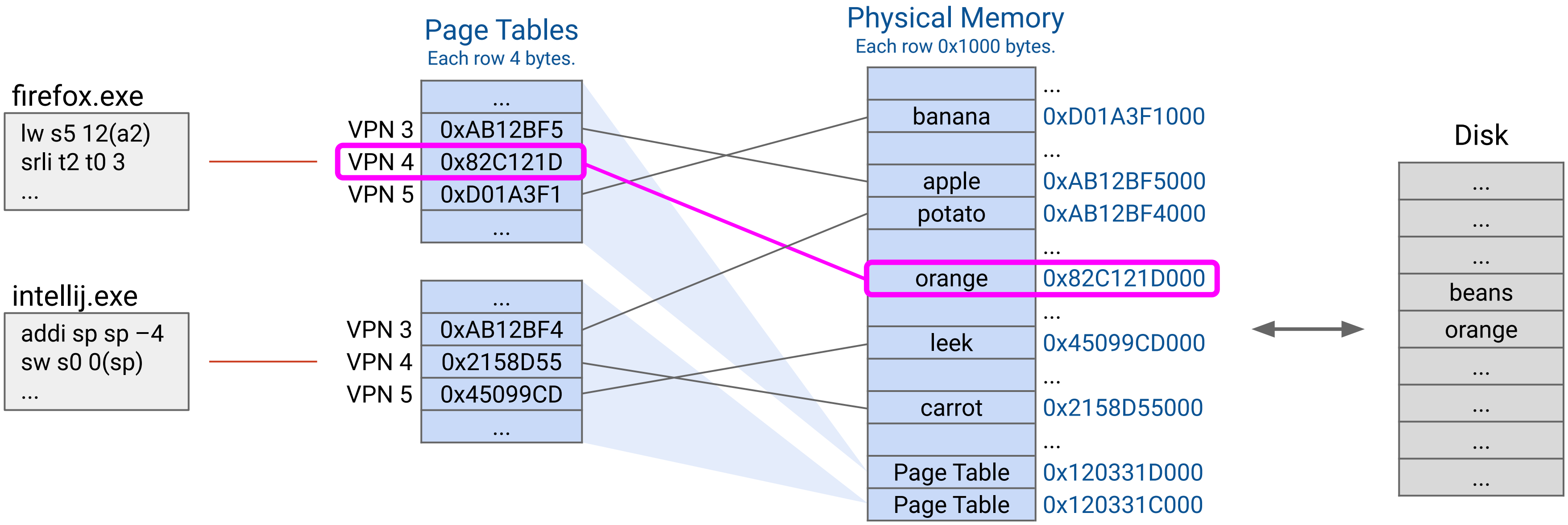
Step 5: Return data to the program.

Requested page says "orange."

Return the 0xA3C'th byte on that page.

(Remember, we used "orange" to represent a page's worth of arbitrary data.)

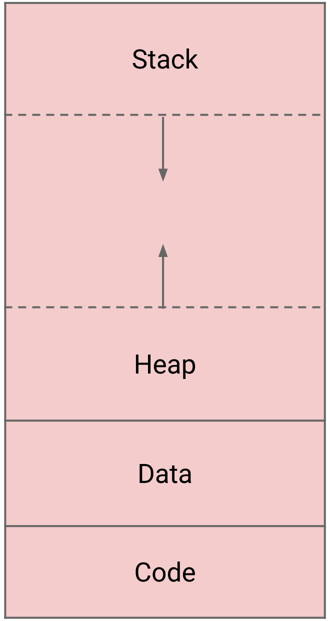




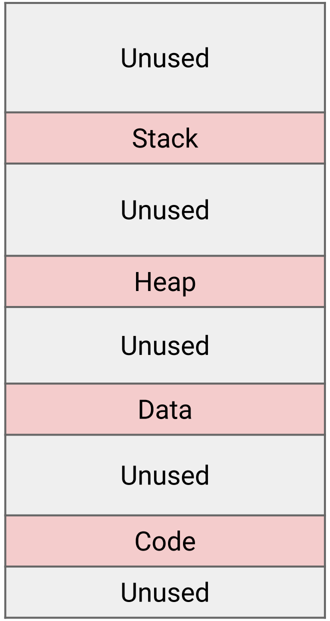
Demand Paging

Loading a ton of pages for every new program is wasteful.

- What if the program is just "hello world"? Most pages are never used.



Our VM abstraction allows a program to use the full virtual address space...



...but some programs use only a tiny amount of memory.

Demand Paging

Loading a ton of pages for every new program is wasteful.

- What if the program is just "hello world"? Most pages are never used.

Solution: **Demand paging**.

- Only load a page into memory if the user requests it.
- When a program starts, the page table says "Disk" for every entry.

firefox.exe's Page Table	
VPN	**PPN**
0x00001	Disk
0x00002	Disk
0x00003	Disk
0x00004	Disk
...	...

Valid Bit

Instead of writing "Disk" in the table, we use a **valid bit**.

- Valid bit = 1: The page is in memory.
  Read the PPN to learn the corresponding physical address.
- Valid bit = 0: The page is on disk. Page fault!
  The PPN value is garbage.

firefox.exe's Page Table	
VPN	**PPN**
...	...
0x00004	0x60C25E6
0x00005	Disk
0x00006	0xEC70DB7
...	...

firefox.exe's Page Table		
Valid?	**VPN**	**PPN**
...	...	...
1	0x00004	0x60C25E6
0	0x00005	0x8173023
1	0x00006	0xEC70DB7
..	...	...

Garbage value.

VM Design Choices

Lecture 33, CS 61C, Fall 2024

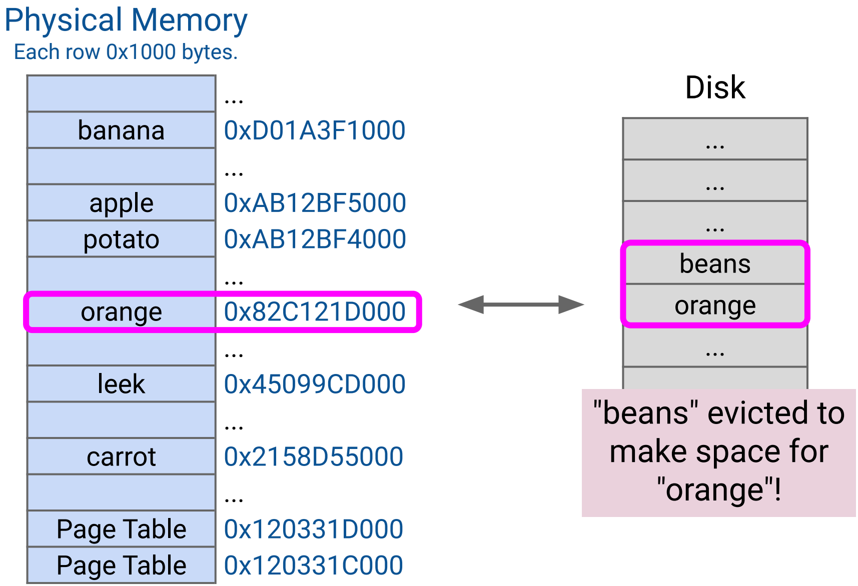
Eviction Policies

On a page fault, if memory is full, we need to *evict* a page.

- Recall: Page fault = load a page from disk into memory.
- Recall: Evict = kick a page out of memory into disk.

How does the OS select which page to evict?

- LRU: Least Recently Used.
- FIFO: First-In, First-Out.
- Random.



Handling Writes

What if the user wants to write data?

Option 1: **Write-through.**

- Update the page in memory. Also, update the page on disk.
- Pro: Simple. Pages are always in sync.
- Con: Expensive. Disk update on every write.

Option 2: **Write-back**.

- Update the page in memory. Don't update the page on disk immediately.
- When the page is evicted from memory, update the page on disk.
- Pro: Cheap. Don't need to update disk every time.
- Con: Complicated. Memory and disk can get out of sync.

Handling Writes

All VM systems use **write-back**.

- Disk accesses take too long. Disk update on every write is way too slow.
- Recall memory analogy: Disk is like going to Pluto.

Write-back requires a dirty bit to keep track of pages that have an unsynced write.

- When evicting a page: If dirty bit = 1, update disk.

When physical page 0x8173023 is evicted, we need to update disk.

firefox.exe's Page Table			
Dirty?	**Valid?**	**VPN**	**PPN**
...	...	...	...
0	1	0x00004	0x60C25E6
1	1	0x00005	0x8173023
0	1	0x00006	0xEC70DB7
...	..	...	...

Benefits of Virtual Memory

Lecture 33, CS 61C, Fall 2024

Benefits of Virtual Memory

We can run programs that require more memory than the computer has.

- Memory paging gives us the illusion of a larger memory.

With **demand paging**, smaller programs don't waste memory.

- Only the pages that actually get used are brought into memory.

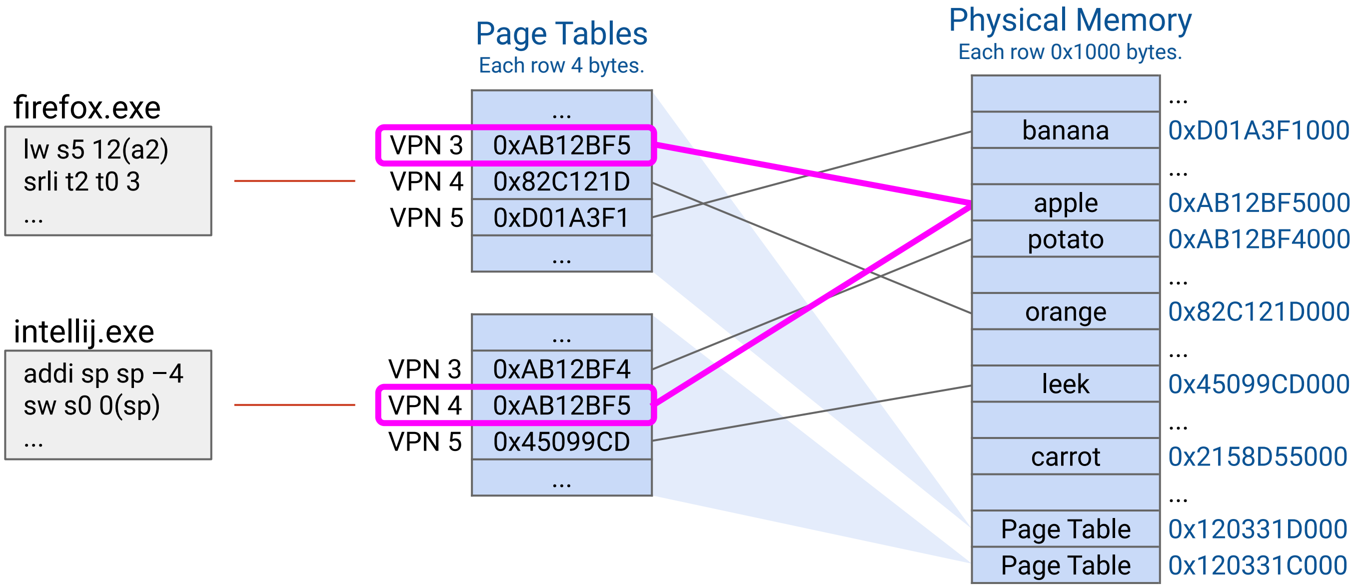
Allows OS to enforce **isolation** between programs.

- Every program has the illusion of its own dedicated (virtual) address space.
- firefox.exe cannot access the memory of intellij.exe.
- Even if both programs access the same virtual address, they map to different physical addresses.
- Errors in one program won't corrupt the memory of other programs.

Memory Sharing

Multiple programs could share memory.

- Just direct both programs to the same physical page.
- Example: Programs might need the same library code, e.g. stdlib.h.



Write Protection

Allows OS to **protect** certain pages.

- OS can mark specific pages as read-only by setting a bit in the page table.
- Writing to a protected page triggers an exception.
  Exceptions are handled by the OS (more later).
- Example: We could mark the code section as read-only.
  Stops the program from overwriting itself while it's executing.

If a user tries to write to VPN 0x00004, the OS will not allow it.

firefox.exe's Page Table

Read-only?	Dirty?	Valid?	VPN	PPN
...	...	...	...	...
1	0	1	0x00004	0x60C25E6
0	1	1	0x00005	0x8173023
0	0	1	0x00006	0xEC70DB7
...	...	..	...	...

Summary: Virtual Memory I

Step 1: The program wants to access memory at a given virtual address.

Step 2: Extract VPN and offset. Use parameters to decide # of VPN bits and # of offset bits.

Step 3: Translate VPN to PPN using table.
Look up the VPN'th index in the table to find the corresponding PPN.
If page fault (entry is invalid), do Steps 3.1–3.2.

Step 4: Concatenate PPN and offset.

Step 5: Return data to the program.

Step 3.1: Load page from disk into memory. This might evict another page (kick it out of memory).

Step 3.2: Update the page table with the location (PPN) of the newly-loaded page.

Parameter to change:	This parameter affects:
Page size	# of offset bits.
Virtual memory size	# of bits in virtual address.
Physical memory size	# of bits in physical address.

# of PPN bits

# of VPN bits

$2^{\text{\# of bits}}$ ← → $\log_2(\text{size})$

Size of page table = # of PTEs × Size per PTE
$= 2^{\text{\# of VPN bits}}$ × # of PPN bits