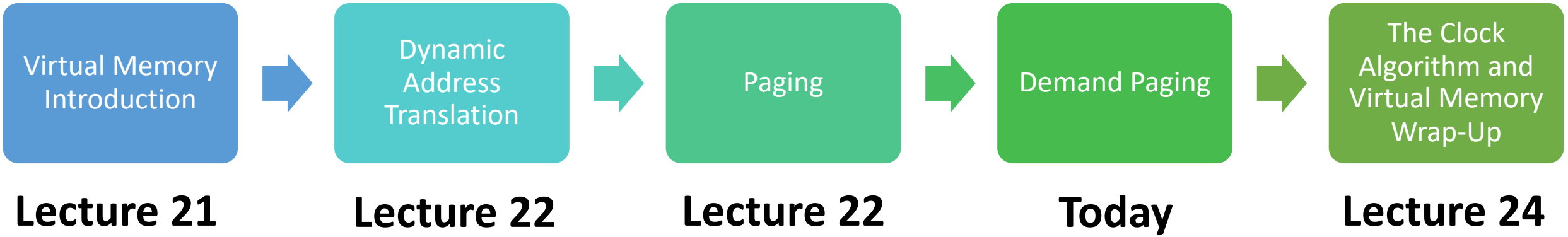
CS111, Lecture 23
Demand Paging

Optional reading:

Operating Systems: Principles and Practice (2nd Edition): Chapter 9

Topic 4: Virtual Memory - How can one set of memory be shared among several processes? How can the operating system manage access to a limited amount of system memory?

CS111 Topic 4: Virtual Memory



assign6: implement *demand paging* system to translate addresses and load/store memory contents for programs as needed.

Learning Goals

- Learn about page maps and how they help translate virtual addresses to physical addresses
- Understand how paging allows us to swap memory contents to disk when we need more physical pages.
- Learn about the benefits of demand paging in making memory look larger than it really is

Plan For Today

- **Recap:** Paging so far
- Page Map Size
- Demand Paging

Plan For Today

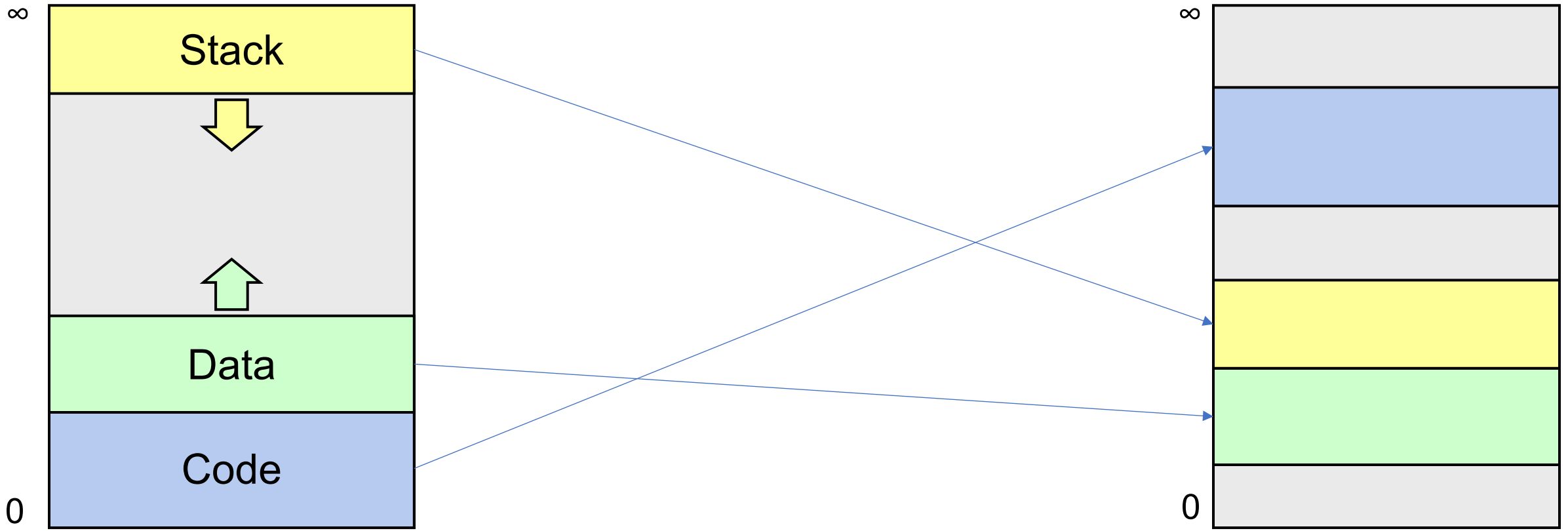
- **Recap: Paging so far**
- Page Map Size
- Demand Paging

Approach #3: Paging

Key Idea: Each process's virtual (and physical) memory is divided into fixed-size chunks called *pages*. (Common size is 4KB pages).

- A "page" of virtual memory maps to a "page" of physical memory. No partial pages
- The **page number** is a numerical ID for a page. We have virtual page numbers and physical page numbers.
- Each process has a *page map ("page table")* with an entry for each virtual page, mapping it to a physical page number and other info such as a protection bit (read-only or read-write).

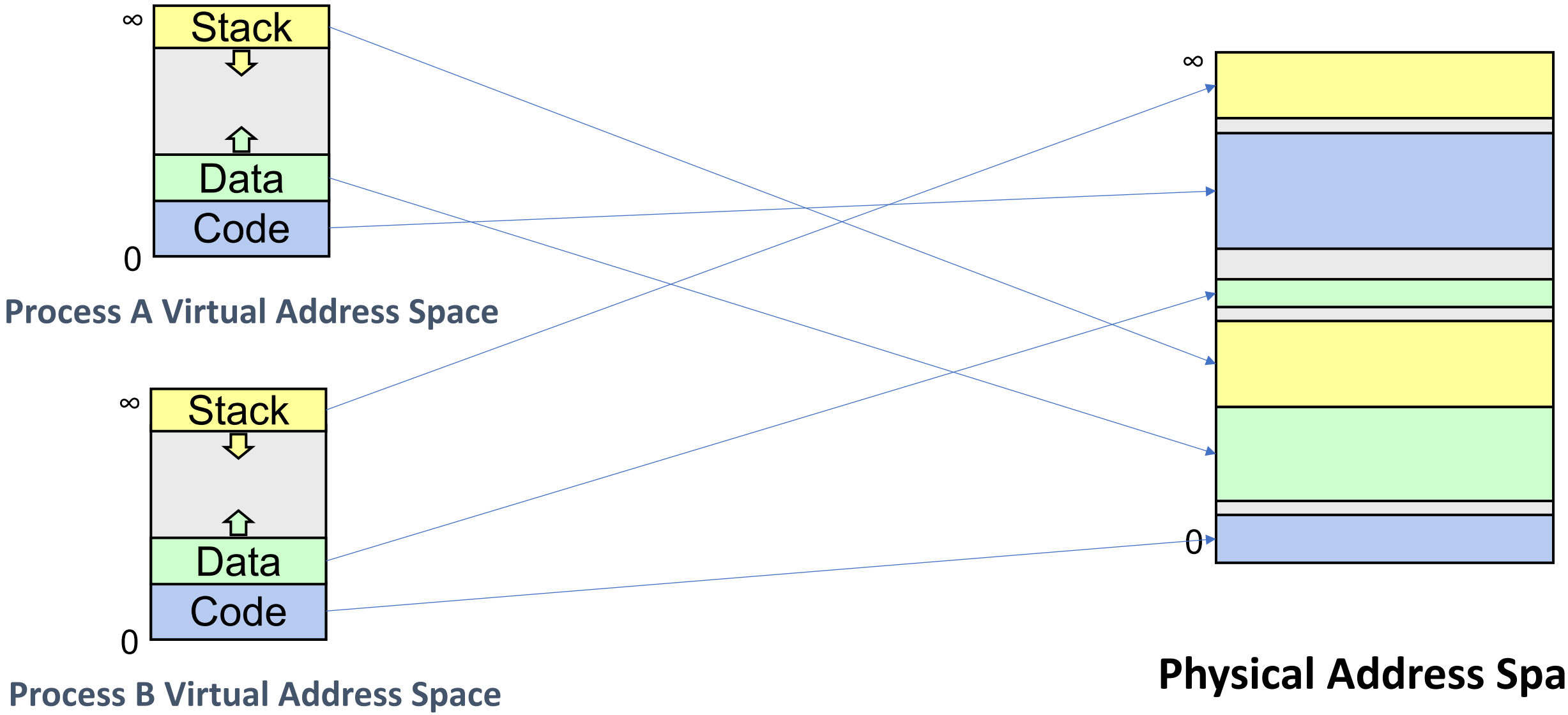
Multiple Segments



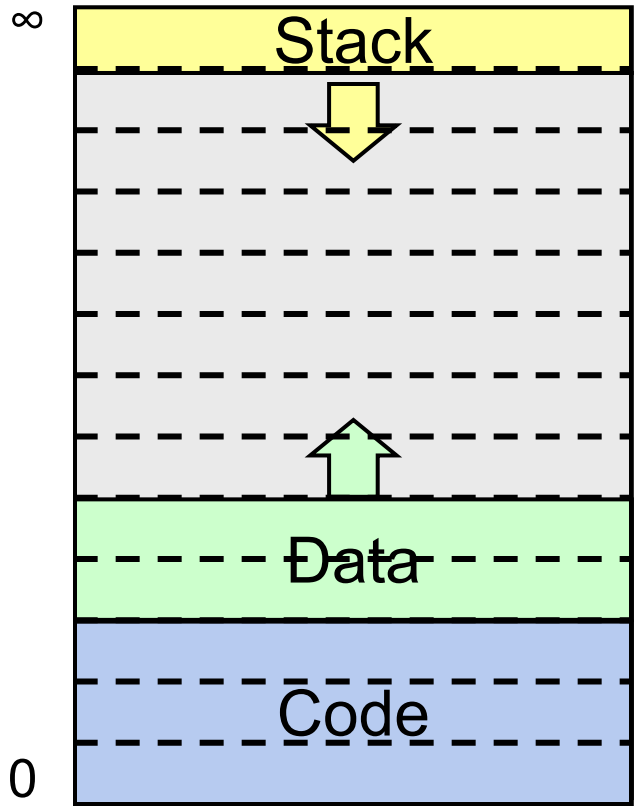
Process A Virtual Address Space

Physical Address Space

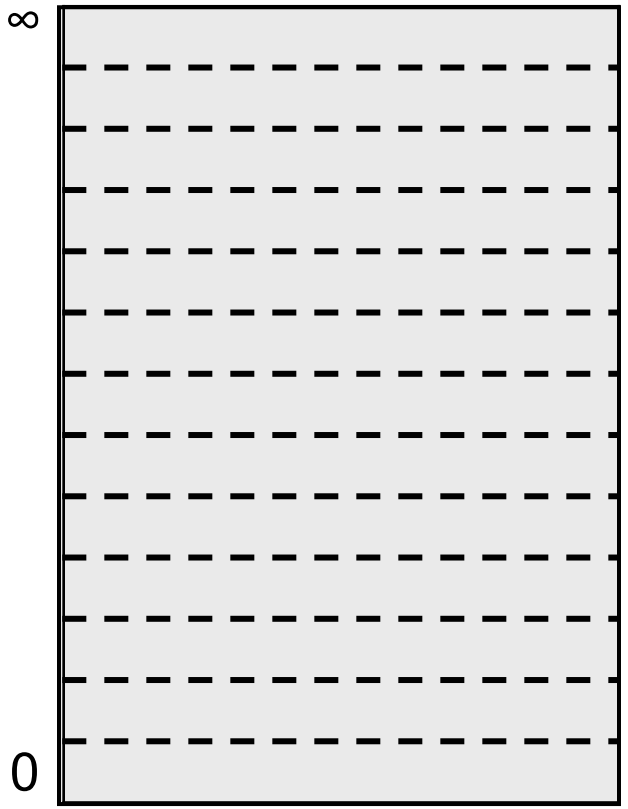
Multiple Segments



Paging

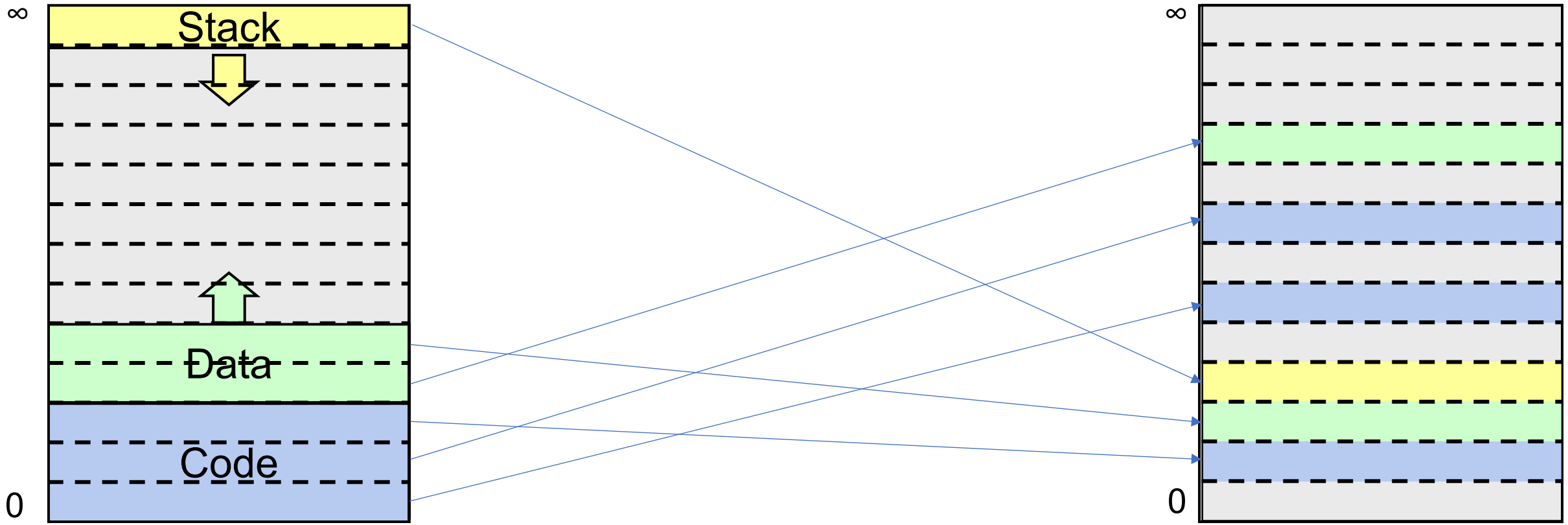


Process A Virtual Address Space



Physical Address Space

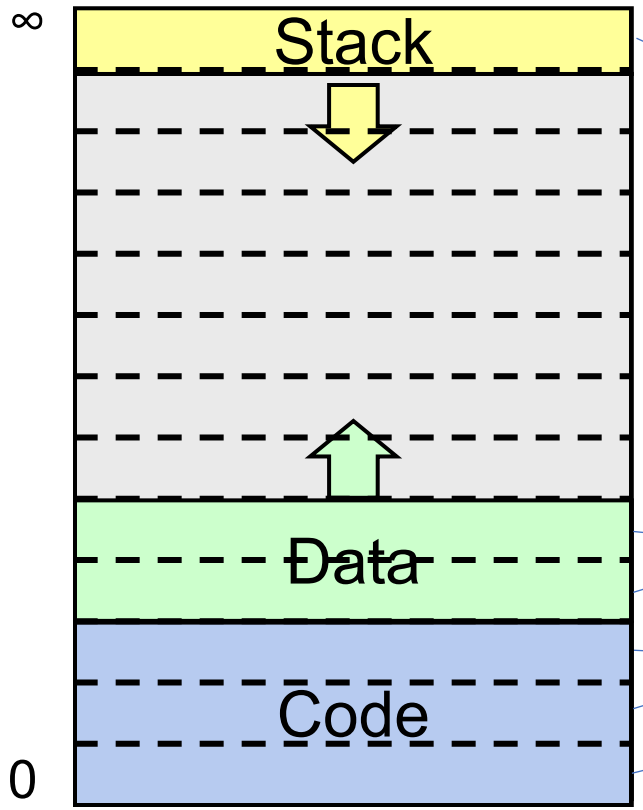
Paging



Process A Virtual Address Space

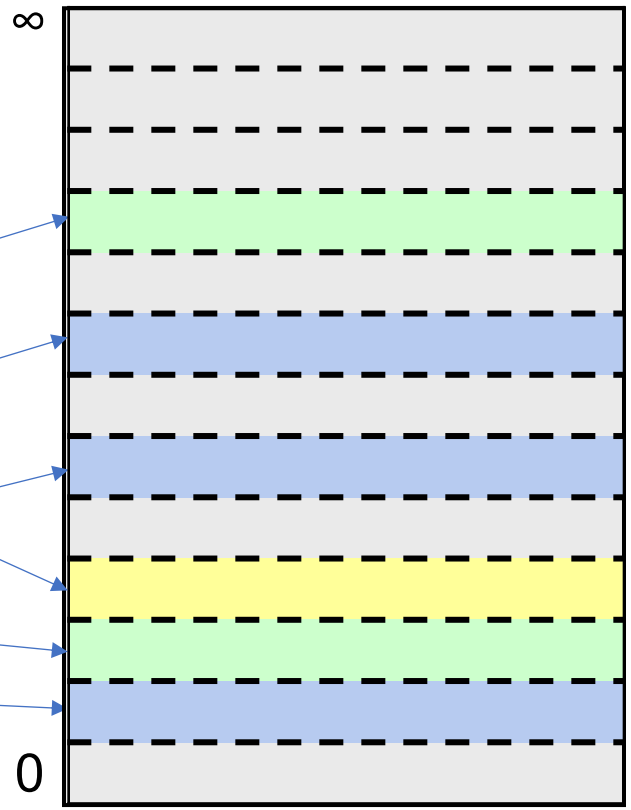
Physical Address Space

Page Map



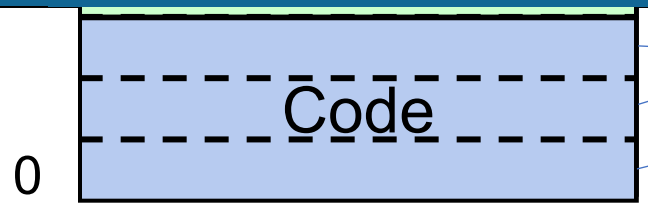
Process A Virtual Address Space

	Physical page #	WR?	PR?
12	3	1	1
11	X	X	0
10	X	X	0
9	X	X	0
8	X	X	0
7	X	X	0
6	X	X	0
5	X	X	0
4	2	1	1
3	9	0	1
2	1	0	1
1	7	0	1
0	5	0	1



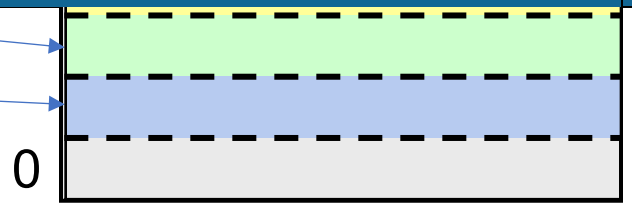
Physical Address Space

Page Map



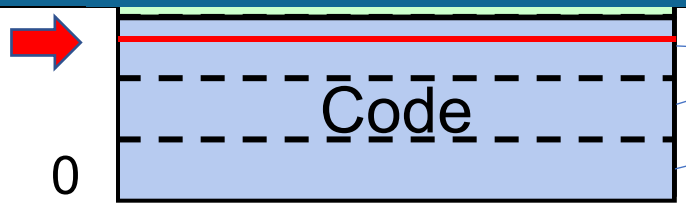
Process A Virtual Address Space

	Physical page #	WR?	PR?
12	3	1	1
11	X	X	0
10	X	X	0
9	X	X	0
8	X	X	0
7	X	X	0
6	X	X	0
5	X	X	0
4	2	1	1
3	9	0	1
2	1	0	1
1	7	0	1
0	5	0	1



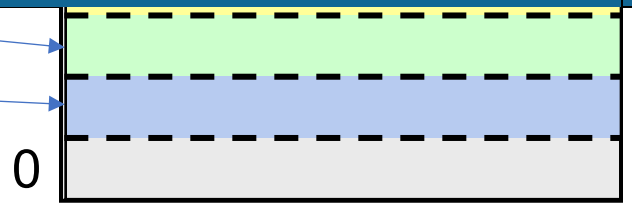
Physical Address Space

Page Map



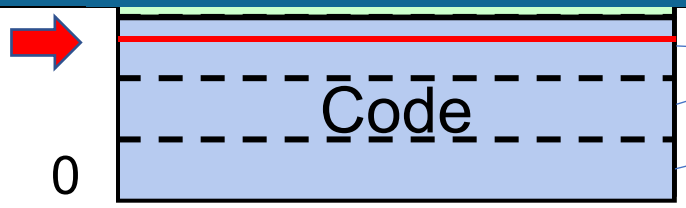
Process A Virtual Address Space

	Physical page #	WR?	PR?
12	3	1	1
11	X	X	0
10	X	X	0
9	X	X	0
8	X	X	0
7	X	X	0
6	X	X	0
5	X	X	0
4	2	1	1
3	9	0	1
2	1	0	1
1	7	0	1
0	5	0	1



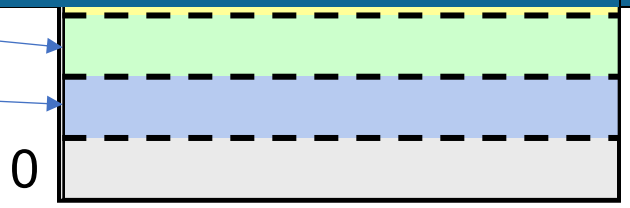
Physical Address Space

Page Map



Process A Virtual Address Space

	Physical page #	WR?	PR?
12	3	1	1
11	X	X	0
10	X	X	0
9	X	X	0
8	X	X	0
7	X	X	0
6	X	X	0
5	X	X	0
4	2	1	1
3	9	0	1
2	1	0	1
1	7	0	1
0	5	0	1

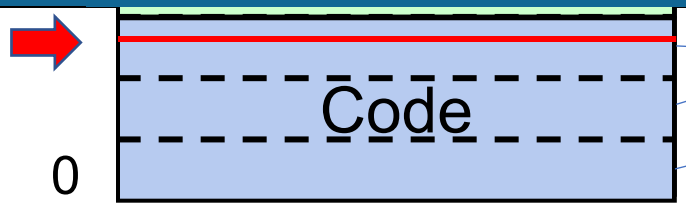


Physical Address Space

Virtual Address

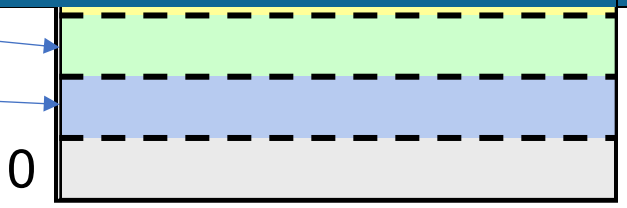
0x2223

Page Map



Process A Virtual Address Space

	Physical page #	WR?	PR?
12	3	1	1
11	X	X	0
10	X	X	0
9	X	X	0
8	X	X	0
7	X	X	0
6	X	X	0
5	X	X	0
4	2	1	1
3	9	0	1
2	1	0	1
1	7	0	1
0	5	0	1



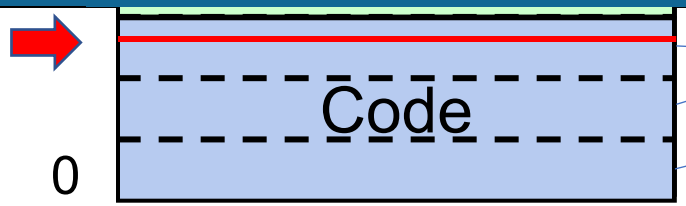
Physical Address Space

Virtual page #	*Offset*
0x2	**0x223**

Virtual Address

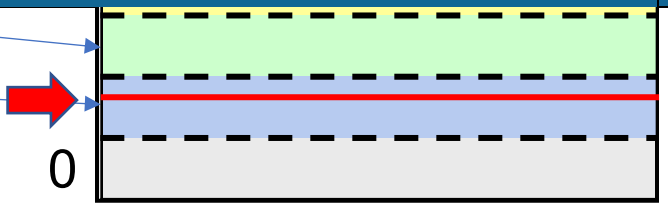
0x2223

Page Map



Process A Virtual Address Space

	Physical page #	WR?	PR?
12	3	1	1
11	X	X	0
10	X	X	0
9	X	X	0
8	X	X	0
7	X	X	0
6	X	X	0
5	X	X	0
4	2	1	1
3	9	0	1
2	1	0	1
1	7	0	1
0	5	0	1



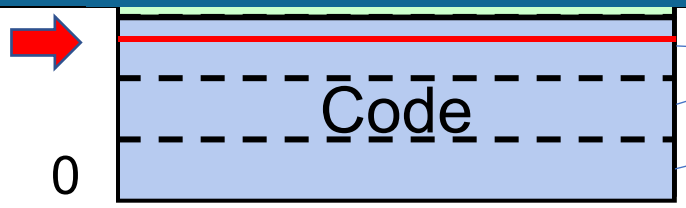
Physical Address Space

Virtual page #	*Offset*
0x2	**0x223**

Virtual Address

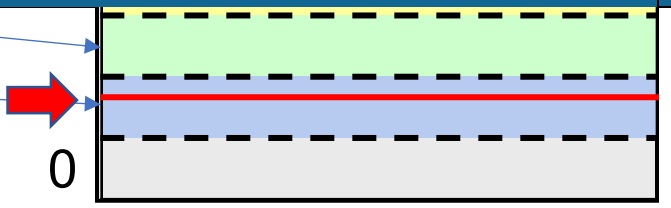
0x2223

Page Map



Process A Virtual Address Space

	Physical page #	WR?	PR?
12	3	1	1
11	X	X	0
10	X	X	0
9	X	X	0
8	X	X	0
7	X	X	0
6	X	X	0
5	X	X	0
4	2	1	1
3	9	0	1
2	1	0	1
1	7	0	1
0	5	0	1



Physical Address Space

Virtual page #	*Offset*
0x2	**0x223**

Virtual Address

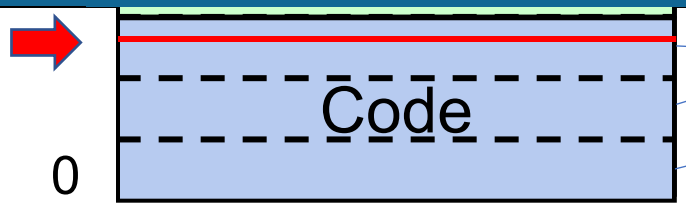
0x2223

Physical page #	*Offset*
???	**0x223**

Physical Address

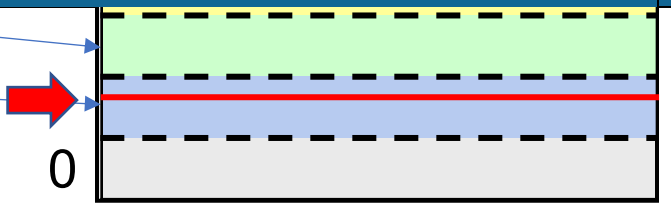
???

Page Map



Process A Virtual Address Space

	Physical page #	WR?	PR?
12	3	1	1
11	X	X	0
10	X	X	0
9	X	X	0
8	X	X	0
7	X	X	0
6	X	X	0
5	X	X	0
4	2	1	1
3	9	0	1
2	1	0	1
1	7	0	1
0	5	0	1



Physical Address Space

Virtual page #	*Offset*
0x2	**0x223**

Virtual Address

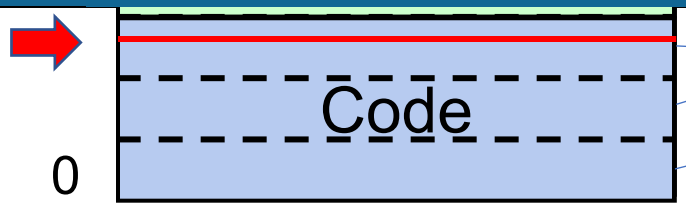
0x2223

Physical page #	*Offset*
0x1	**0x223**

Physical Address

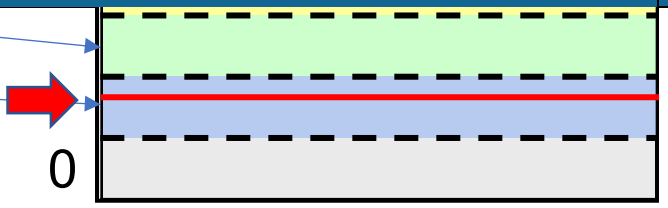
???

Page Map



Process A Virtual Address Space

	Physical page #	WR?	PR?
12	3	1	1
11	X	X	0
10	X	X	0
9	X	X	0
8	X	X	0
7	X	X	0
6	X	X	0
5	X	X	0
4	2	1	1
3	9	0	1
2	1	0	1
1	7	0	1
0	5	0	1



Physical Address Space

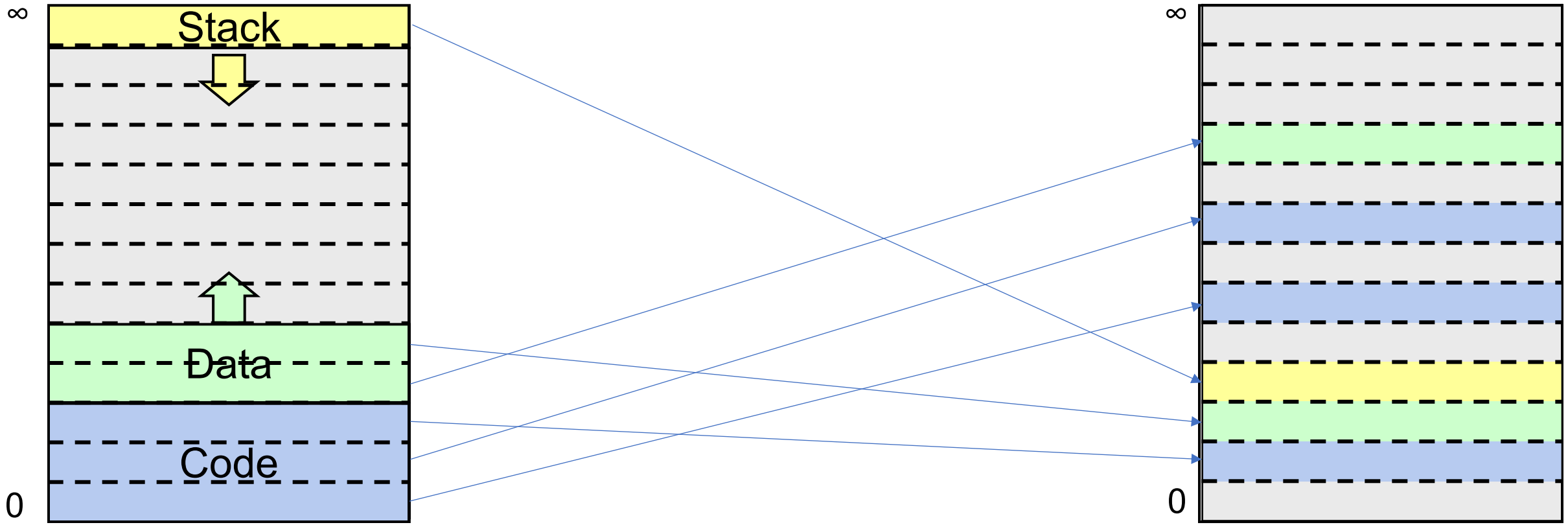
Virtual page #	*Offset*
0x2	**0x223**

Virtual Address
0x2223

Physical page #	*Offset*
0x1	**0x223**

Physical Address
0x1223

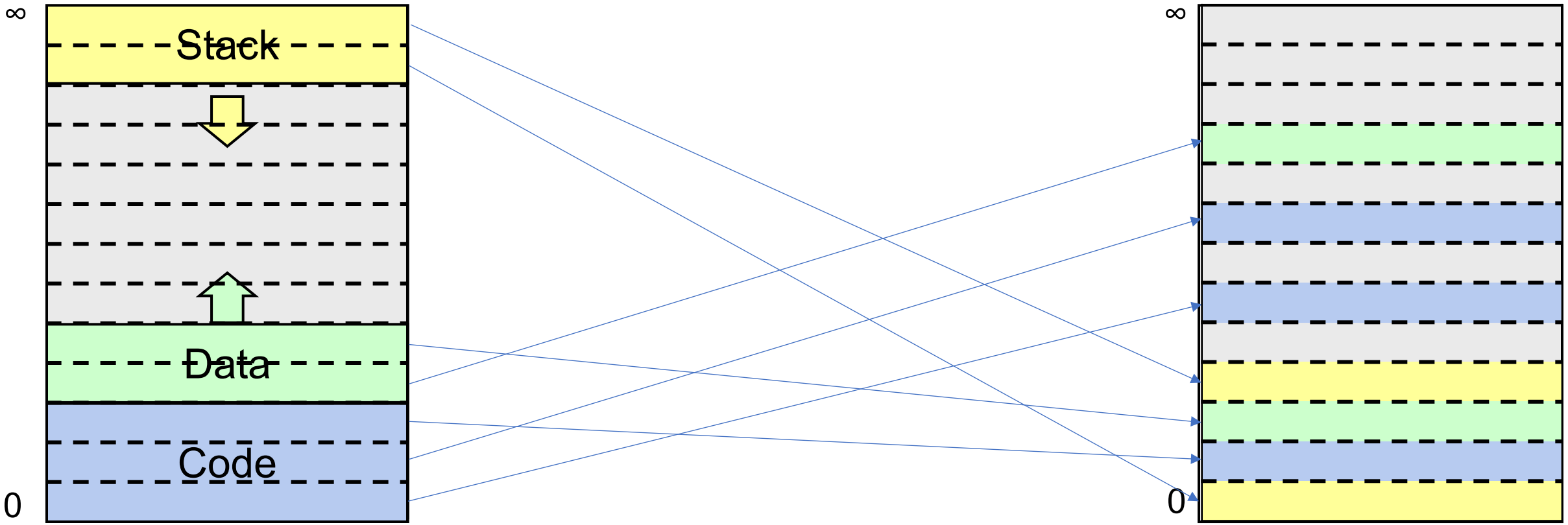
Requesting More Memory



Process A Virtual Address Space

Physical Address Space

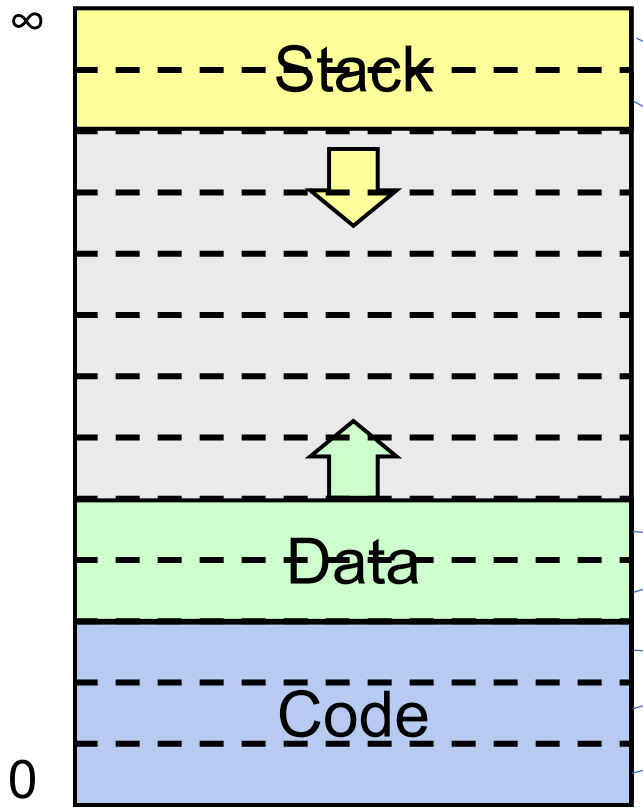
Requesting More Memory



Process A Virtual Address Space

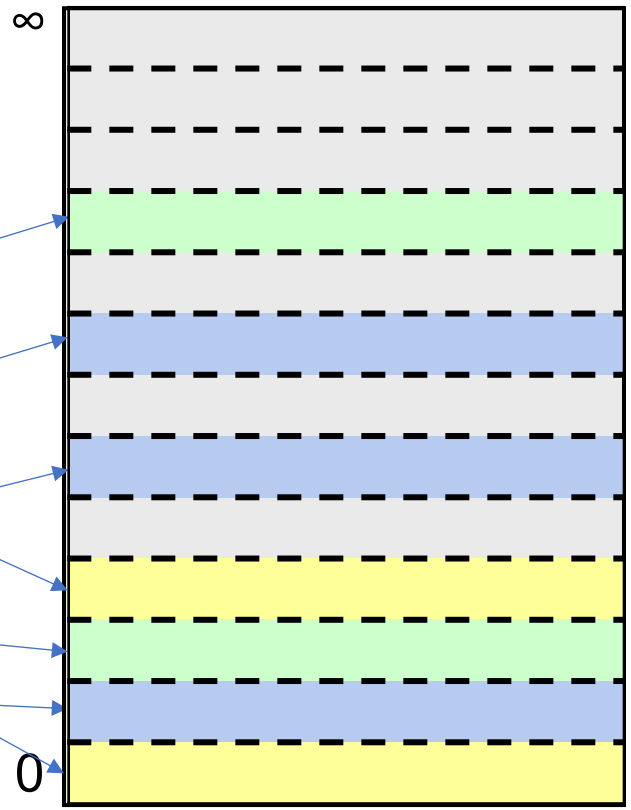
Physical Address Space

Requesting More Memory



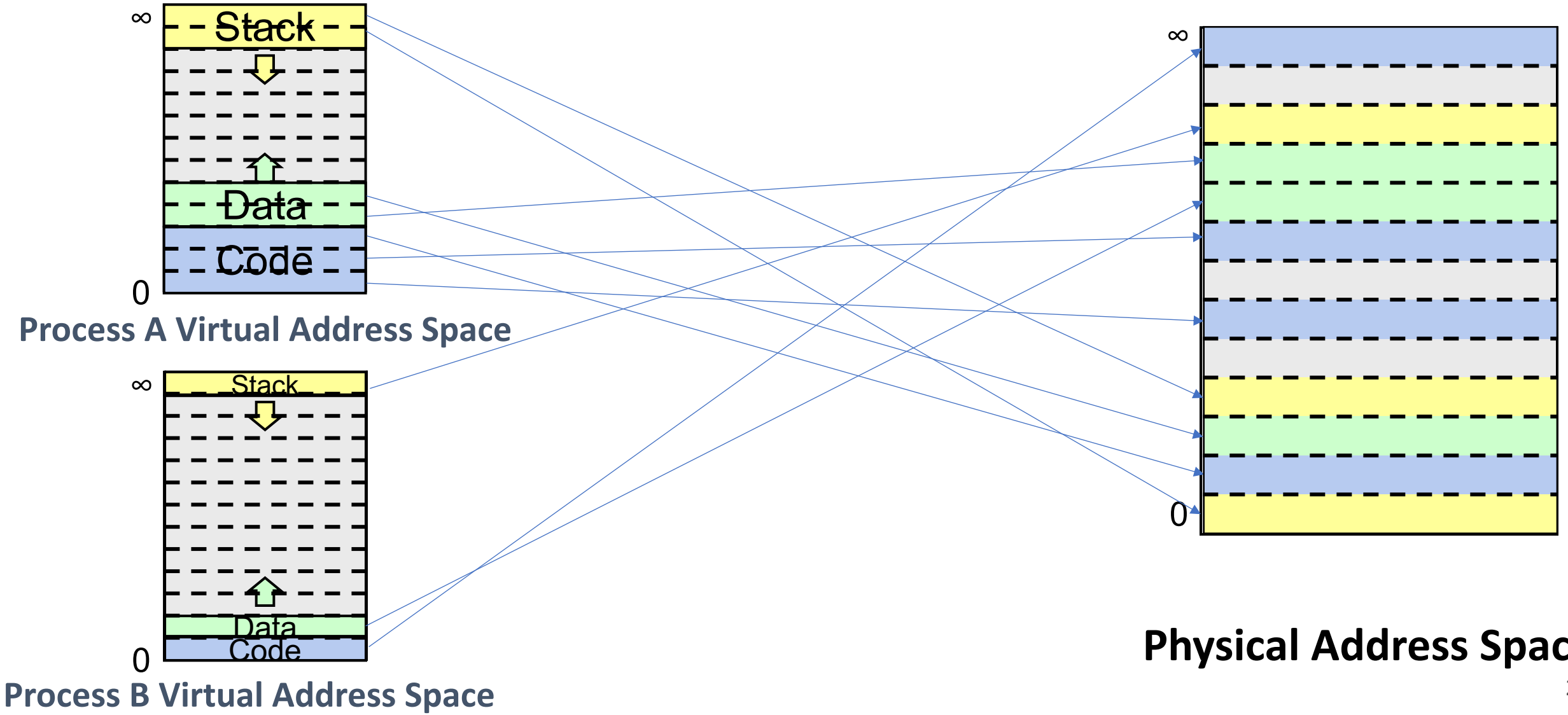
Process A Virtual Address Space

	Physical page #	WR?	PR?
12	3	1	1
11	0	1	1
10	X	X	0
9	X	X	0
8	X	X	0
7	X	X	0
6	X	X	0
5	X	X	0
4	2	1	1
3	9	0	1
2	1	0	1
1	7	0	1
0	5	0	1

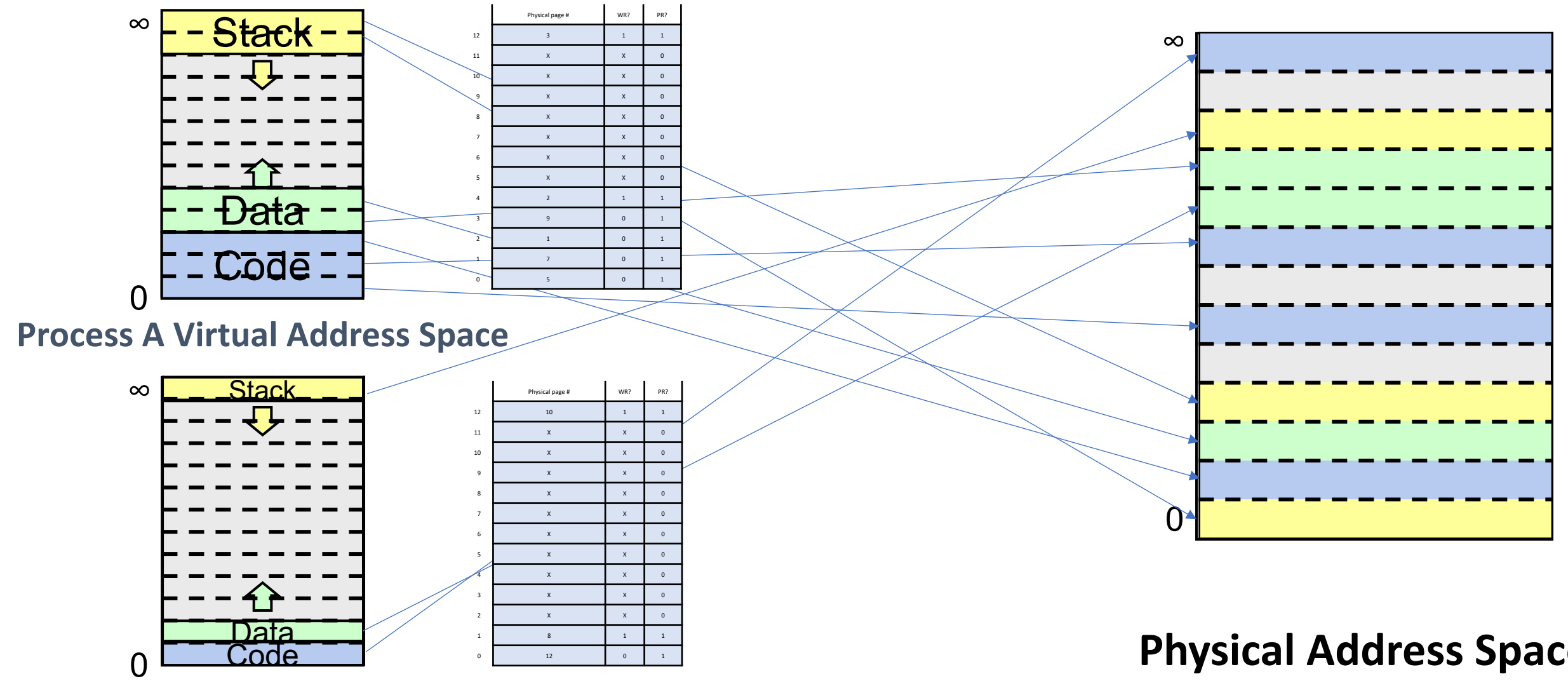


Physical Address Space

Paging


∞
Stack
Data
Code
0
Process A Virtual Address Space
∞
Stack
Data
Code
0
Process B Virtual Address Space
∞
0
Physical Address Space

Each Process Has A Page Map



Paging Summary

Each process has a *page map ("page table")* with an entry for every virtual page, mapping it to a physical page number and other info such as a protection bit (read-only or read-write) and whether it is present.

- The page map is stored in contiguous memory
- All pages the same size – no more external fragmentation! (but some internal fragmentation if not all of a page is used)

Problem: how big is a single process's page map? You said an entry for *every* page?

Plan For Today

- **Recap:** Paging so far
- **Page Map Size**
- Demand Paging

Page Map Size

Problem: how big is a single process's page map? An entry for *every* page?

Example with x86-64: 36-bit virtual page numbers, 8-byte map entries

How many possible virtual page #s? 2^{36}

2^{36} virtual pages x 8 bytes per page entry = ???

Page Map Size

Problem: how big is a single process's page map? An entry for *every* page?

Example with x86-64: 36-bit virtual page numbers, 8-byte map entries

How many possible virtual page #s? 2^{36}

2^{36} virtual pages x 8 bytes per page entry = **512GB!!** (2^{39} bytes)

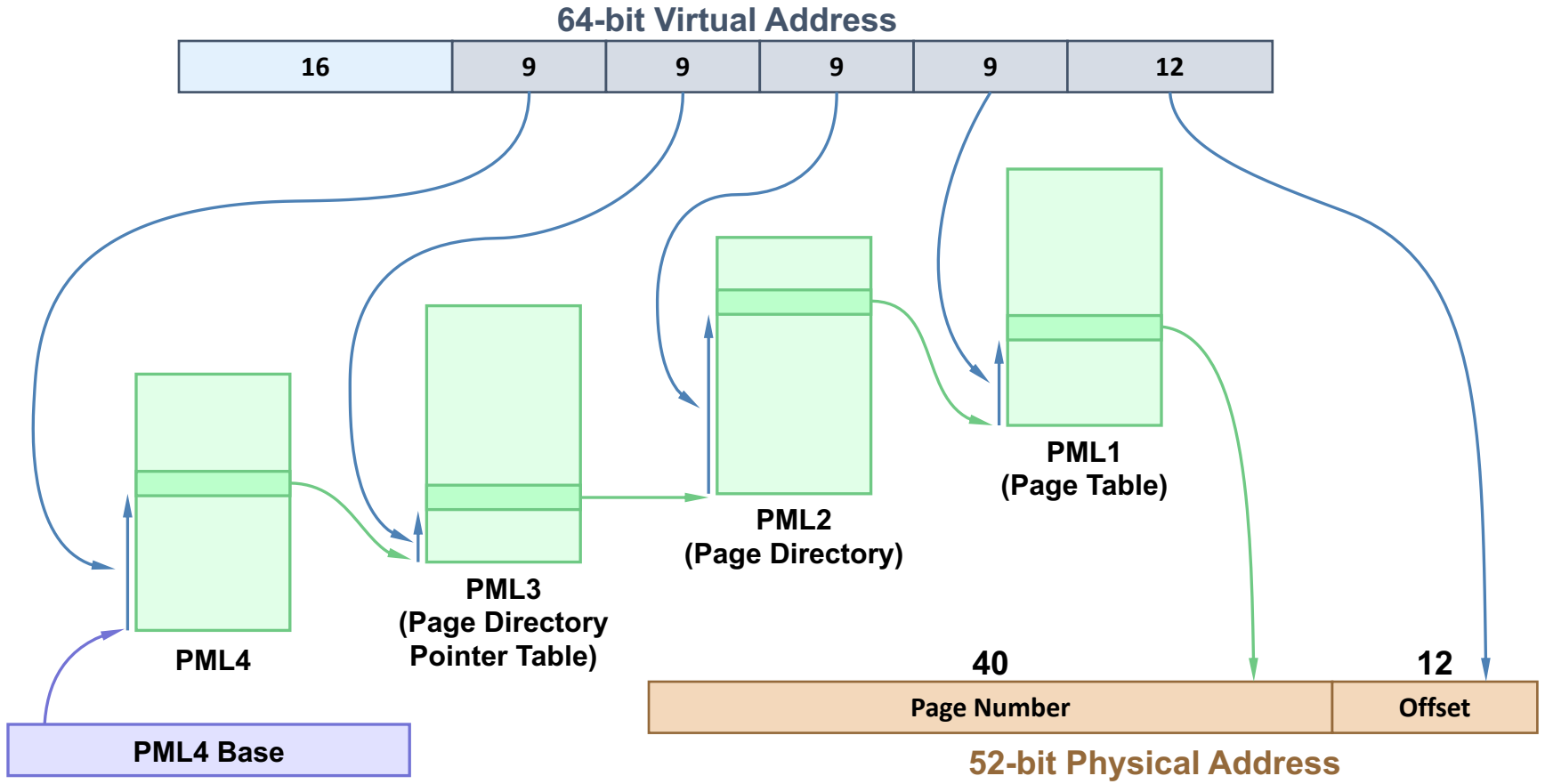
Plus, most processes are small, so most pages will be "not present". And even large processes use their address space sparsely (e.g. code at bottom, stack at top).

Page Map Size

x86-64 solution: represent the page map as a multi-level *tree.*

- Top level of page map has entries for *ranges of virtual pages* (0 to 2^{27}-1), 2^{27} to 2^{54} – 1, etc.). **Only if** any pages in that range are present, that entry points to a lower level in the tree. If not, it doesn't (saves space).
- Lower levels follow a similar structure – entry for ranges of pages, and they only map to something if at least one of the pages in that range is present.
- The lowest level of the tree contains actual physical page numbers.

x86-64 Page Map Tree Structure



*Don’t worry about specifics for now!

assign6

On assign6, you'll implement your own virtual memory system using paging:

- You'll intercept memory requests
- You'll maintain a page map mapping virtual addresses to physical ones

Plan For Today

- Recap: Paging so far
- Page Map Size
- **Demand Paging**

Demand Paging

If memory is in high demand, we could fill up all of memory, since a process needs all its pages in memory to run.

Thought: does a process really need all its allocated pages in memory?

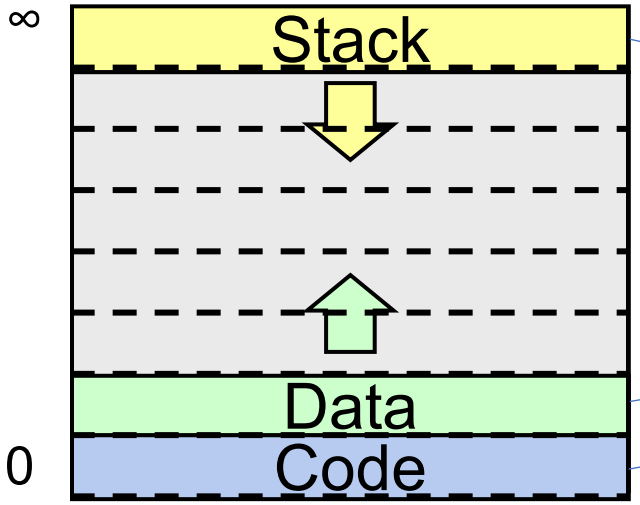
Let's say memory is full, and a process wants another page. We could "borrow" a used physical page – we'll store its existing contents on disk, and then use the page for this new data. If the old contents are referenced later, we'll load them back into a physical page.

Overall goal: make physical memory look larger than it is.

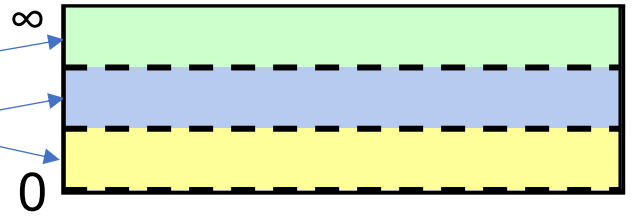
Demand Paging

- Locality – most programs spend most of their time using a small fraction of their code and data
- Keep in memory the information that is being used, and keep unused information on disk, moving info back and forth as needed.
- Ideally: we have a memory system with the performance of main memory and the cost/capacity of disk!

Demand Paging



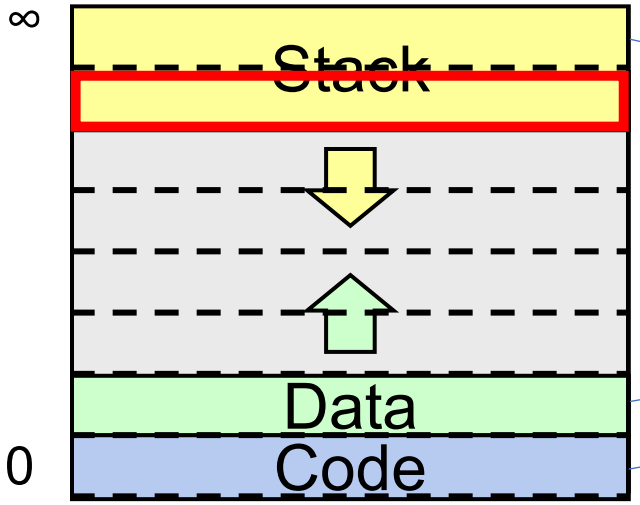
Process A Virtual Address Space



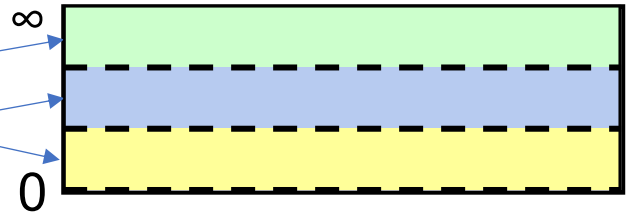
Physical Address Space

	Physical page #	WR?	PR?
7	0	1	1
6	X	X	0
5	X	X	0
4	X	X	0
3	X	X	0
2	X	X	0
1	2	0	1
0	1	0	1

Demand Paging



Process A Virtual Address Space

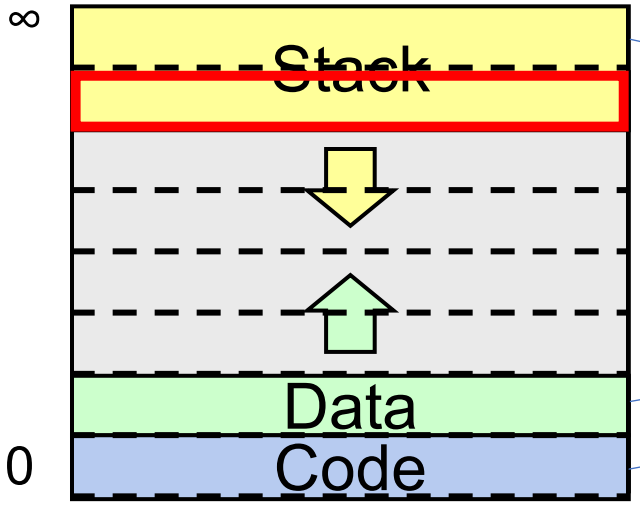


Physical Address Space

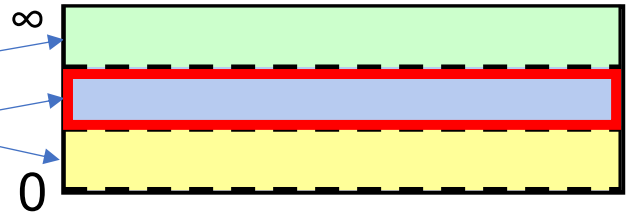
	Physical page #	WR?	PR?
7	0	1	1
6	X	X	0
5	X	X	0
4	X	X	0
3	X	X	0
2	X	X	0
1	2	0	1
0	1	0	1

1. Pick an existing physical page and swap it to disk.

Demand Paging

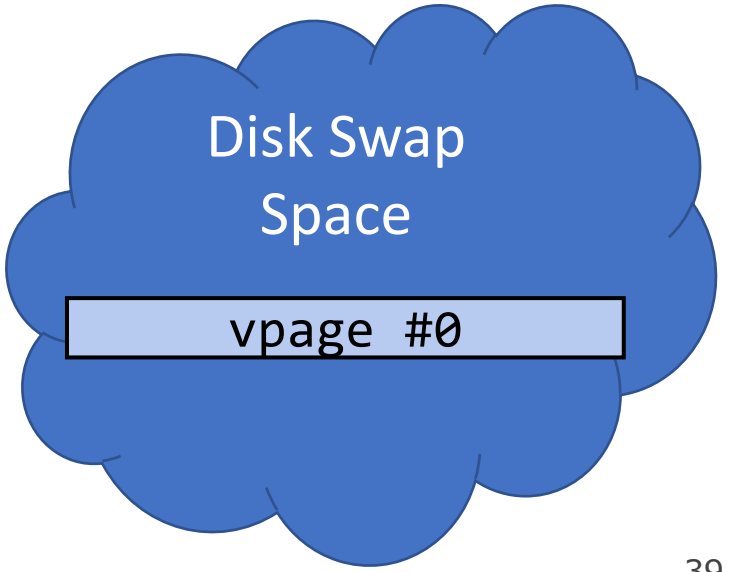


Process A Virtual Address Space



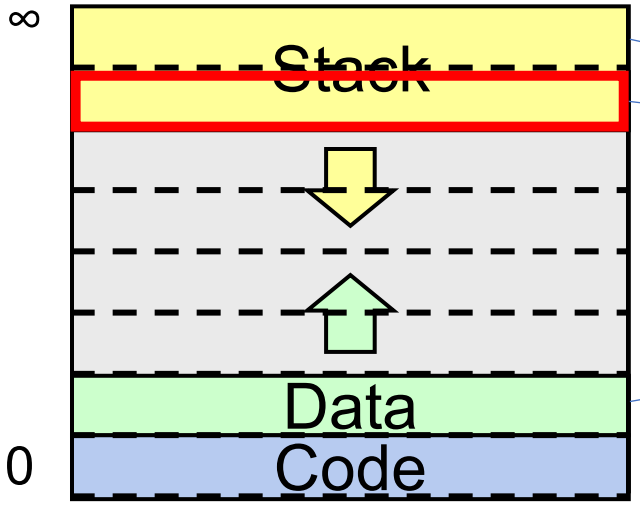
Physical Address Space

	Physical page #	WR?	PR?
7	0	1	1
6	X	X	0
5	X	X	0
4	X	X	0
3	X	X	0
2	X	X	0
1	2	0	1
0	1	0	0

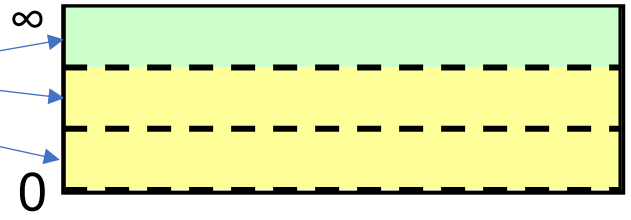


1. Pick an existing physical page and swap it to disk, mark not present.

Demand Paging

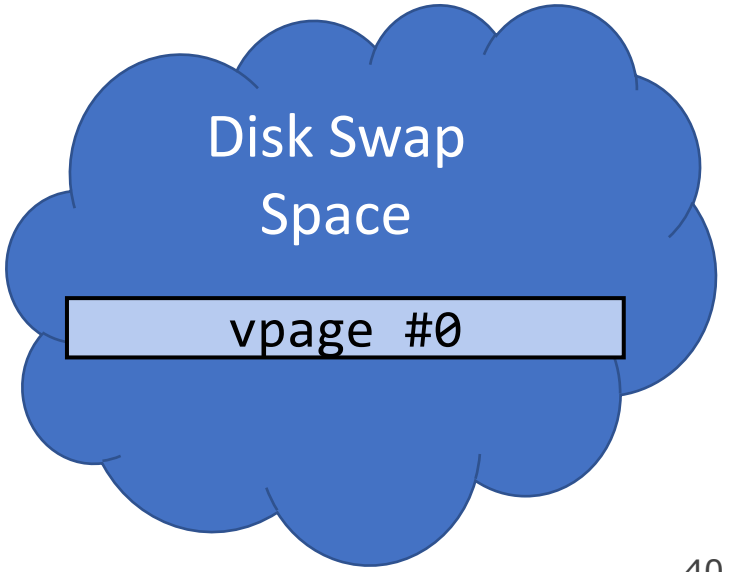


Process A Virtual Address Space



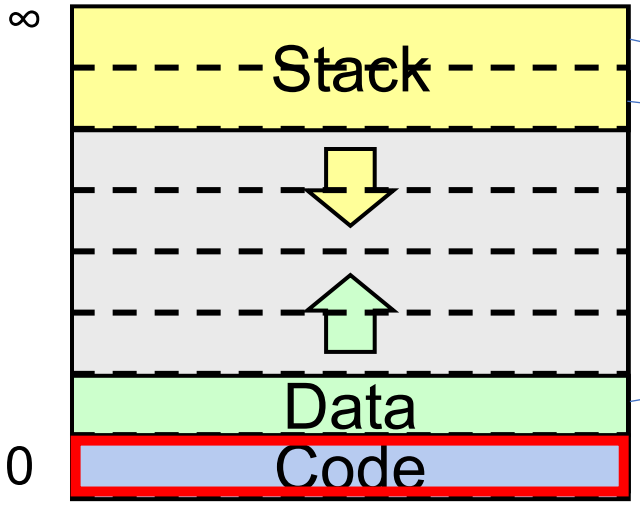
Physical Address Space

	Physical page #	WR?	PR?
7	0	1	1
6	1	1	1
5	X	X	0
4	X	X	0
3	X	X	0
2	X	X	0
1	2	0	1
0	1	0	0

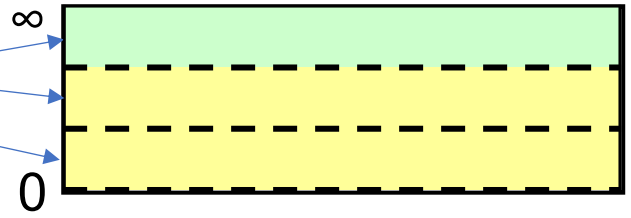


2. Map this physical page to the new virtual page.

Demand Paging

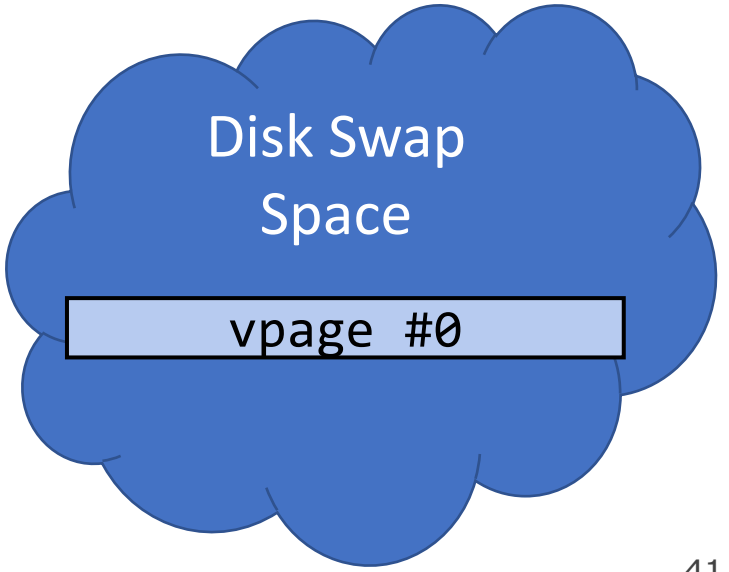


Process A Virtual Address Space



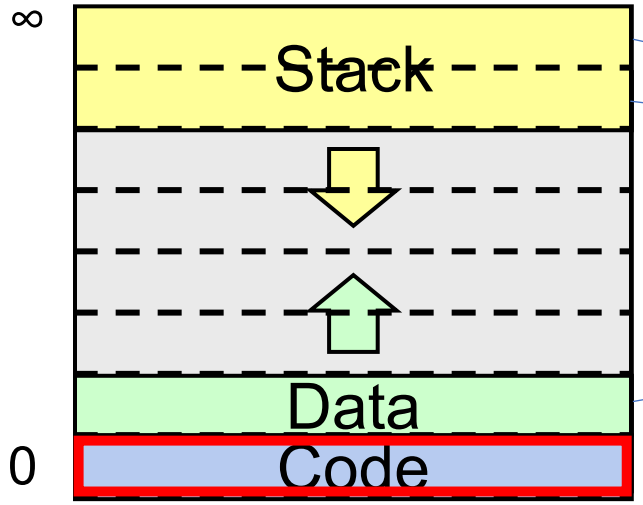
Physical Address Space

	Physical page #	WR?	PR?
7	0	1	1
6	1	1	1
5	X	X	0
4	X	X	0
3	X	X	0
2	X	X	0
1	2	0	1
0	1	0	0

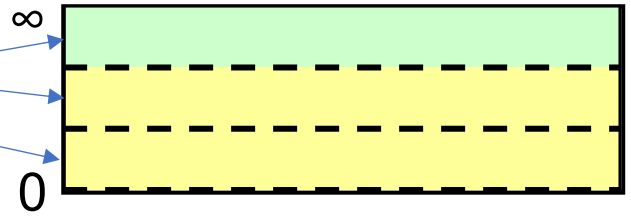


1. We look in the page map and see it's not present.

Demand Paging



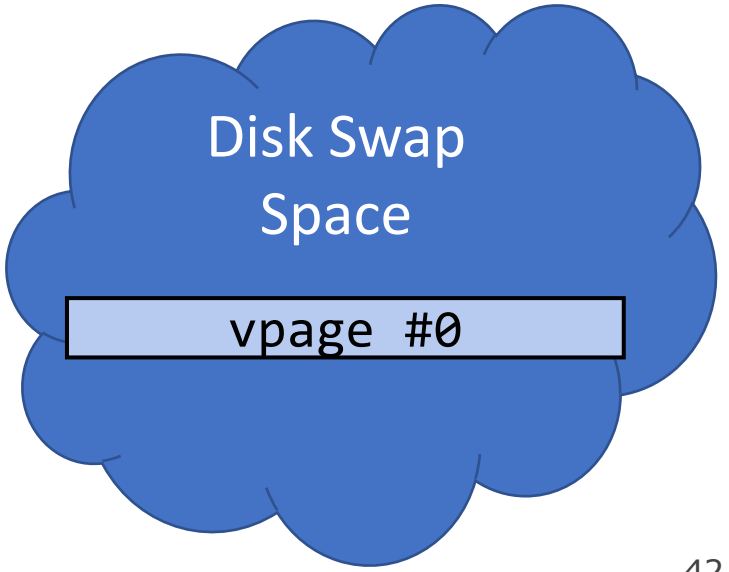
Process A Virtual Address Space



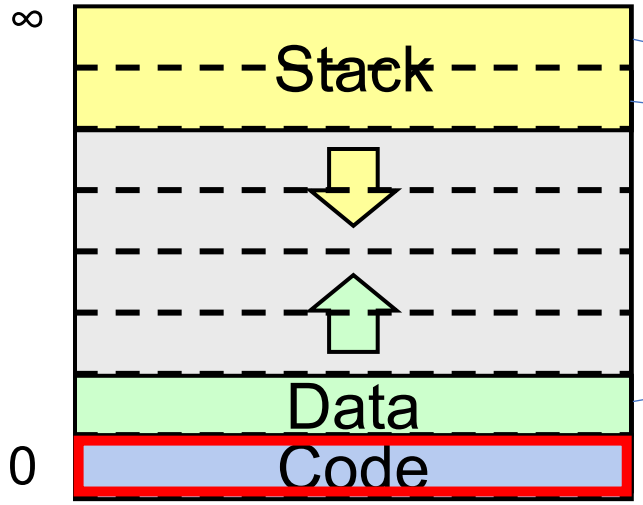
Physical Address Space

	Physical page #	WR?	PR?
7	0	1	1
6	1	1	1
5	X	X	0
4	X	X	0
3	X	X	0
2	X	X	0
1	2	0	1
0	1	0	0

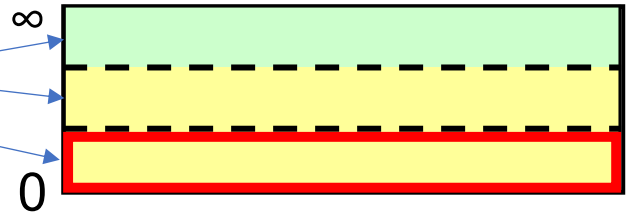
2. But it is stored in disk swap, so we load it back in (kicking another page if needed).



Demand Paging



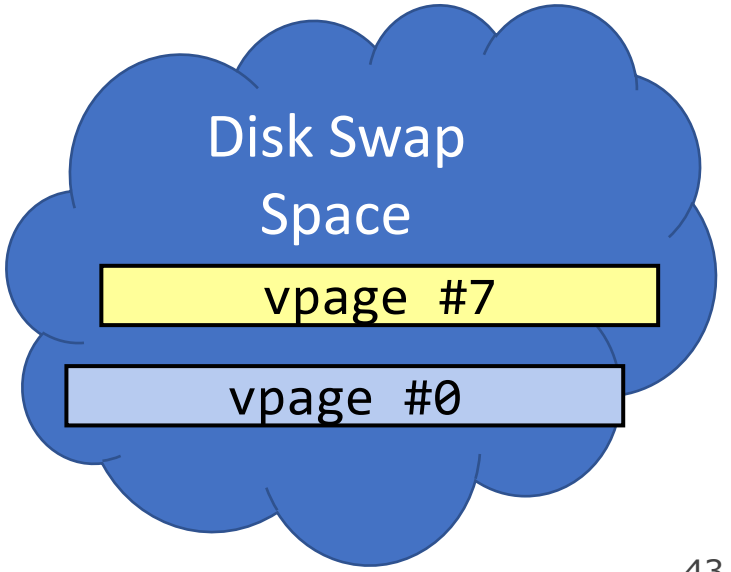
Process A Virtual Address Space



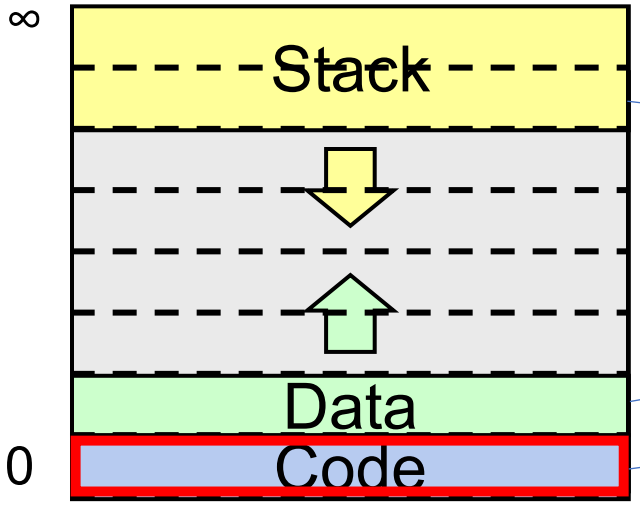
Physical Address Space

	Physical page #	WR?	PR?
7	0	1	0
6	1	1	1
5	X	X	0
4	X	X	0
3	X	X	0
2	X	X	0
1	2	0	1
0	1	0	0

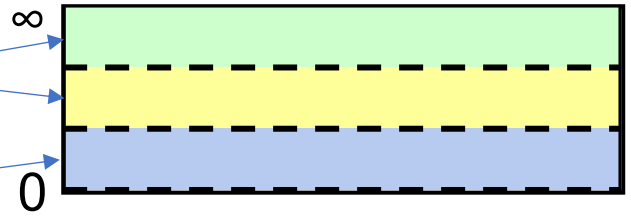
2. But it is stored in disk swap, so we load it back in (kicking another page if needed).



Demand Paging

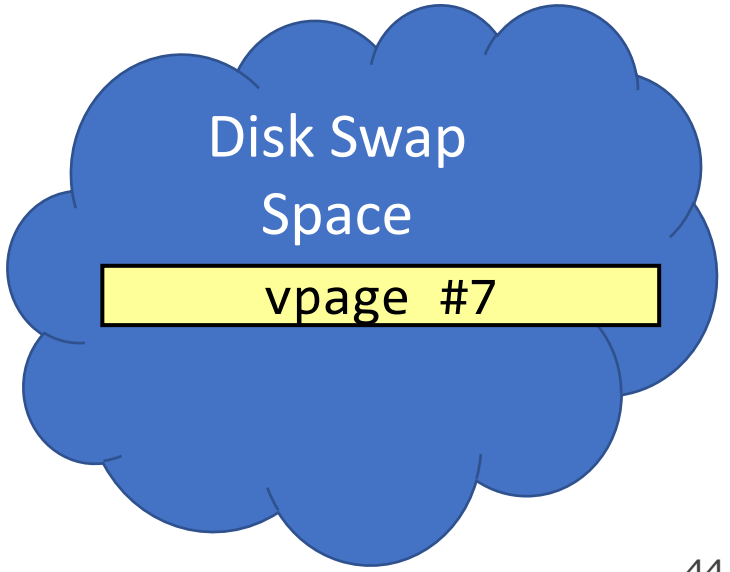


Process A Virtual Address Space



Physical Address Space

	Physical page #	WR?	PR?
7	0	1	0
6	1	1	1
5	X	X	0
4	X	X	0
3	X	X	0
2	X	X	0
1	2	0	1
0	0	0	1



2. But we look in the disk swap and see it is stored there, so we load it back in (kicking another page if needed).

Demand Paging

If we need another page but memory is full:

1. Pick a page to kick out
2. Write it to disk
3. Mark the old page map entry as not present
4. Update the new page map entry to be present and map to this physical page

Demand Paging

If the program accesses a page that was swapped to disk:

1. Triggers a page fault (not-present page accessed)
2. We see disk swap contains data for this page
3. Get a new physical page (perhaps kicking out another one)
4. Load the data from disk into that page
5. Update the page map with this new mapping

Disk Swap

We don't always need to write a swapped-out page to disk – e.g. read-only code pages can always be loaded from executable. And we may have initial data for a page that wasn't previously swapped out.

There are three categories of pages for swapping to disk:

1. **Read-only code pages**: read from executable when needed
2. **Initialized data pages:** on first access, read from executable. Once loaded, save to swap file since contents may have changed.
3. **Uninitialized data pages:** e.g. stack, heap – on first access, just clear memory to all zeros. Save to swap file as needed.

Thrashing

This can provide big benefits – but what potential scenario would lead demand paging to slow the system way down?

If the pages being actively used don't all fit in memory, the system will spend all its time reading and writing pages to/from disk and won't get much work done.

- Called *thrashing*
- The page we kick to disk will be needed very soon, so we will bring it back and kick another page, which will be needed very soon, etc….
- Progress of the program will make it look like access time of memory is as slow as disk, rather than disks being as fast as memory. ☹
- With personal computers, users can notice thrashing and kill some processes

Page Fetching

When should we bring pages into memory?

- Most modern OSes start with no pages loaded, load pages when referenced ("demand fetching").
- Alternative: *prefetching* - try to predict when pages will be needed and load them ahead of time (requires predicting the future…)

Which pages should we throw out of memory if we need more space?

Page Replacement

If we need another physical page but all memory is used, **which page should we throw out?**

- Random? (works surprisingly well!)
- FIFO? (throw out page that's been in memory the longest) – fairness
- Would be nice if we could pick page whose next access is farthest in the future, but we'd need to predict the future…
- LRU (least-recently-used)? Replace page that was accessed the longest time ago.

More next time…

Recap

- Recap: Paging so far
- Page Map Size
- Demand Paging

Lecture 24 takeaway: We can make memory appear larger than it is by swapping pages to disk when we need more space and swapping them back later.

Next time: how to choose which pages to swap to disk (the clock algorithm).