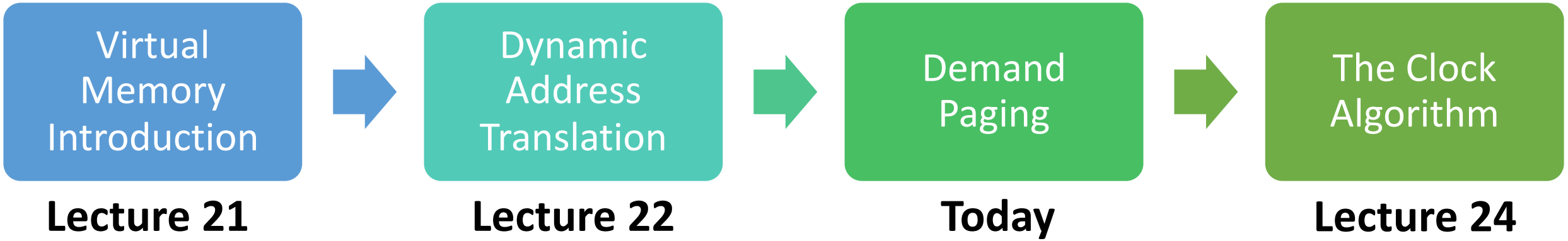
CS111, Lecture 23
Demand Paging

Optional reading:

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

CS111 Topic 4: Virtual Memory

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?*



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:** Base and bound, multiple segments, and paging
- Page Map Size
- Demand Paging

Plan For Today

- **Recap: Base and bound, multiple segments, and paging**
- Page Map Size
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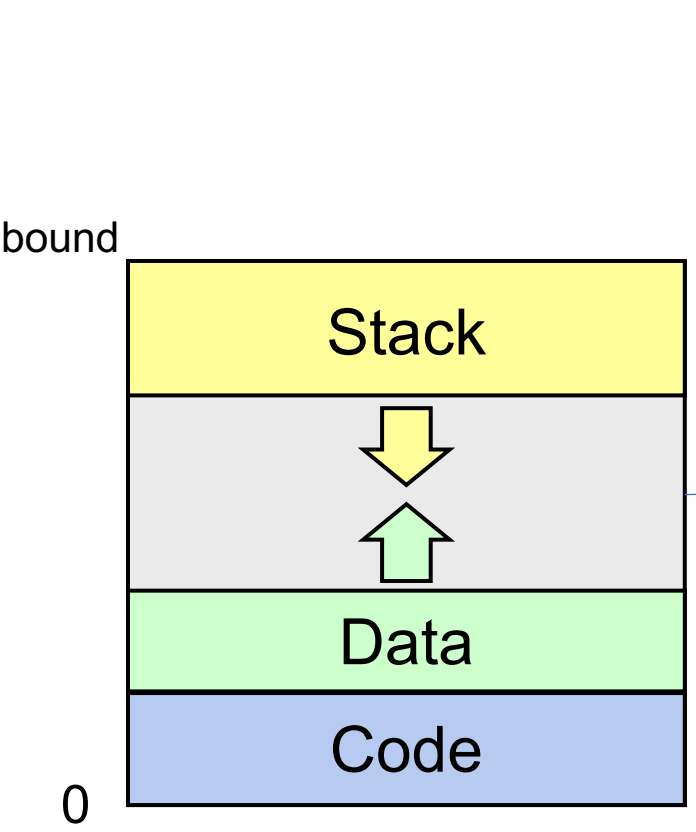
Dynamic Address Translation

Key question: how do the MMU / OS translate from virtual addresses to physical ones? Three designs we'll consider:

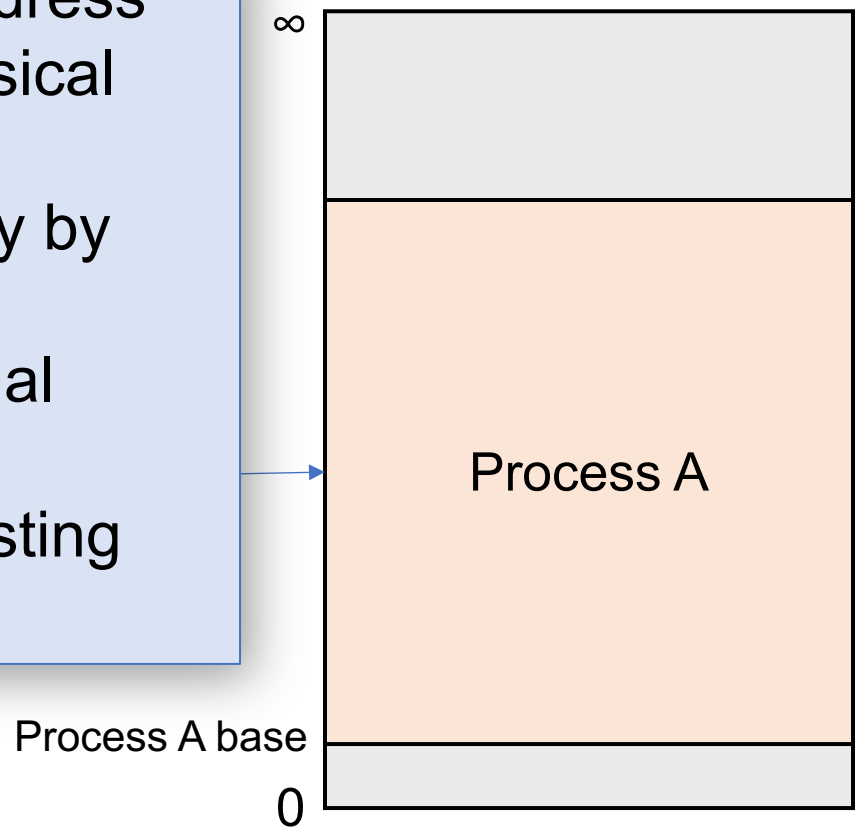
1. **Base and bound**
2. **Multiple Segments**
3. **Paging**

Base and Bound

- Must map entire virtual address space contiguously in physical memory.
- Move it in physical memory by modifying the base.
- The base is pinned to virtual address 0.
- Make more space by adjusting the bound.

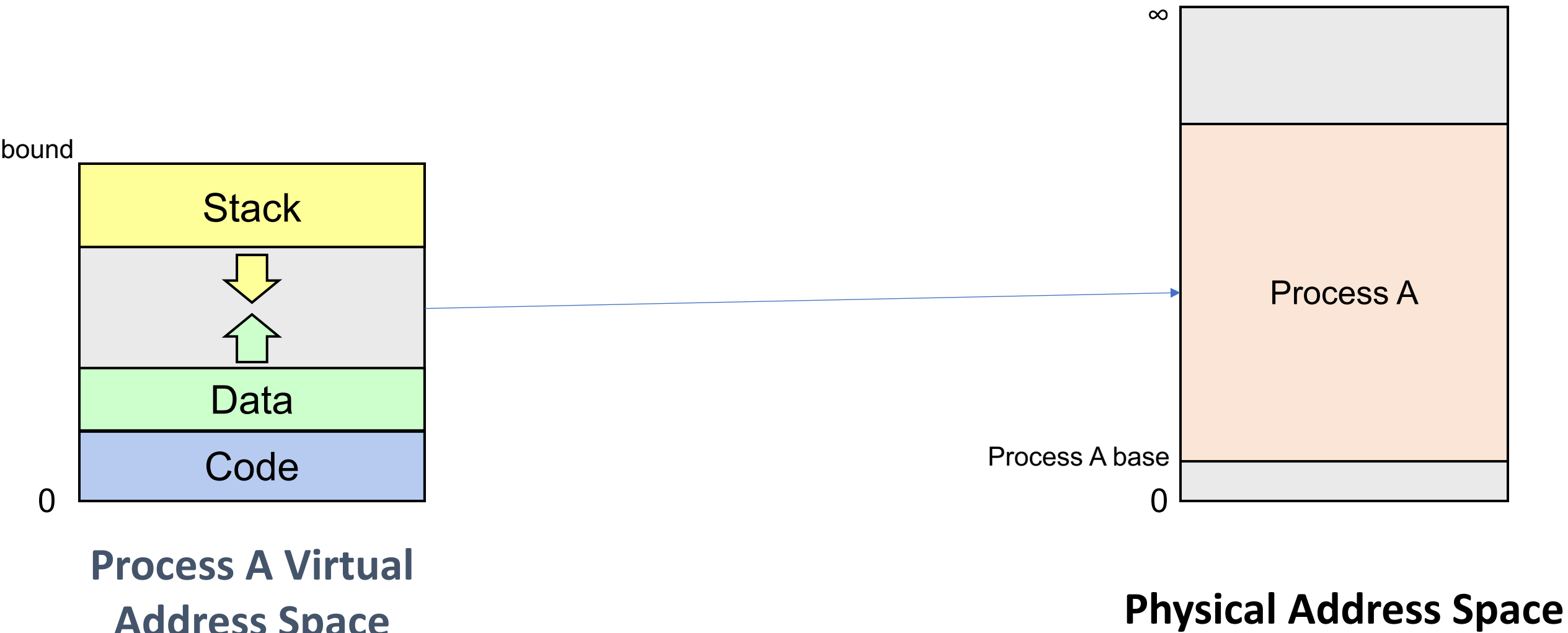


Process A Virtual Address Space



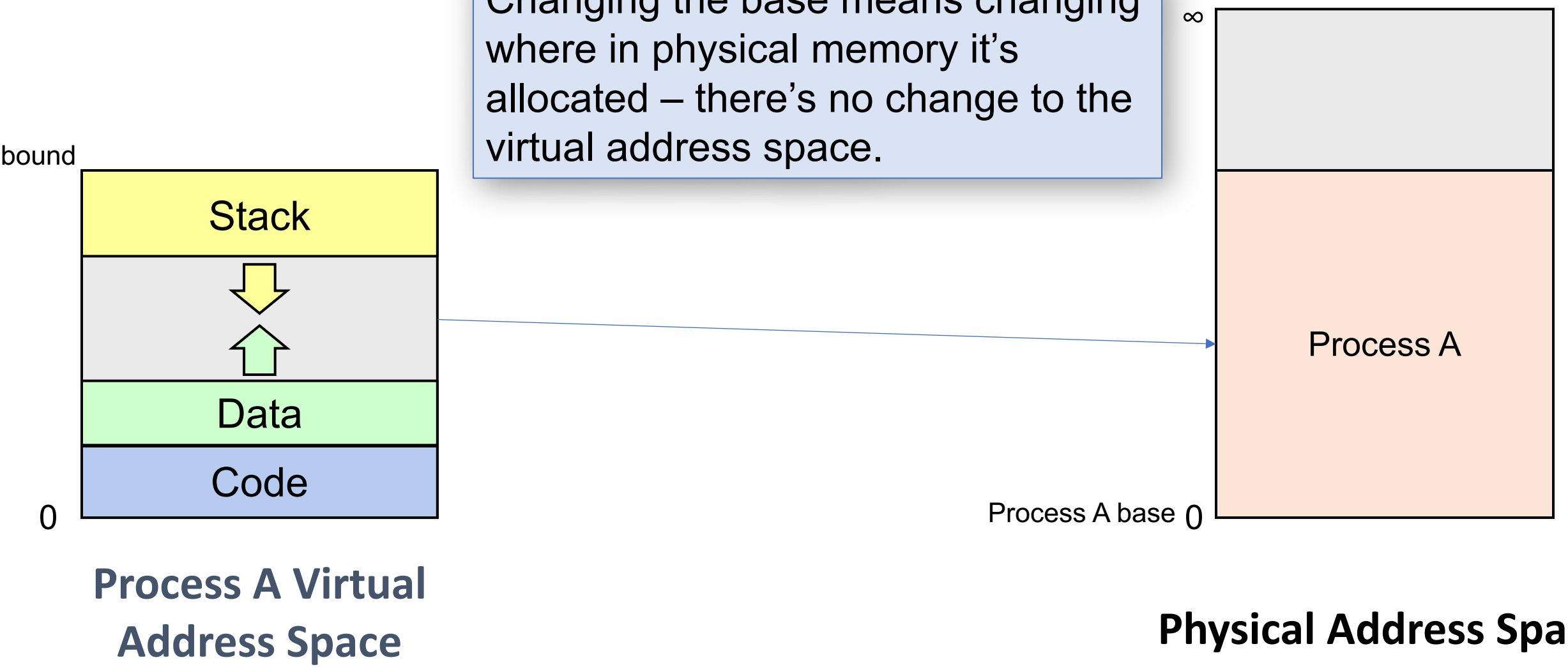
Physical Address Space

Base and Bound – Changing Base



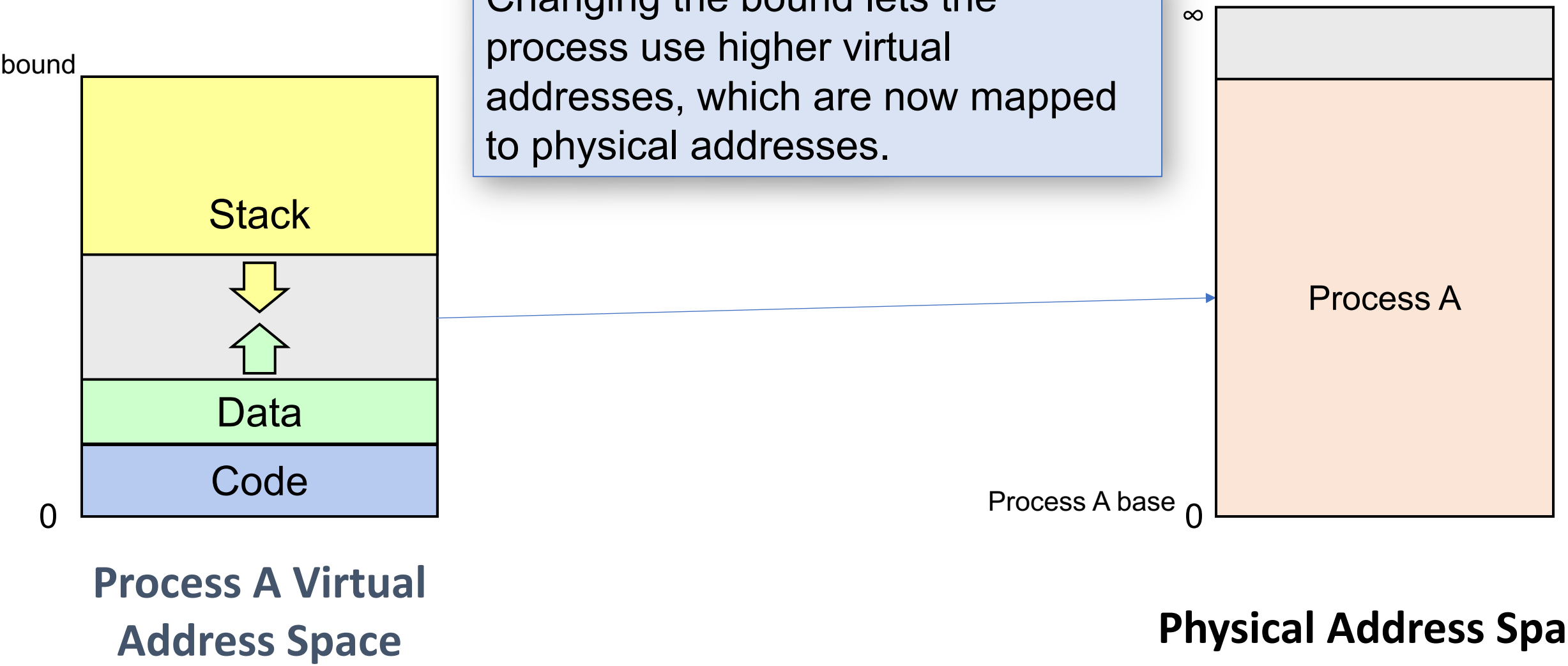
Base and Bound – Changing Base

Changing the base means changing where in physical memory it's allocated – there's no change to the virtual address space.



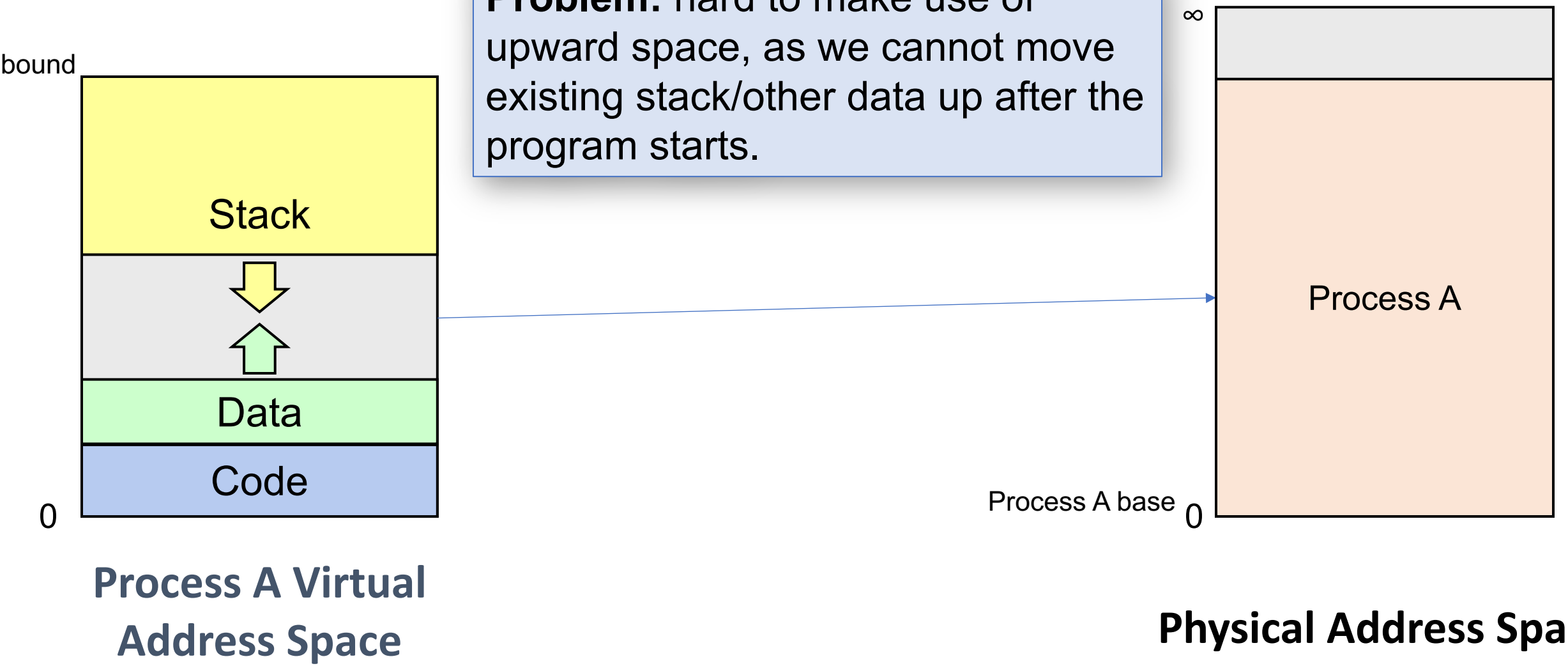
Base and Bound – Changing Bound

Changing the bound lets the process use higher virtual addresses, which are now mapped to physical addresses.

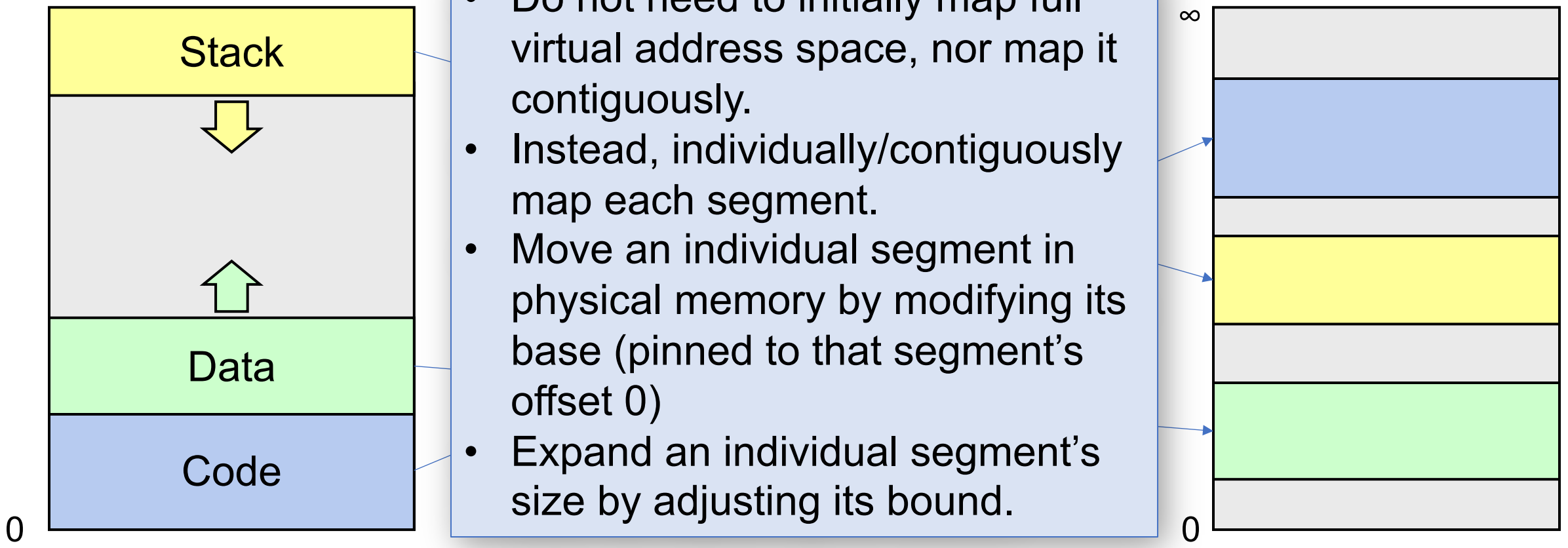


Base and Bound – Changing Bound

Problem: hard to make use of upward space, as we cannot move existing stack/other data up after the program starts.



Multiple Segments

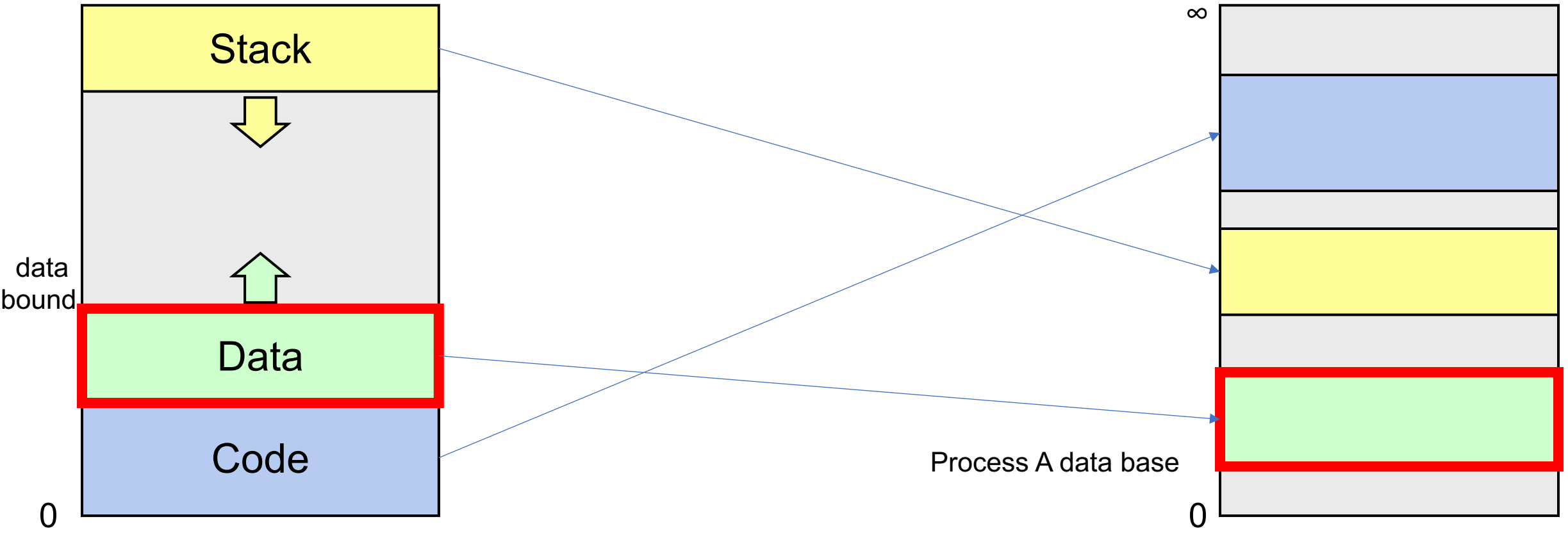


- Do not need to initially map full virtual address space, nor map it contiguously.
- Instead, individually/contiguously map each segment.
- Move an individual segment in physical memory by modifying its base (pinned to that segment's offset 0)
- Expand an individual segment's size by adjusting its bound.

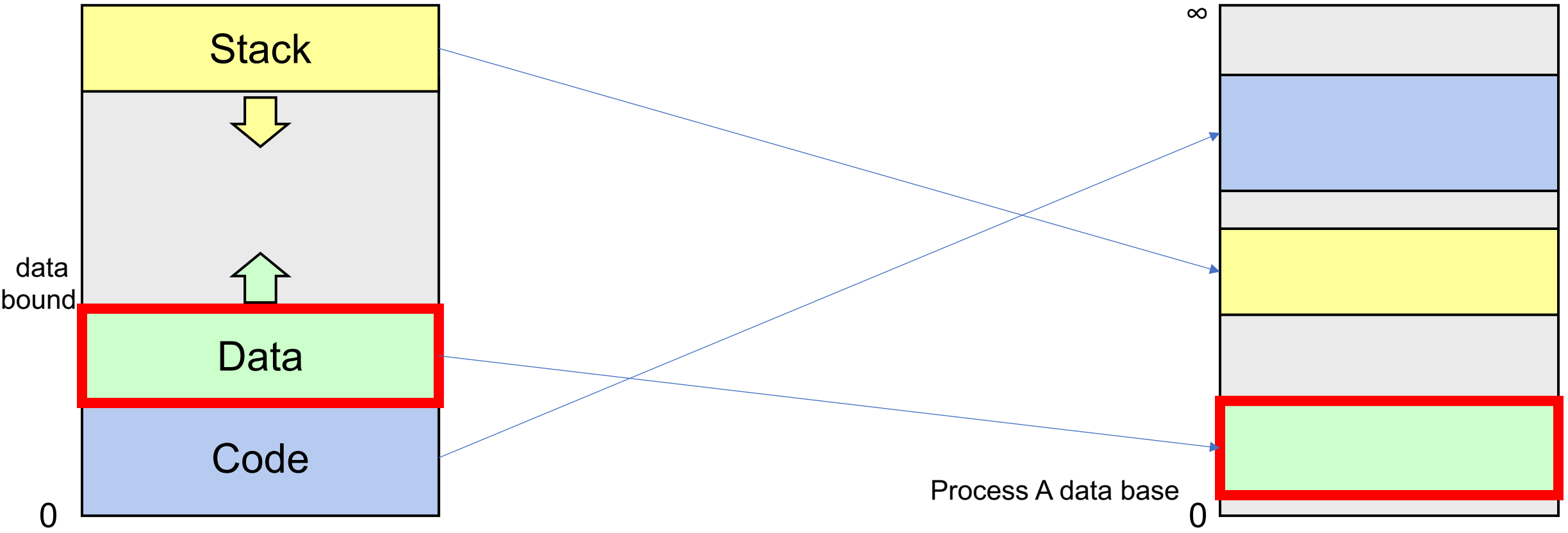
Process A Virtual Address Space

Physical Address Space

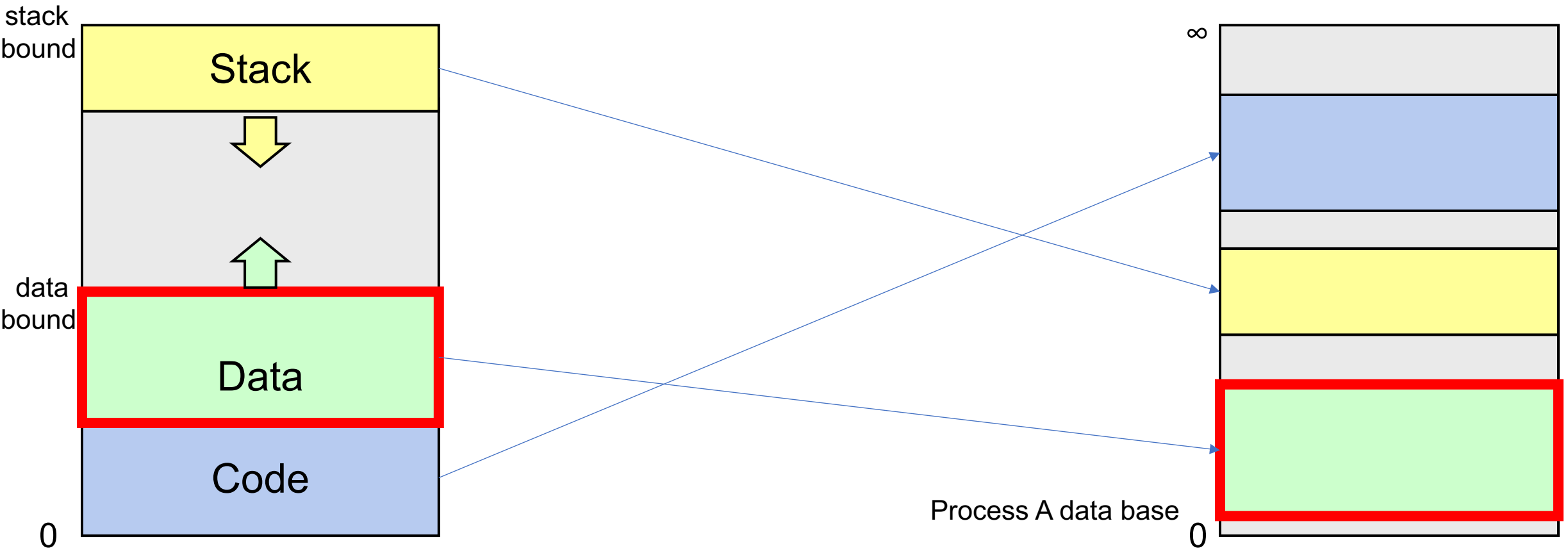
Multiple Segments – Changing A Base



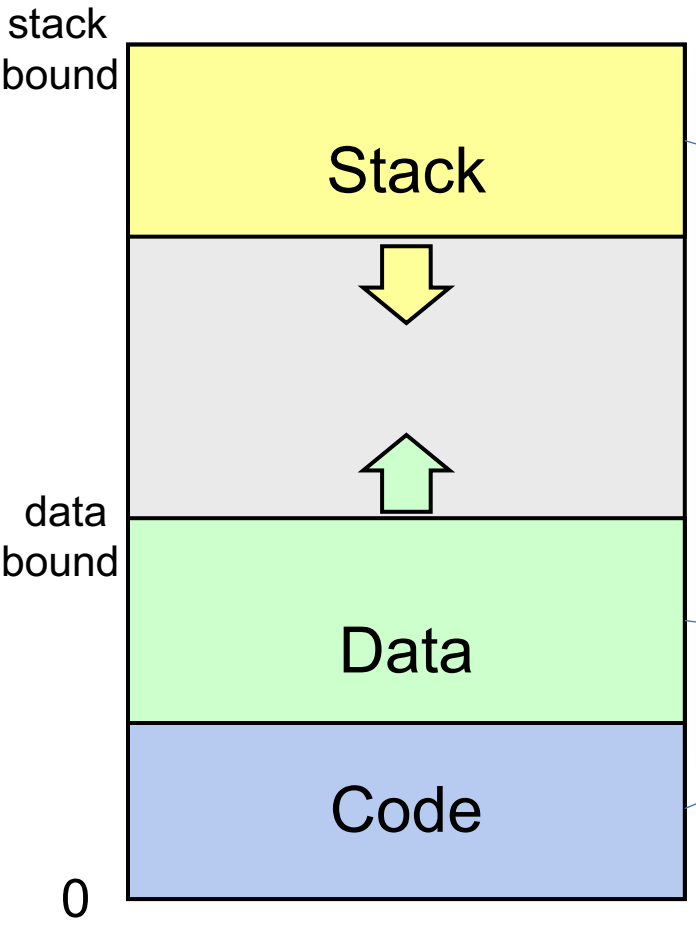
Multiple Segments – Changing A Base



Multiple Segments – Changing A Bound

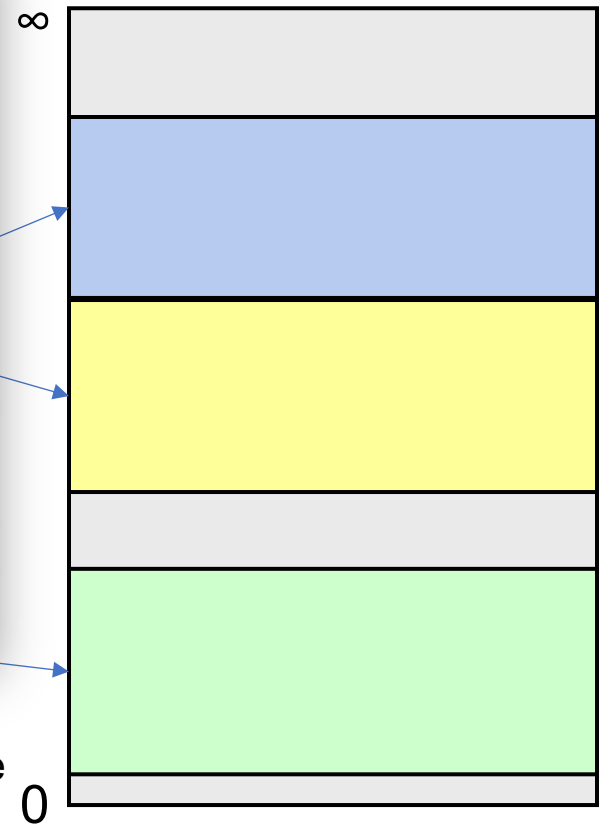


Multiple Segments – Changing A Bound



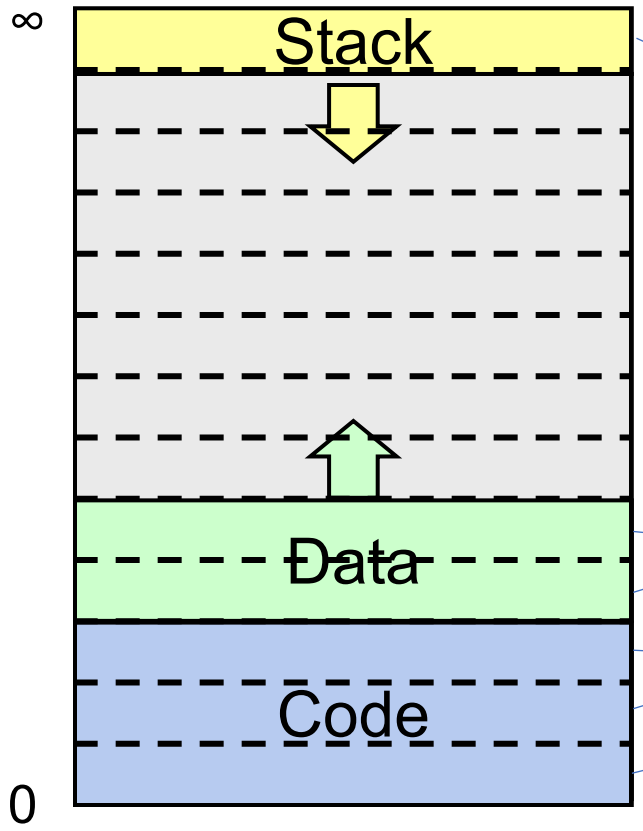
Process A Virtual Address Space

- Buffer space between stack + heap doesn't need to be initially mapped.
- Growing a segment upwards works well for the heap, but not for the stack, for the same reason as base and bound: we can't move existing stack data after the program starts.



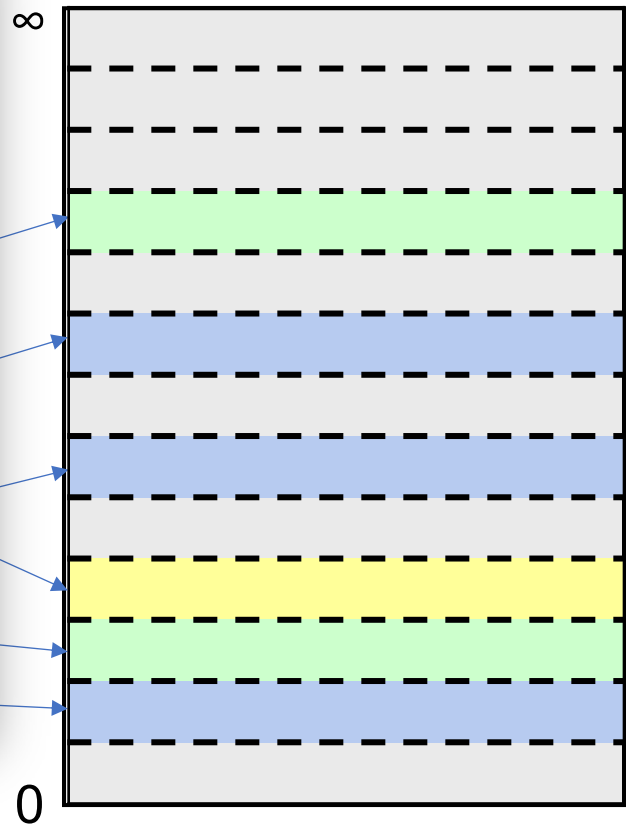
Physical Address Space

Paging



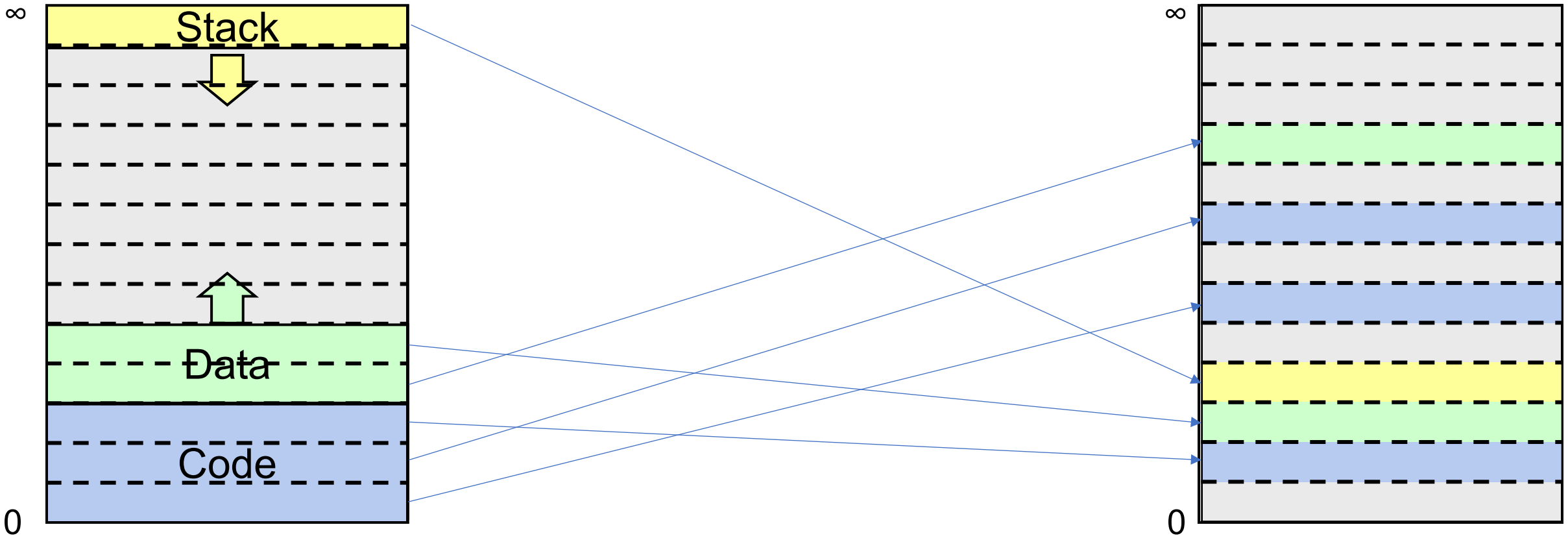
Process A Virtual Address Space

- Do not need to map each segment contiguously. Instead, we map just one page at a time.
- We can later map more pages either up or down, **because the start of the segment is not pinned to a physical address**.
- We can move each page separately in physical memory by modifying the page map.



Physical Address Space

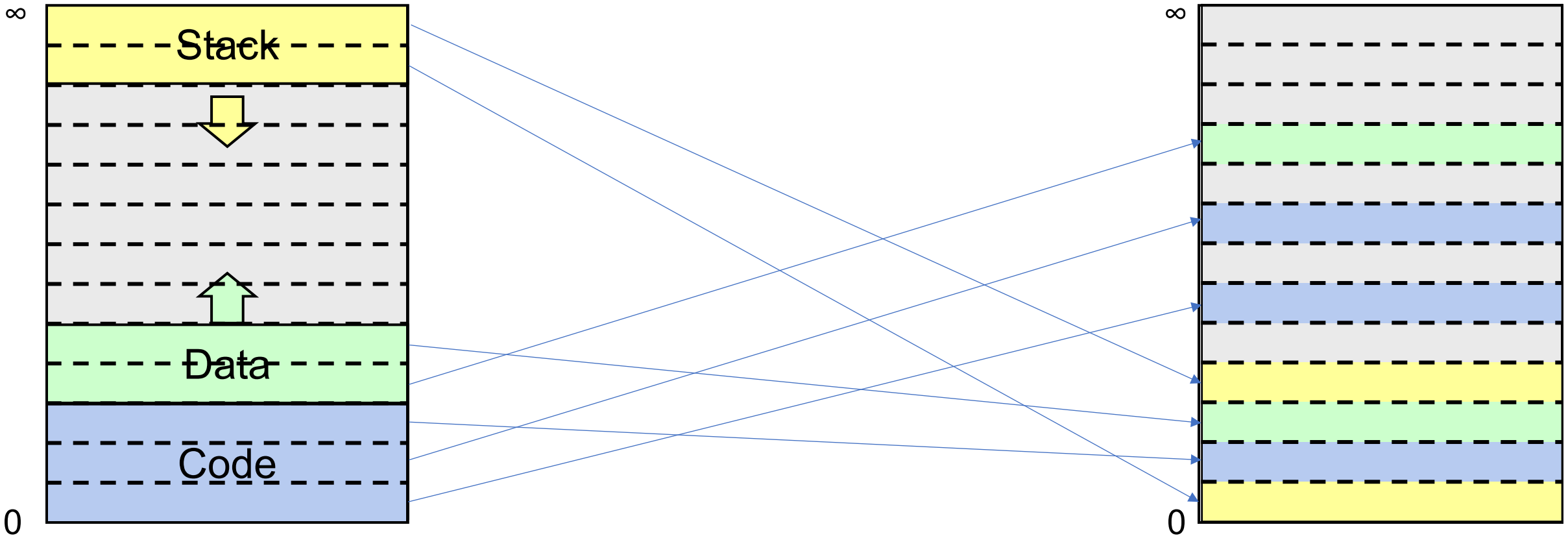
Paging



Process A Virtual Address Space

Physical Address Space

Paging



Process A Virtual Address Space

Physical Address Space

Paging

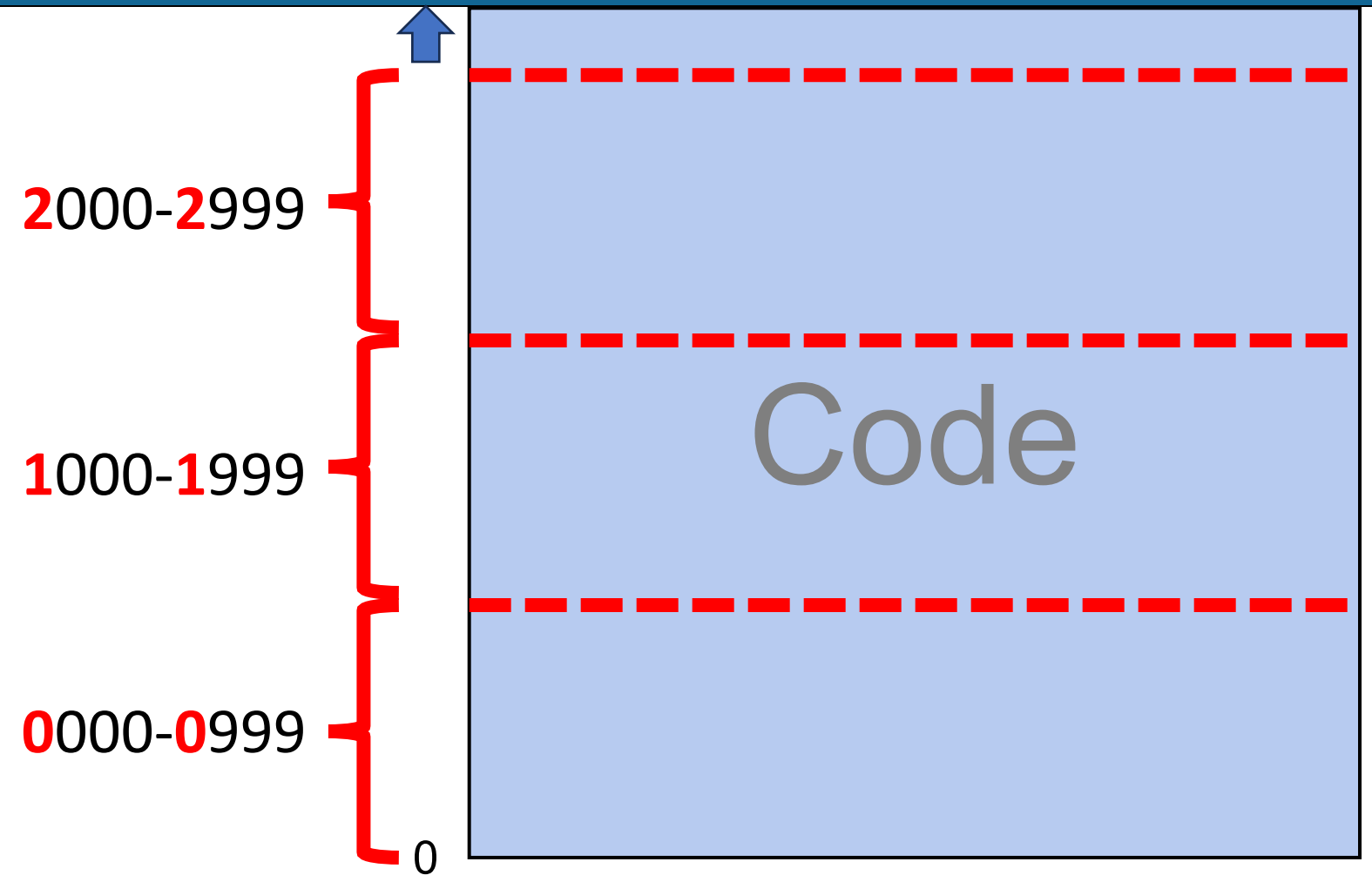
Key Idea: Each process's virtual (and physical) memory is divided into fixed-size chunks called *pages*. (Common size is 4KB pages).

- A "page" of virtual memory maps to a "page" of physical memory. No partial pages. No more external fragmentation! (but some internal fragmentation if not all of a page is used).
- 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).
- A memory address can tell us the page number and offset within that page.

Virtual Address Encodes Page + Offset

Key idea: if you pick a page size that is a power of the base, the upper digits identify the page #.

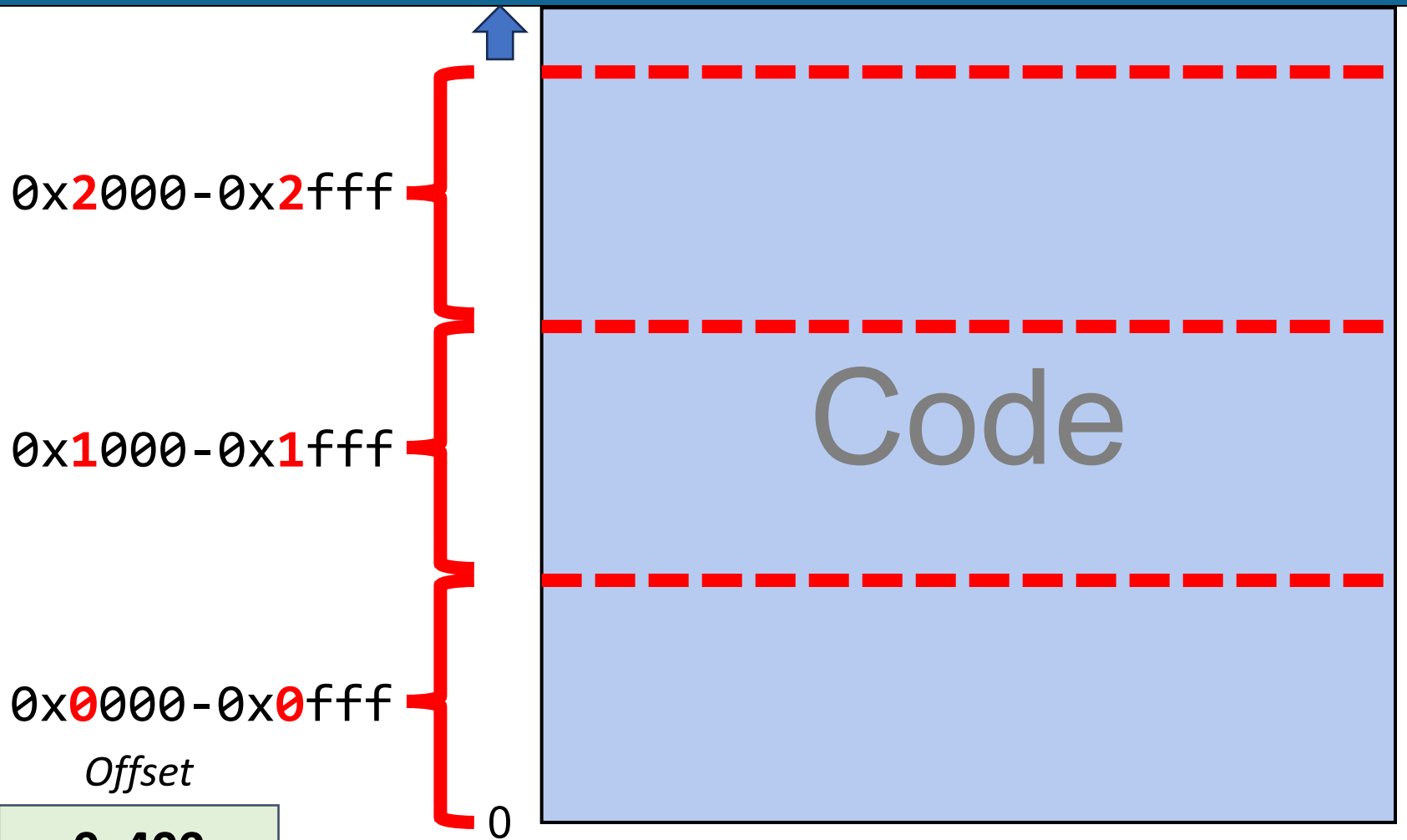
E.g. base 10, say page size = 10^3 = 1000:



Virtual Address Encodes Page + Offset

Key idea: if you pick a page size that is a power of the base, the upper digits identify the page #.

E.g. base 16, say page size = 16^3 = 4096:

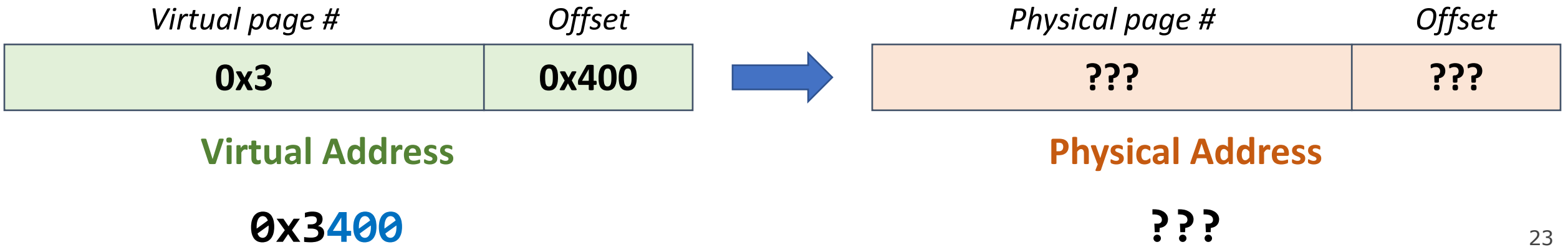


Virtual page #	*Offset*
0x323	**0x400**

Virtual Address **0x323400**

Page Map

Index	Physical page #	Writeable?
…	…	…
3	0x2342	1
2	0x12625	1
1	0x13241	0
0	0x256	0



Page Map

Index	Physical page #	Writeable?
…	…	…
3	0x2342	1
2	0x12625	1
1	0x13241	0
0	0x256	0

Virtual Address

0x3400

Physical Address

???

Page Map

Index	Physical page #	Writeable?
…	…	…
3	0x2342	1
2	0x12625	1
1	0x13241	0
0	0x256	0

Virtual Address

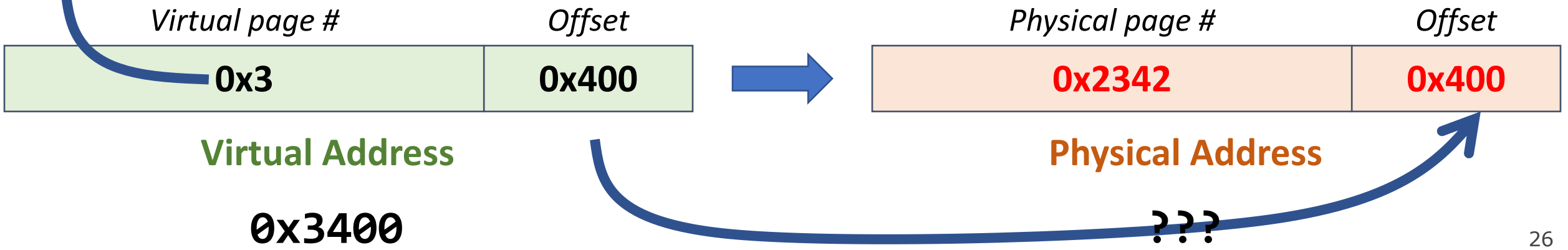
0x3400

Physical Address

???

Page Map

Index	Physical page #	Writeable?
…	…	…
3	0x2342	1
2	0x12625	1
1	0x13241	0
0	0x256	0



Page Map

Index	Physical page #	Writeable?
…	…	…
3	0x2342	1
2	0x12625	1
1	0x13241	0
0	0x256	0

Virtual Address

0x3400

Physical Address

0x2342400

Paging

On each memory reference:

- Look up info for that virtual page in the page map
- If it's a valid virtual page number, get the physical page number it maps to, and combine it with the specified offset to produce the physical address.

Problem: what about invalid page numbers? I.e. how do we know/represent which pages are valid or invalid?

Plan For Today

- **Recap:** Base and bound, multiple segments, and paging
- **Page Map Size**
- Demand Paging

Paging

Problem: what about invalid page numbers? I.e. how do we know/represent which pages are valid or invalid?

Solution: have entries in the page map for *all* pages, including invalid ones. Add an additional field marking whether it's valid ("present").

The page map is stored in contiguous memory.

Page Map

Index	Physical page #	Writeable?	Present?
…	…	…	…
3	0x2342	1	1
2	XXX	X	0
1	0x13241	0	1
0	XXX	X	0

Page Map

Index	Physical page #	Writeable?	Present?
…	…	…	…
3	0x2342	1	1
2	XXX	X	0
1	0x13241	0	1
0	XXX	X	0

If there is a memory access in virtual pages 0 or 2 here, it would trap due to an invalid memory reference.

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 does that entry point to a lower level in the tree (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.

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:** Base and bound, multiple segments, and paging
- Page Map Size
- **Demand Paging**

Running Out Of Memory

If memory is in high demand, we could fill up all of memory, since a process needs all its pages in memory to run. What should we do in that case?

- Prohibit further program memory requests until some is freed? Not ideal.
- Another idea – what if we kicked out a page and used that page? We could save a page to disk, use the page for new data, and load the old data back in to a physical page later if it's still needed.

We can make physical memory look larger than it is!

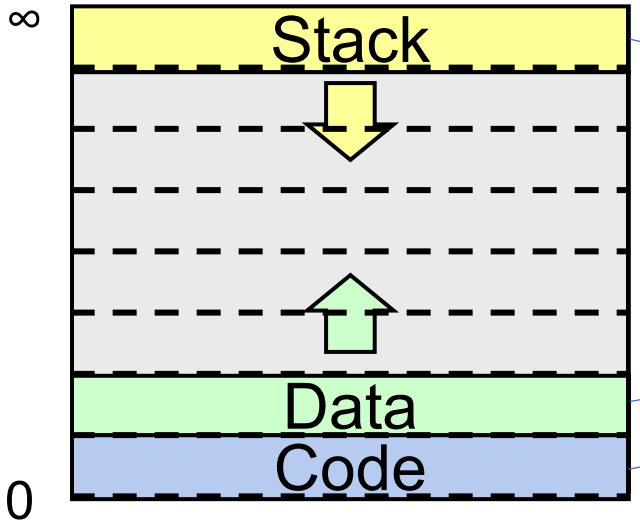
Demand Paging

Overall goal: allow programs to run without all their information in memory.

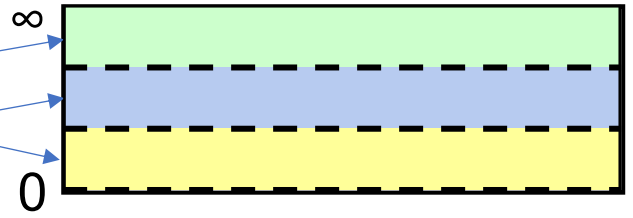
- Keep in memory the information that is being used.
- Keep unused information on disk in *paging file* (also called backing store, or swap space)
- Move information back and forth as needed.
- Locality – most programs spend most of their time using a small fraction of their code and data

Ideally: we have a memory system with the performance of main memory and the cost/capacity of disk!

Demand Paging



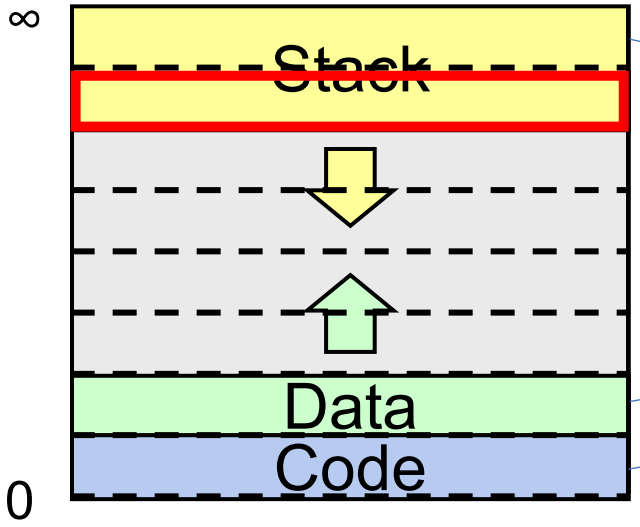
Process A Virtual Address Space



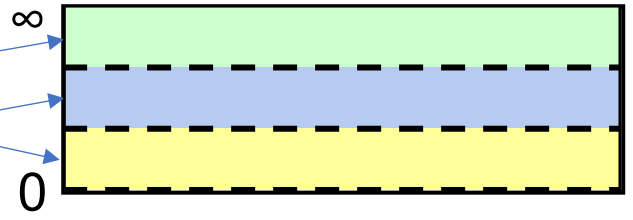
Physical Address Space

	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

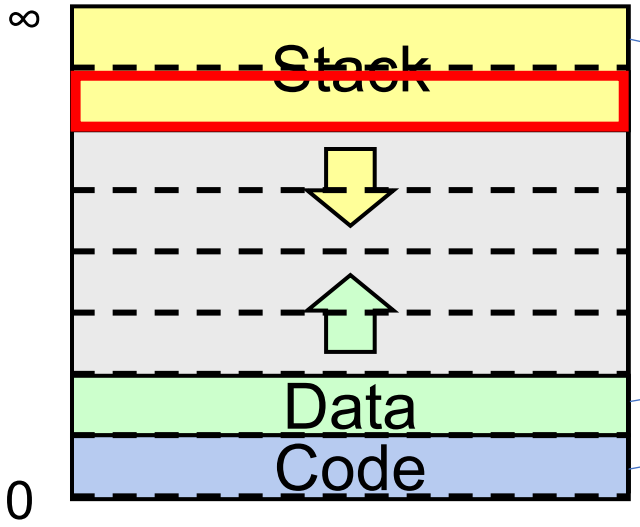


Physical Address Space

	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



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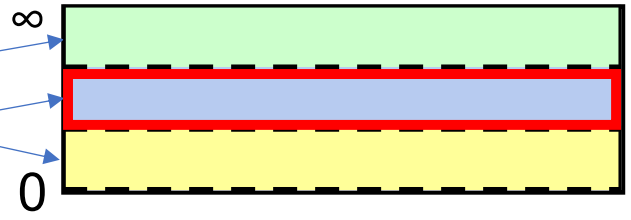

Physical Address Space

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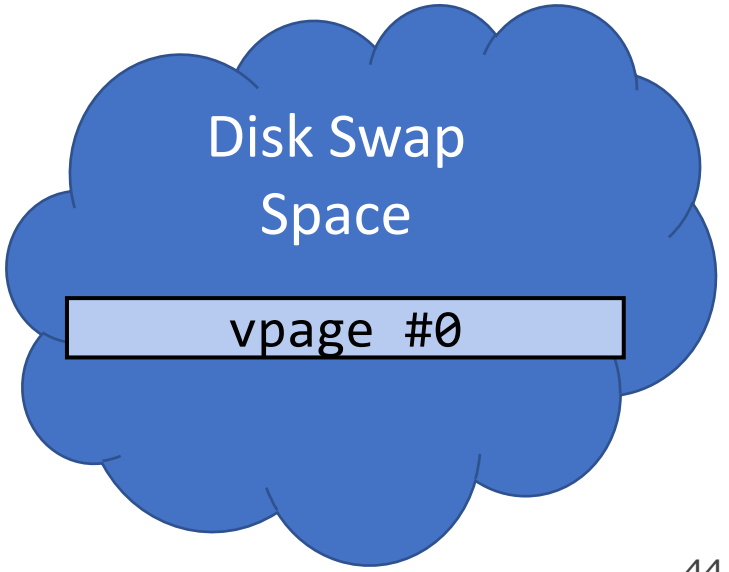
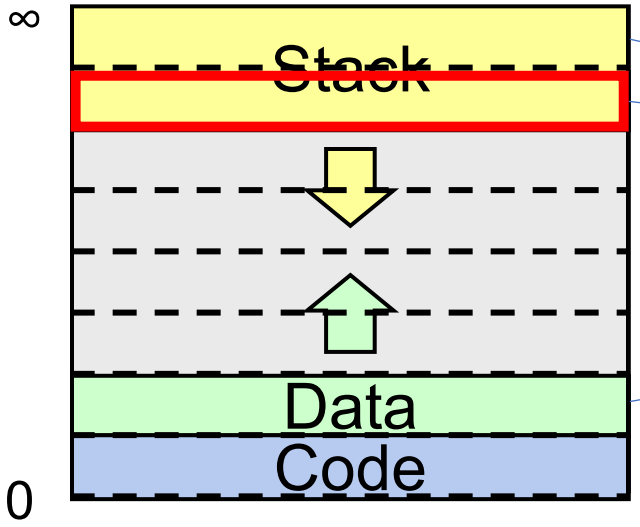
4	X	X	0
3	X	X	0
2	X	X	0
1	2	0	1
0	1	0	0

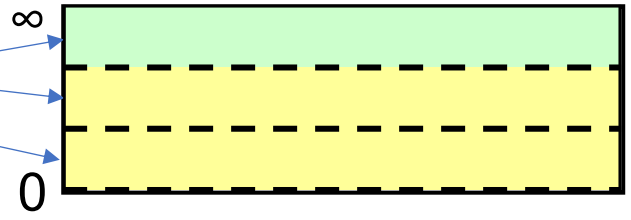


1. Pick an existing physical page and swap it to disk, mark not present.

Demand Paging



Process A Virtual Address Space



Physical Address Space

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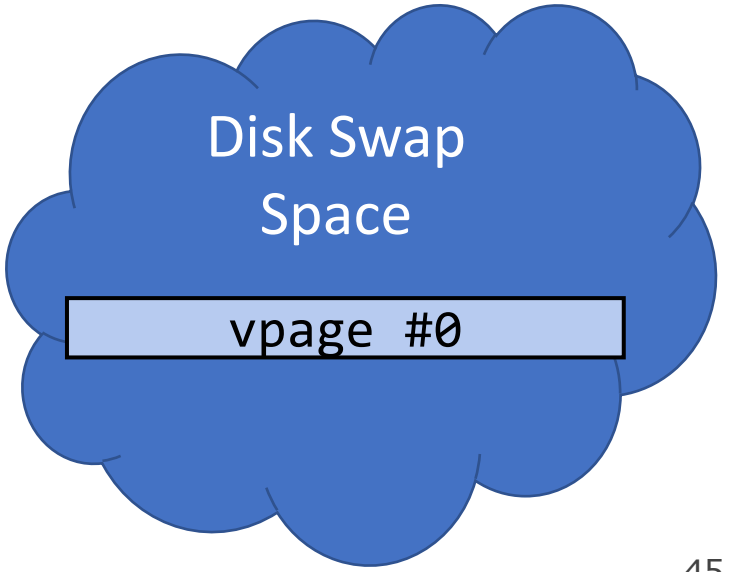
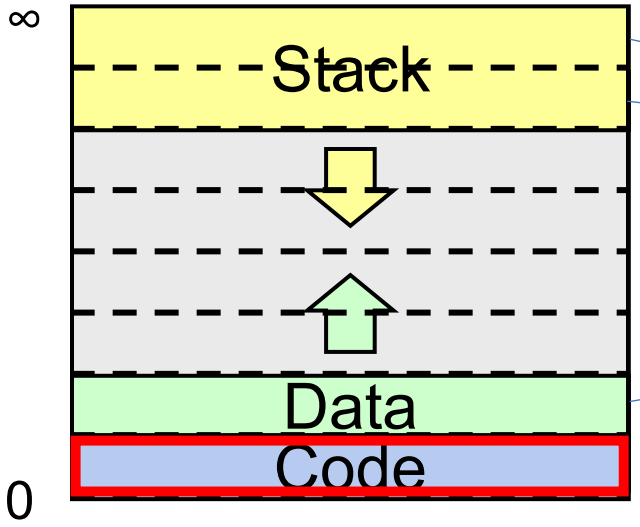
5	X	X	0
4	X	X	0
3	X	X	0
2	X	X	0
1	2	0	1
0	1	0	0



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

Demand Paging



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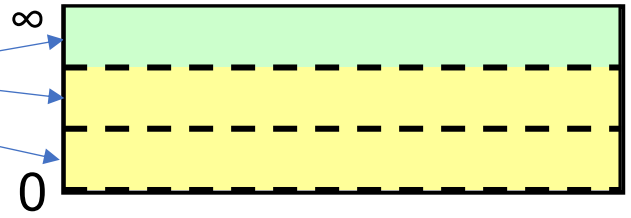

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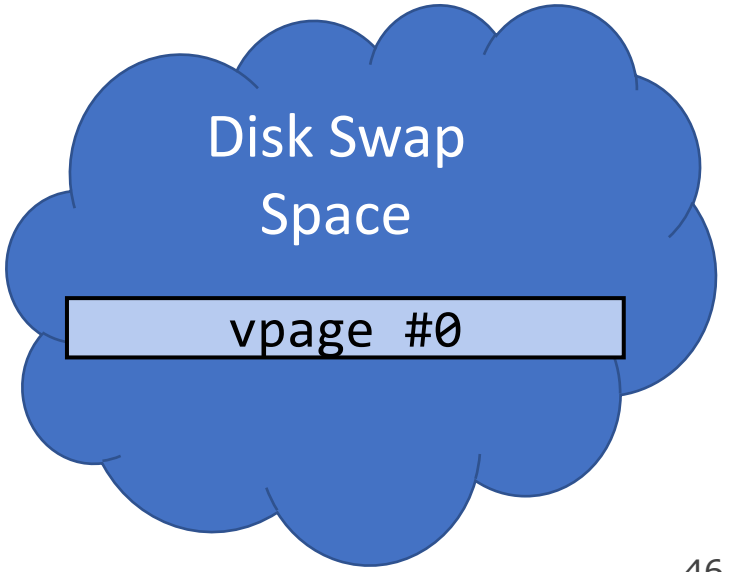
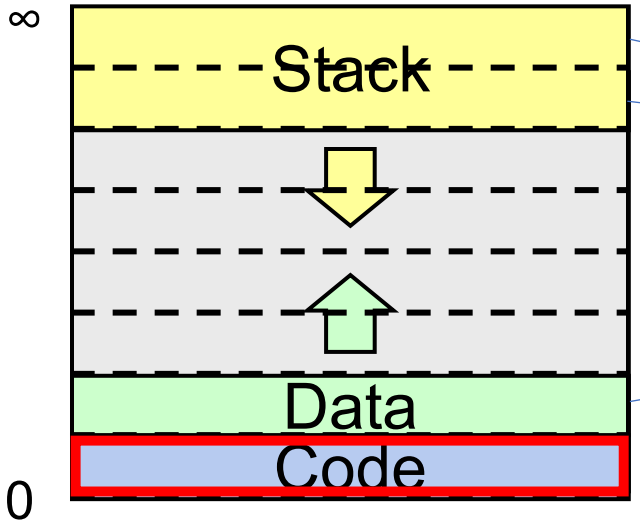


1. We look in the page map and see it's not present.

Demand Paging



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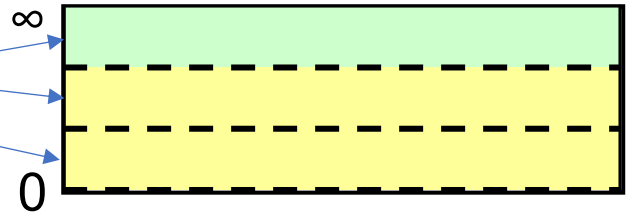
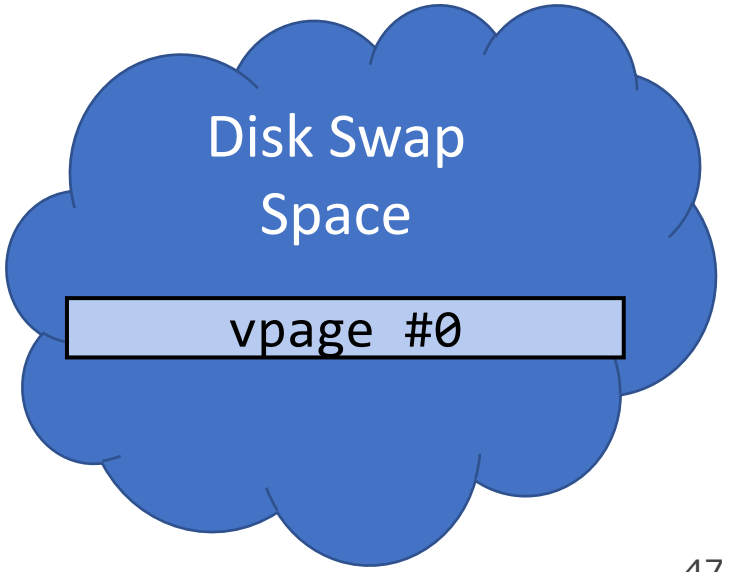


Physical Address Space

	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).



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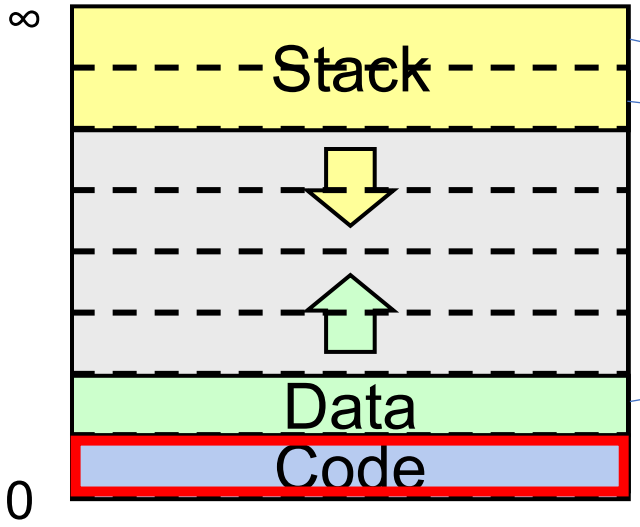
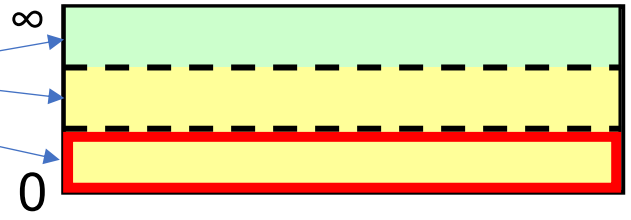


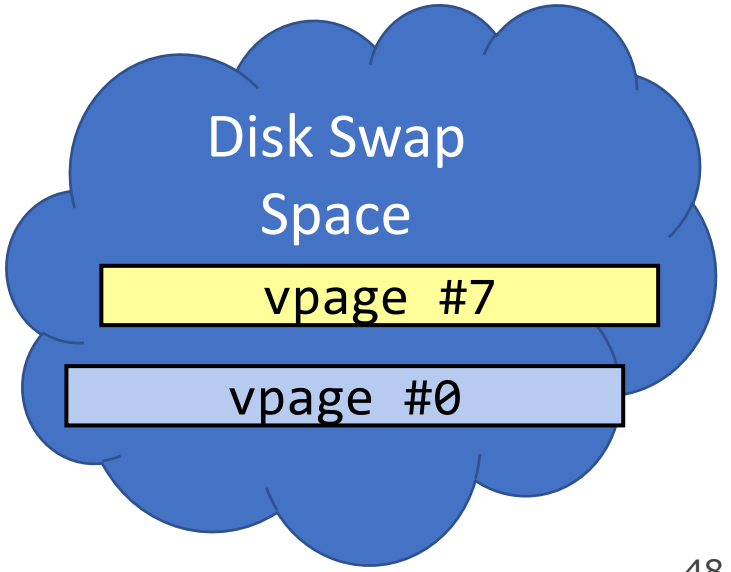
Process A Virtual Address Space



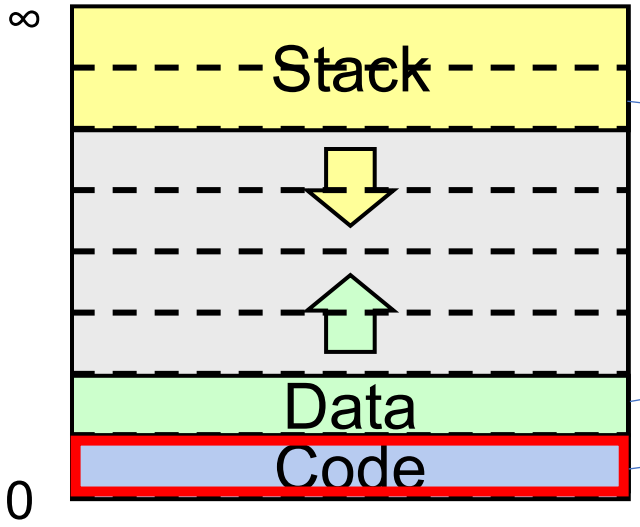
Physical Address Space

	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

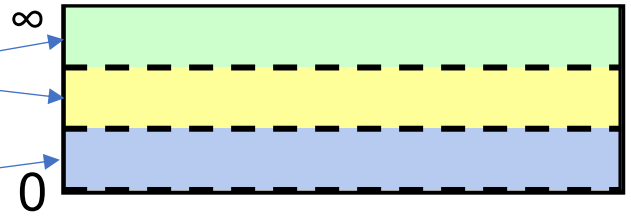
2. But it is stored in disk swap, so we load it back in (kicking another page if needed).



Demand Paging



Process A Virtual Address Space



Physical Address Space

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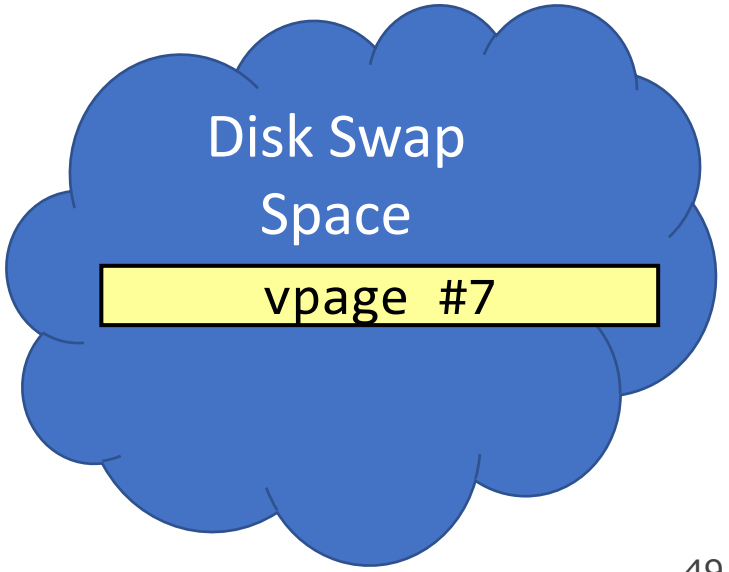
2	X	X	0
1	2	0	1
0	0	0	1

2. But it is stored in disk swap, 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

Thrashing

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

Respond on PollEv: pollev.com/cs111fall23
or text CS111FALL23 to 22333 once to join.

What potential scenario would lead demand paging to slow the system way down?

Nobody has responded yet.

Hang tight! Responses are coming in.

Thrashing

Demand paging 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 Replacement

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

- Random? (works surprisingly well!)

More next time…

Recap

- **Recap:** Base and bound, multiple segments, and paging
- Page Map Size
- Demand Paging

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

Lecture 23 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. But thrashing can occur when the system spends all its time doing disk operations and little time on actual work.