CS111, Lecture 21
Virtual Memory Introduction

Optional reading:

Operating Systems: Principles and Practice (2^{nd} Edition): Chapter 8

<u>Topic 4: Virtual Memory</u> - 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

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?*

Why is answering this question important?

- We can understand one of the most "magical" responsibilities of OSes – making one set of memory appear as several!
- Exposes challenges of allowing multiple processes to share memory while remaining isolated
- Allows us to understand exactly what happens when a program accesses a memory address

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

CS111 Topic 4: Virtual Memory

Virtual Memory Introduction → Dynamic Address Translation → Demand Paging → The Clock Algorithm

Today | **Lecture 22** | **Lecture 23** | **Lecture 24**

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

Learning Goals

- Understand the goals of sharing memory
- Reason about the tradeoffs in implementing memory sharing mechanisms
- Understand what impact virtual memory has on our programs

Plan For Today

- Goals of sharing memory
- Single-tasking
- Load-time relocation
- Introducing virtual memory
- Dynamic address translation
  - Approach #1: Base and Bound

```
cp -r /afs/ir/class/cs111/lecture-code/lect21 .
```

Plan For Today

- **Goals of sharing memory**
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Sharing Memory

So far, we've seen how the OS can run multiple threads or processes concurrently by sharing CPU cores (e.g. taking turns with a single core). Another key sharing aspect: **they must share a limited amount of system memory.**

Virtual memory is a mechanism for multiple processes to simultaneously use system memory.

Sharing Memory

What are our goals for sharing memory?

- **Multitasking** – allow multiple processes to be memory-resident at once
- **Transparency** – no process should need to know memory is shared. Each must run regardless of the number and/or locations of processes in memory.
- **Isolation** – processes must not be able to corrupt each other
- **Efficiency** (both of CPU and memory) – shouldn't be degraded badly by sharing

To understand how we can share memory, let's first look at what a single process's memory needs are.

Plan For Today

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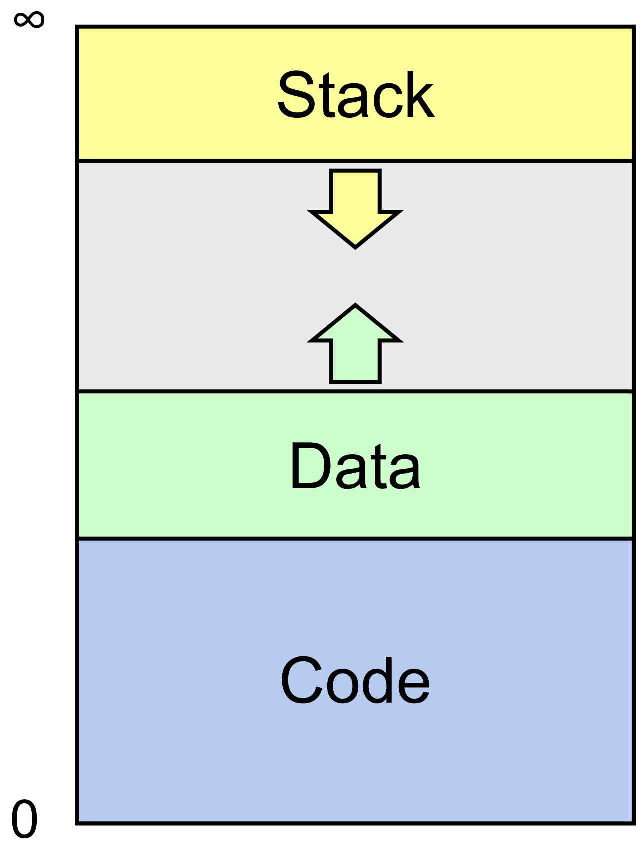
Single-Tasking

Let's start with a system that can just run one user process at a time. What does memory look like?

- A process's memory is a collection of *segments* (sections)
- **Code** ("text") – program code
- **Data** – constants, heap
- **Stack** – stack frames for functions
- Stack grows down, heap grows up as more space is needed

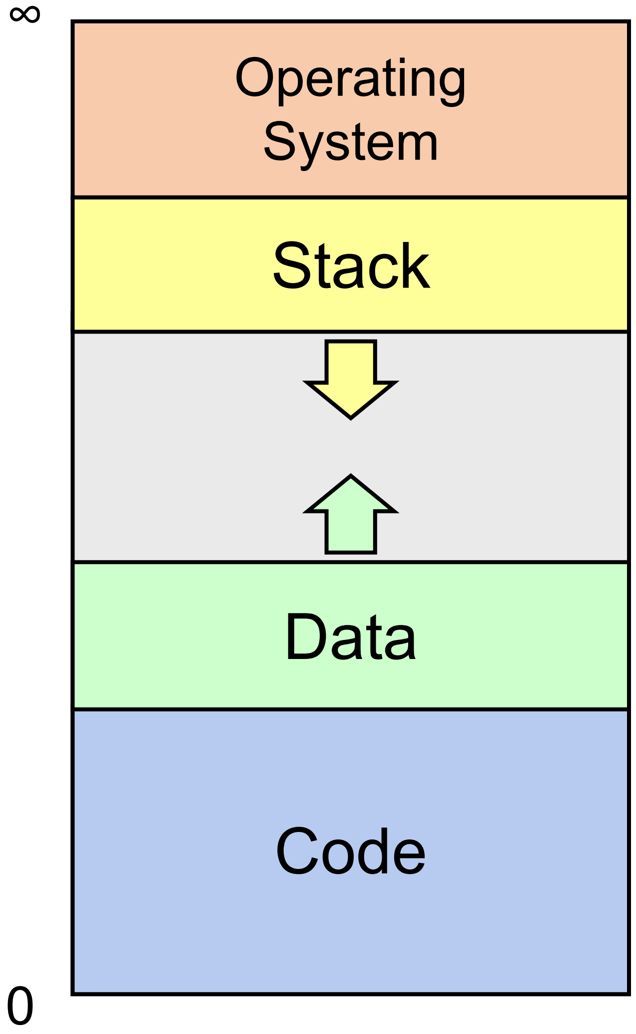


(for Unix/Linux – Windows essentially the same)

Single-Tasking

Let's start with a system that can just run one user process at a time. What does memory look like?

- The OS also needs memory space!
- Reserve highest memory addresses for OS
- **Problem:** rogue programs could mess with OS memory, corrupt the system



Challenge: to run multiple processes, how can we split up memory to give each process space?

Pre-virtual-memory-idea #1: Let’s reserve contiguous blocks in memory for each process.

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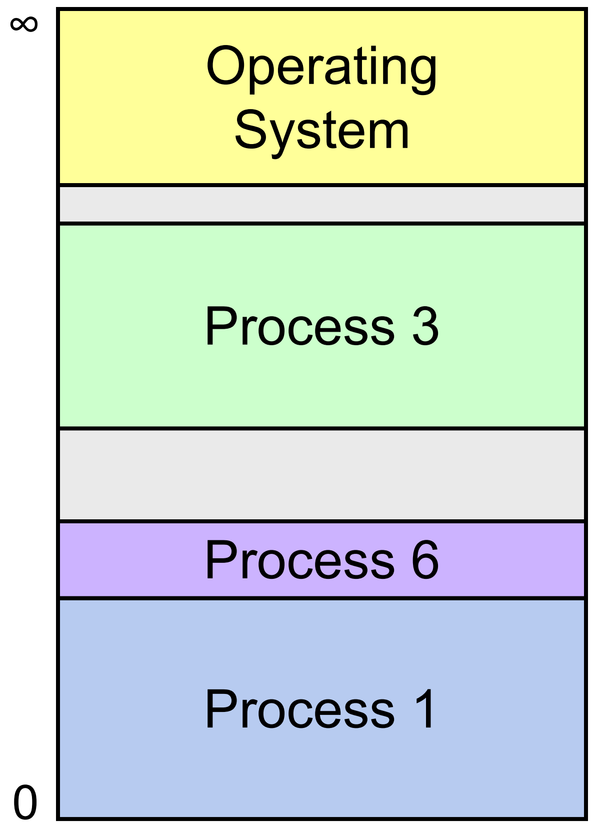
Load-Time Relocation

- When a process is loaded to run, place it in a designated memory space.
- That memory space is for everything for that process – stack/data/code
- Interesting fact – when a program is compiled, it is compiled assuming its memory starts at address 0. Therefore, we must update its addresses when we load it to match its real starting address.
- Use first-fit or best-fit allocation to manage available memory.

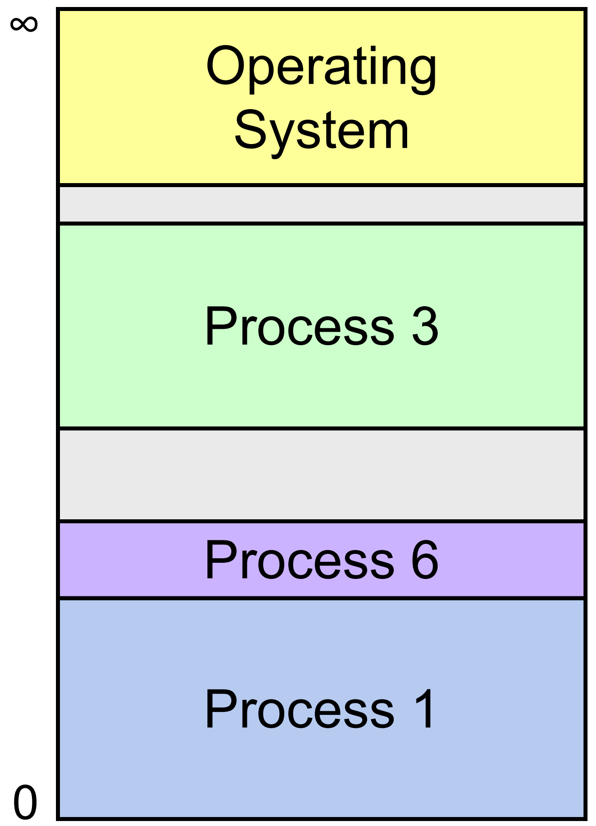
What are the problems with this approach?



Load-Time Relocation

What are the problems with this approach?

- No isolation – one process can corrupt another or the OS
- Must decide process memory size ahead of time
- Challenges with allocating memory for new processes – memory fragmentation
- Can’t move once we load the process
- Need to update pointers in executable before running



Idea #2: Instead of translating addresses at load-time, let's translate <u>on the fly</u>. We'll put every process in its own "virtual world" where it thinks it can access all addresses, and the OS will translate every memory access to a "real address".

Plan For Today

- Goals of sharing memory
- Single-tasking
- Load-time relocation
- **Introducing virtual memory**
- Dynamic address translation
  - Approach #1: Base and Bound

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Introducing Virtual Memory

Virtual memory is a mechanism that allows multiple processes to simultaneously use system memory.

- Program addresses are *virtual* (fake) – the OS maps them to *physical* (real) addresses in memory.
- The OS must keep track of virtual -> physical "translations" and translate every memory access.
- The OS doesn't need to map all virtual addresses unless needed – it can provide new memory on the fly, and can give more than computer actually has
- The OS can even temporarily kick memory contents to disk until a program needs it again.
- Example of **virtualization** – making one thing look like another, or many of them

Demo: Virtual Memory Implications

memory.c and **htop**

```
cp -r /afs/ir/class/cs111/lecture-code/lect21 .
```

Introducing Virtual Memory

Virtual memory is a mechanism that allows multiple processes to simultaneously use system memory.

Three key questions:

- What are the benefits of the OS intercepting memory addresses?
- How does the OS translate from virtual to physical addresses?
- What are the tradeoffs in different virtual memory implementations?

Plan For Today

- Goals of sharing memory
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- **Dynamic address translation**
  - Approach #1: Base and Bound

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Dynamic Address Translation

Let's have the OS intercept every memory reference a process makes.

- The OS can prohibit processes from accessing certain addresses (e.g. OS memory or another process's memory)
- Gives the OS lots of flexibility in managing memory
- Every process can now think that it is located starting at address 0
- The OS will translate each process's address to the real one it's mapped to, and can have different translations for each process

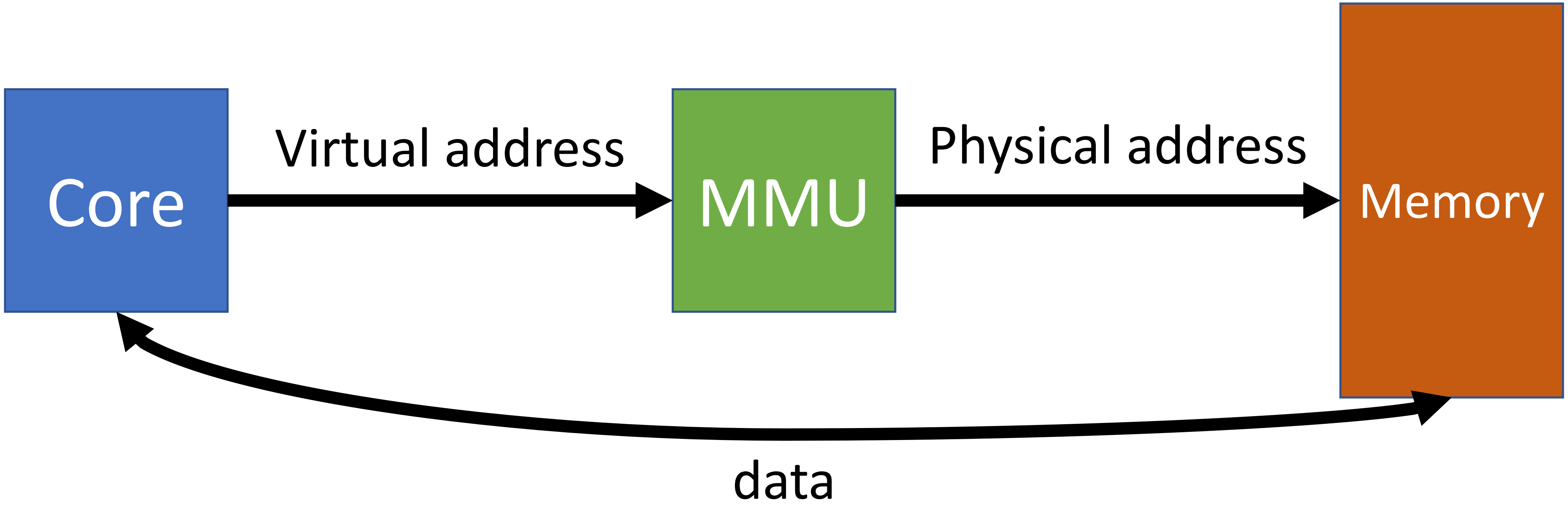
Problem: intercepting and translating *every* memory reference is expensive! How can we do this?

Solution: hardware support

Dynamic Address Translation

We will add a *memory management unit* (MMU) in hardware that changes addresses dynamically during every memory reference.

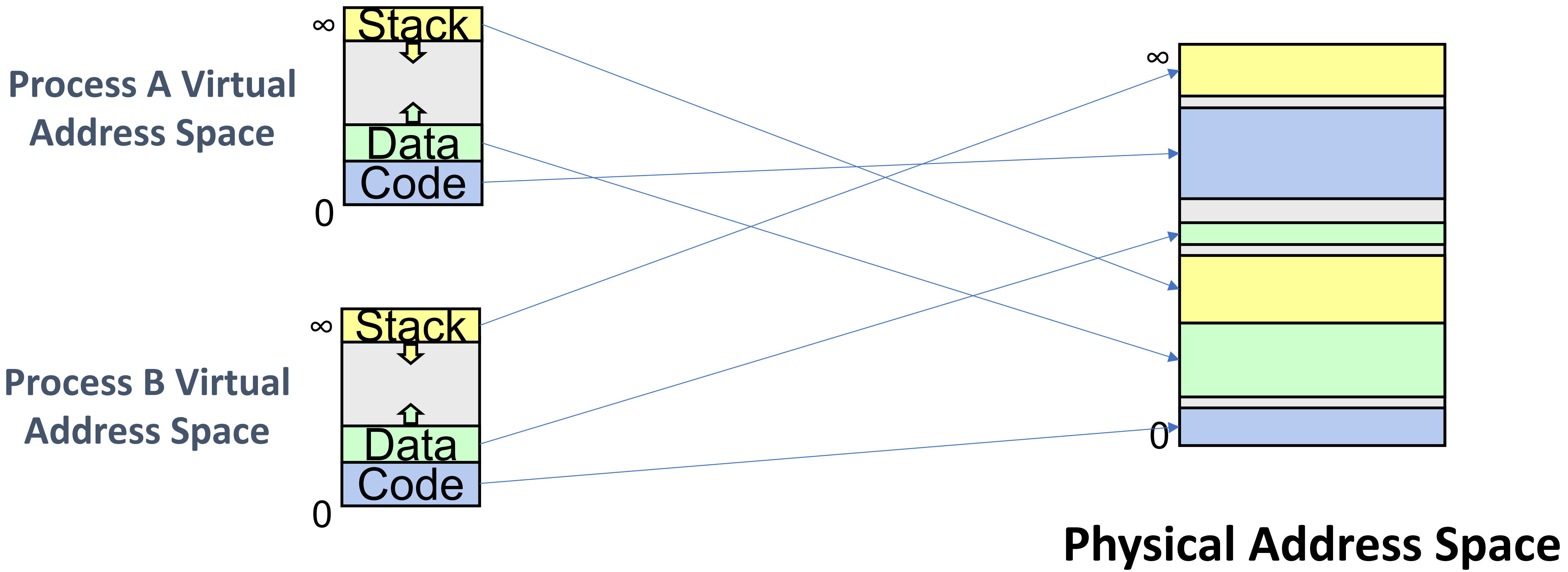
- *Virtual address* is what the program sees
- *Physical address* is the actual location in memory



Dynamic Address Translation

Key Idea: there are now *two views of memory,* and they can look very different:

- **Virtual address space** is what the program sees
- **Physical address space** is the actual allocation of memory



Dynamic Address Translation

- **Transparency** – virtual addresses allow a program's view of memory to be different than the real view; doesn't know its memory is e.g., split up.
- **Isolation** – OS intercepts memory references and can prevent rogue accesses

Key question: how does the MMU translate from a virtual address to a physical address? *We'll see several different approaches over the next few lectures.*

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**

Plan For Today

- Goals of sharing memory
- Single-tasking
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- Introducing virtual memory
- **Dynamic address translation**
  - **Approach #1: Base and bound**

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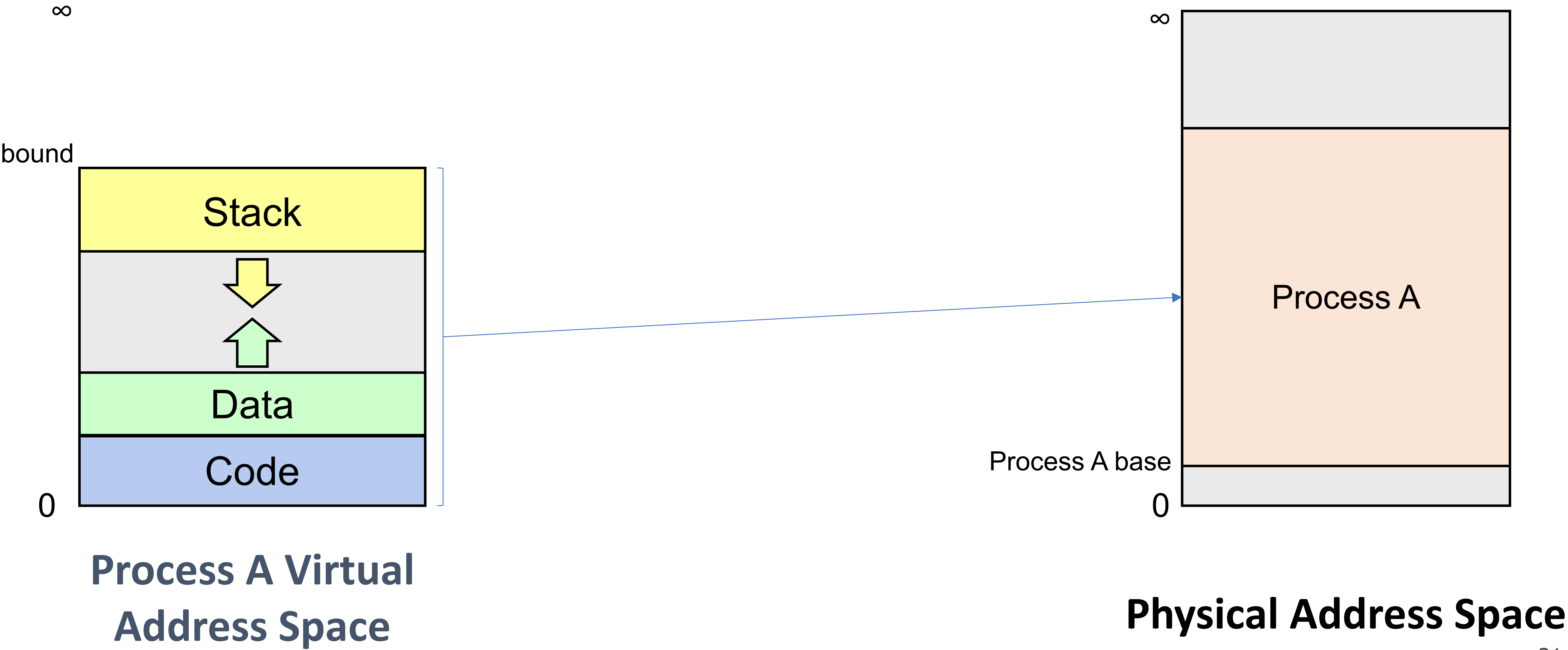
Approach #1: Base and Bound

Key Idea: Let's use the **load-time relocation** idea of contiguous allocation, but with the MMU.

- Every process's virtual address space is mapped to a contiguous region of physical memory.
- When a program accesses a virtual address, translate it by adding the ***base*** for that process – the physical address its memory really starts at.
- We specify the process's memory size by setting a ***bound*** for it; if a process accesses an an invalid virtual address >= bound, OS triggers an error.

Base and Bound



Approach #1: Base and Bound

- "base" is physical address starting point – corresponds to virtual address 0
- "bound" is one greater than the highest allowable **virtual** memory address
- Each process has own base/bound. Stored in PCB and loaded into two registers when running.

On each memory reference:

- Compare virtual address to bound, trap if >= (invalid memory reference)
- Otherwise, add base to virtual address to produce physical address

Approach #1: Base and Bound

Example: let’s say process A has **base = 1000**, **bound = 5000.** What happens if:

- It accesses virtual address **6000**?
- It accesses virtual address **0**?

Approach #1: Base and Bound

Example: let's say process A has **base = 1000**, **bound = 5000.** What happens if:

- It accesses virtual address **6000**? Invalid memory reference.
- It accesses virtual address **0**? Accesses physical address **1000**.

Approach #1: Base and Bound

Example: let's say process B has **base = 6000, bound = 2000.** What happens if:

- It accesses virtual address **6000**?
- It accesses virtual address **1000**?

Respond on PollEv: pollev.com/cs111
or text CS111 to 22333 once to join.

Process B has base = 6000, bound = 2000. What happens when it accesses virtual addresses 1) 6000 and 2) 1000?

- Accesses 1) physical address 12000 and 2) physical address 7000 — 0%
- Accesses 1) physical address 0 and 2) physical address 3000 — 0%
- ✅ 1) Invalid memory reference and 2) physical address 7000 — 0%
- Gets memory errors for both references — 0%

Approach #1: Base and Bound

Example: let’s say process B has **base = 6000, bound = 2000.** What happens if:

- It accesses virtual address **6000**? Invalid memory reference.
- It accesses virtual address **1000**? Accesses physical address **7000**.

Approach #1: Base and Bound

- Key idea: each process appears to have a completely private memory whose size is determined by the bound register.
- The only physical address is in the base register, controlled by the OS. Process sees only virtual addresses!
- OS can update a process's base/bound if needed! E.g. it could move physical memory to a new location or increase bound.

Approach #1: Base and Bound

What are some benefits of this approach?

- Inexpensive translation – just doing addition
- Doesn't require much additional space – just per-process base + bound
- The separation between virtual and physical addresses means we can move the physical memory location and simply update the base, or we could even *swap* memory to disk and copy it back later when it's actually needed.

What are some drawbacks of this approach?

- One contiguous region per program
- Fragmentation
- Growing can only happen upwards with the bound
- Doesn't support read-only regions of memory within a process

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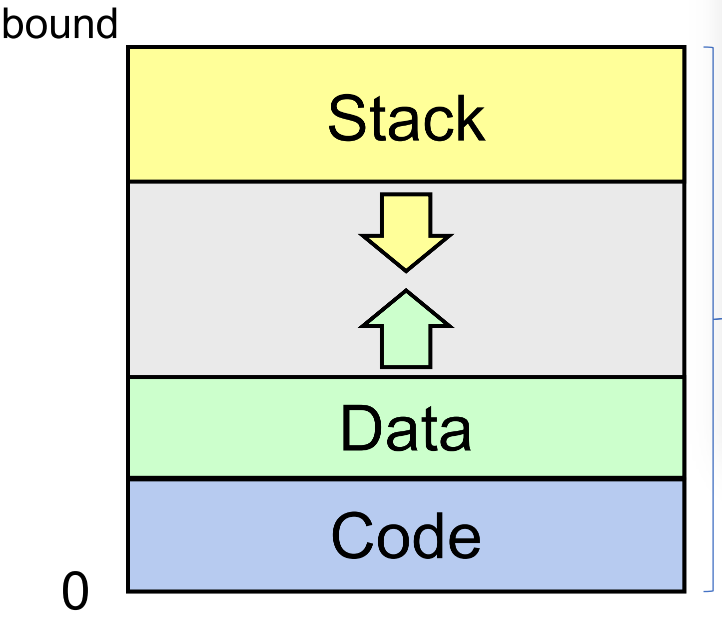
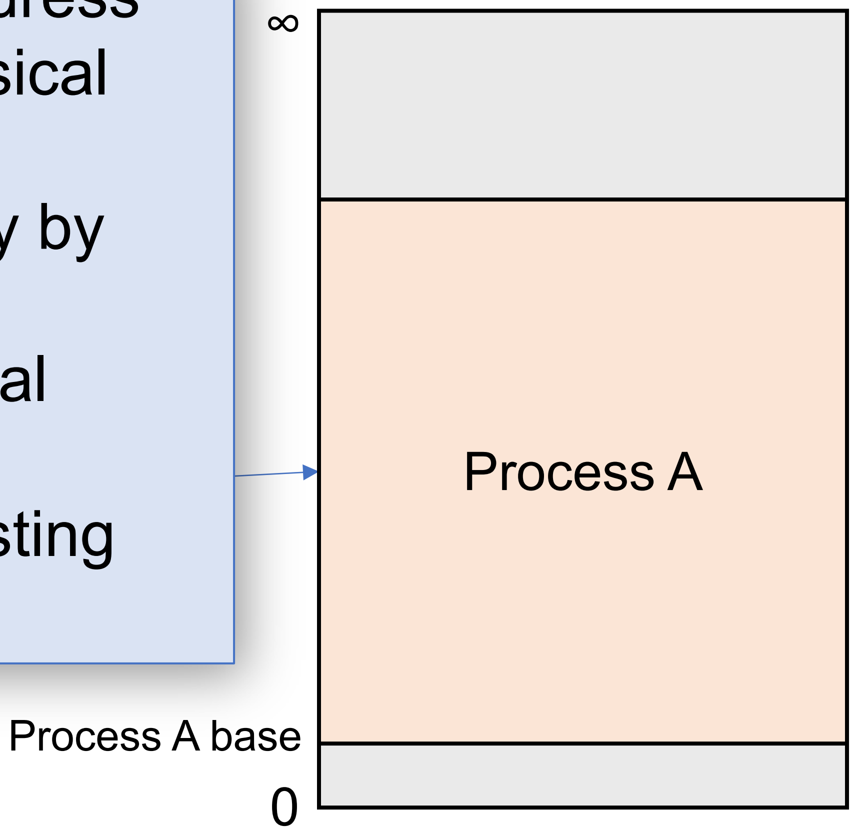
Base and Bound



Process A Virtual Address Space

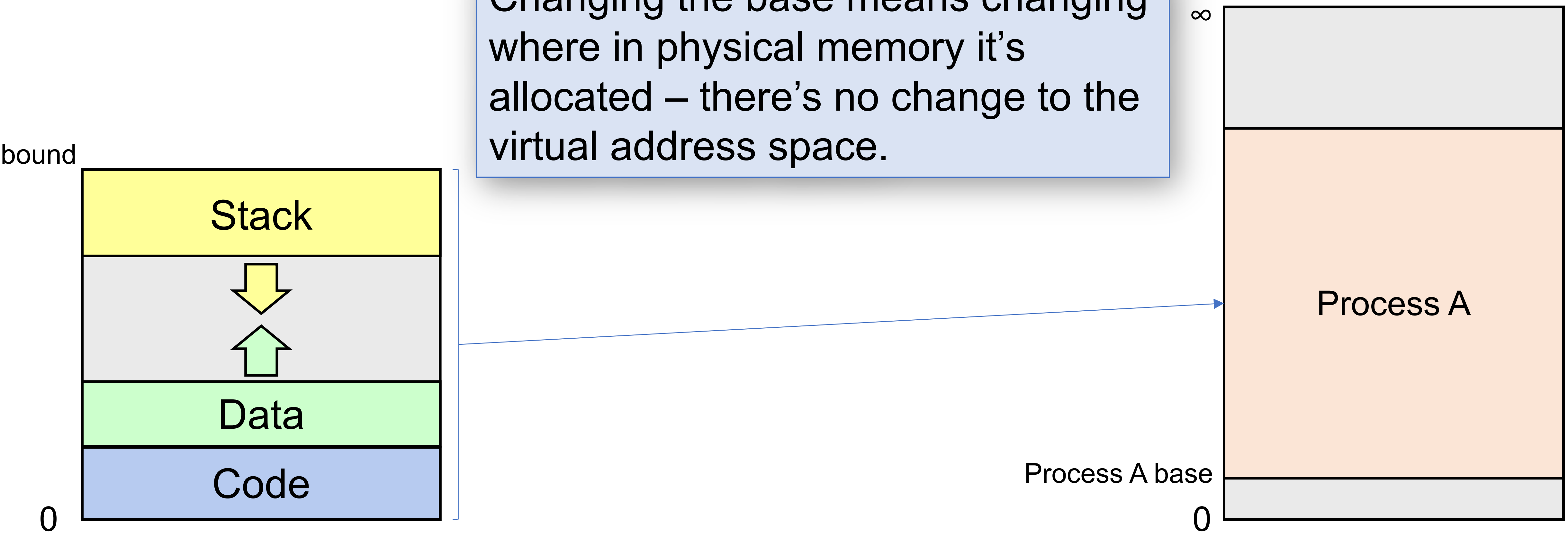
- Must map entire virtual address space contiguously in physical memory.
- Move it in physical memory by modifying the base.
- The base is pinned to virtual address 0.
- Make more space by adjusting the bound.



Physical Address Space

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.



Process A Virtual Address Space

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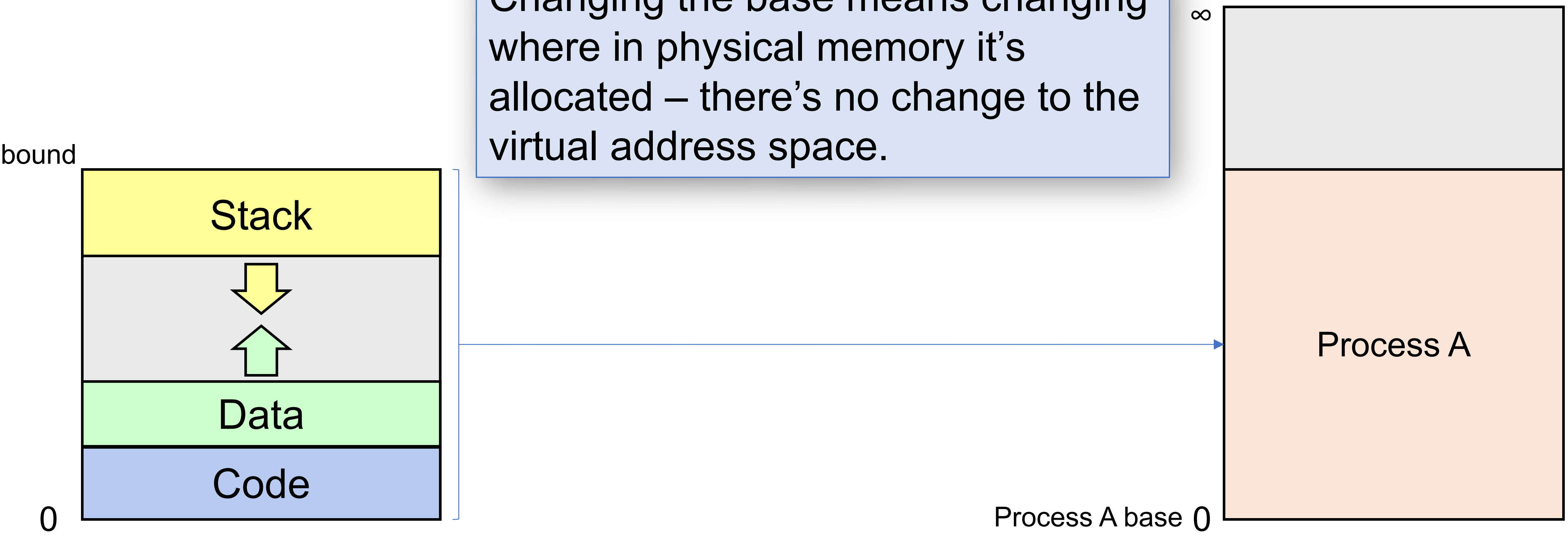
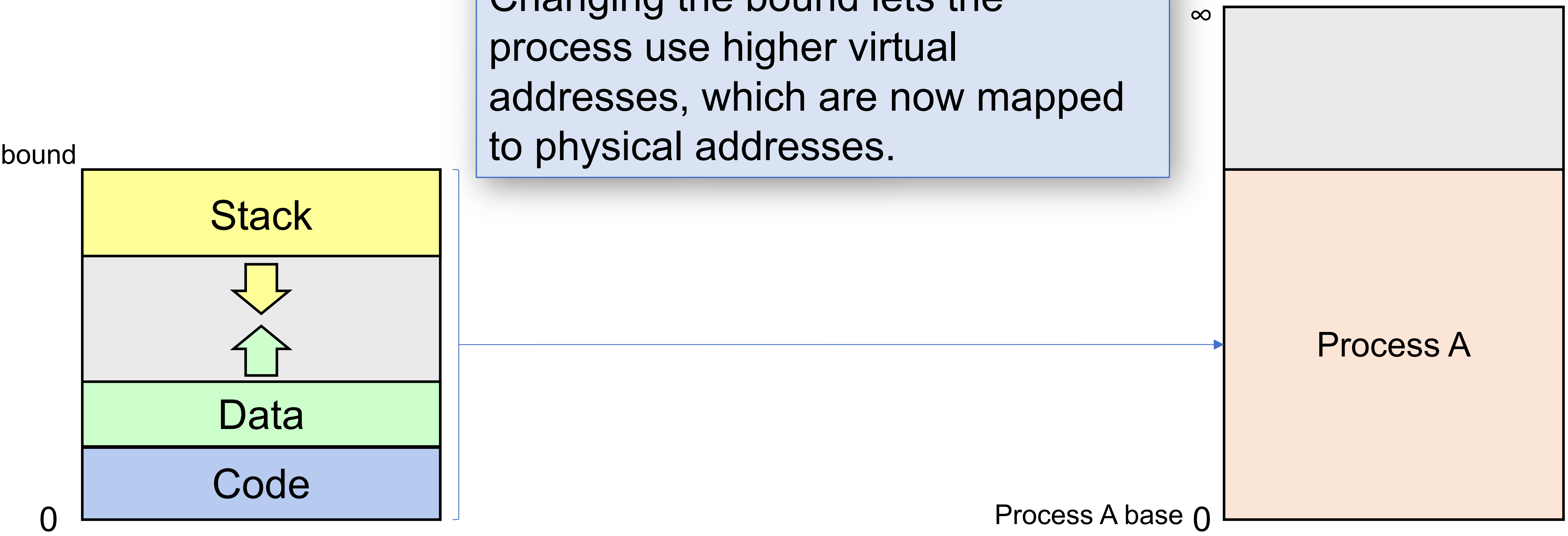


Process A Virtual Address Space

Physical Address Space

Base and Bound – Changing Bound

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



Process A Virtual Address Space

Physical Address Space

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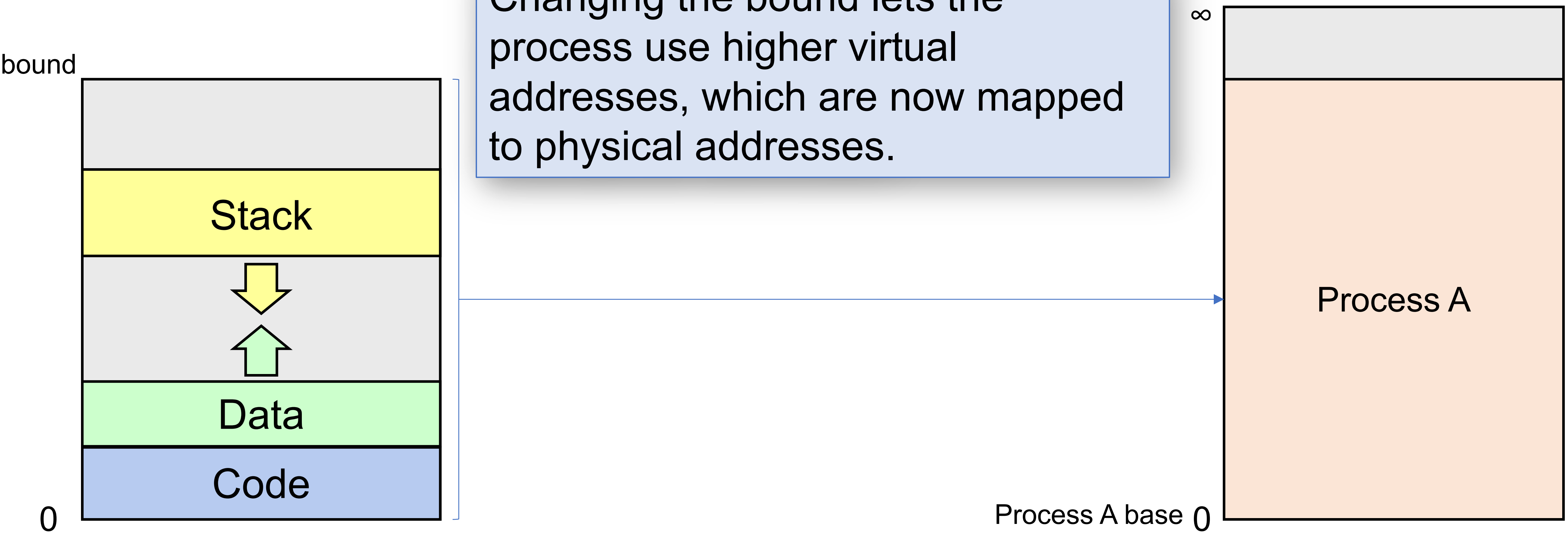
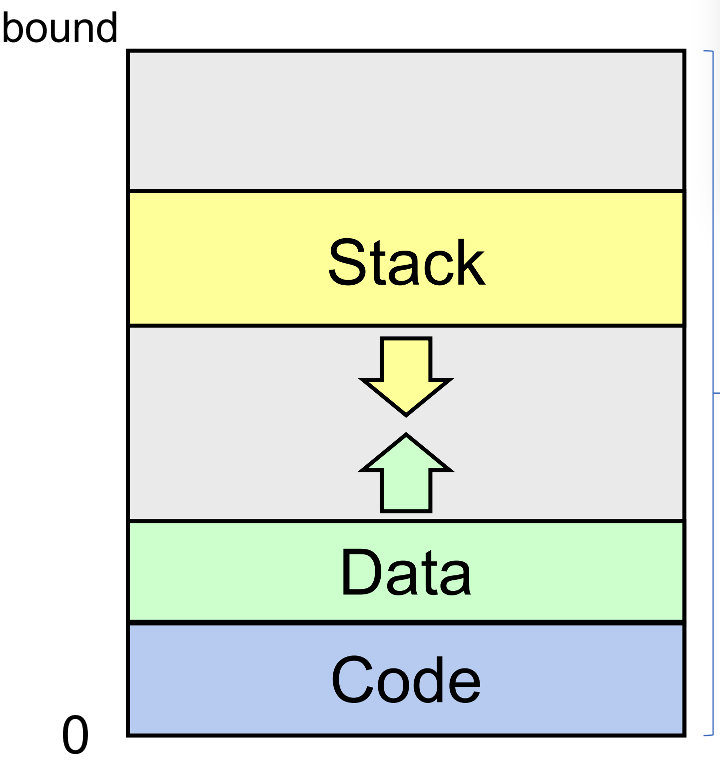


Process A Virtual Address Space

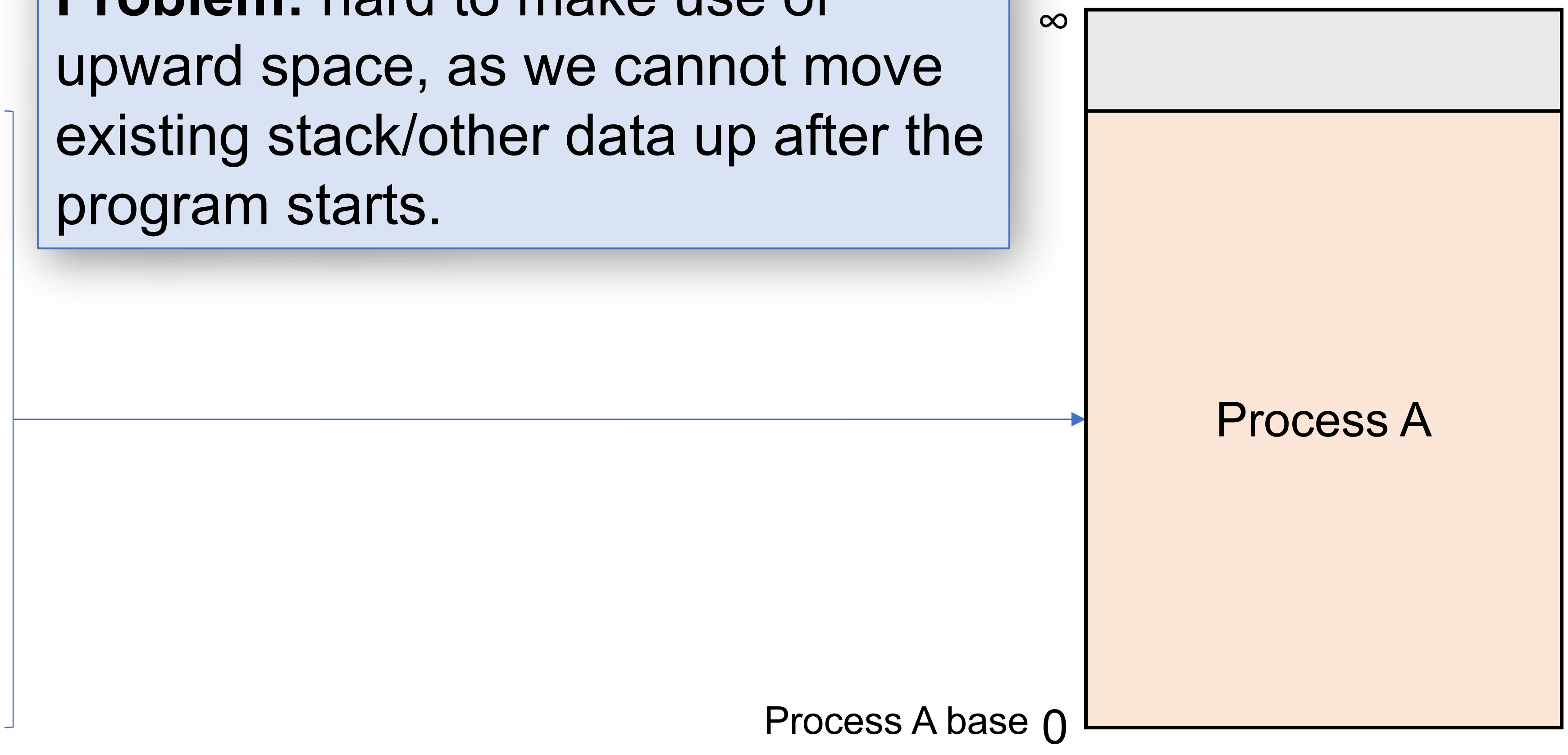
Physical Address Space

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.



Process A Virtual Address Space



Physical Address Space

Recap

- Introducing virtual memory
- Single-tasking
- Goals of sharing memory
- Load-time relocation
- Dynamic address translation
  - Approach #1: Base and Bound

Next time: more about dynamic address translation

Lecture 21 takeaway: Virtual memory is a mechanism that allows multiple processes to simultaneously use system memory. There are two views of memory: virtual and physical. The hardware MMU translates from virtual to physical addresses. Base and bound is one approach to implement virtual memory.