CS111, Lecture 21
Virtual Memory Introduction

Optional reading:

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

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?
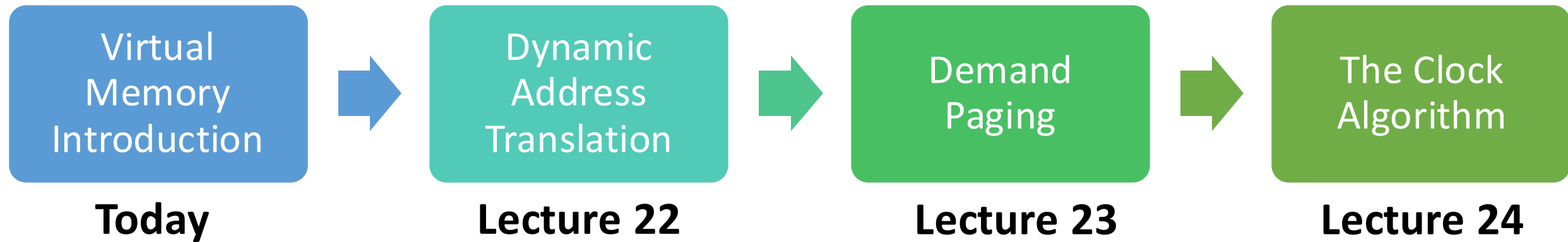
CS111 Topic 4: Virtual Memory

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**

- Single-tasking

- Load-time relocation

- Introducing virtual memory

- Dynamic address translation
  - Approach #1: Base and Bound

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

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

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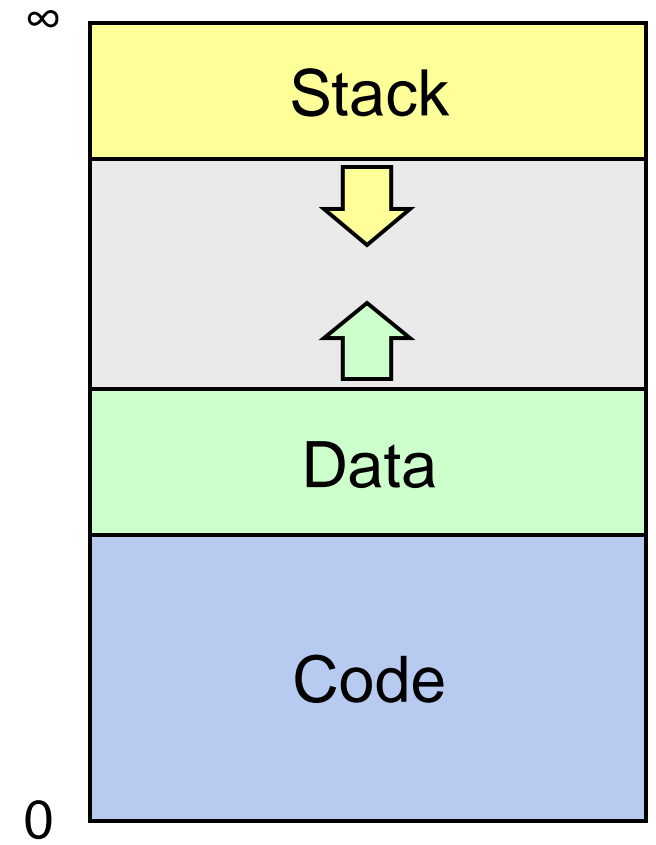 - Approach #1: Base and Bound

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

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)

∞

| Stack |
| --- |
| ⬇ ⬆ |
| Data |
| Code |

0

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 (addresses are all real, not fake)

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

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| Operating System |
| Stack |
| ⬇ ⬆ |
| Data |
| Code |

0
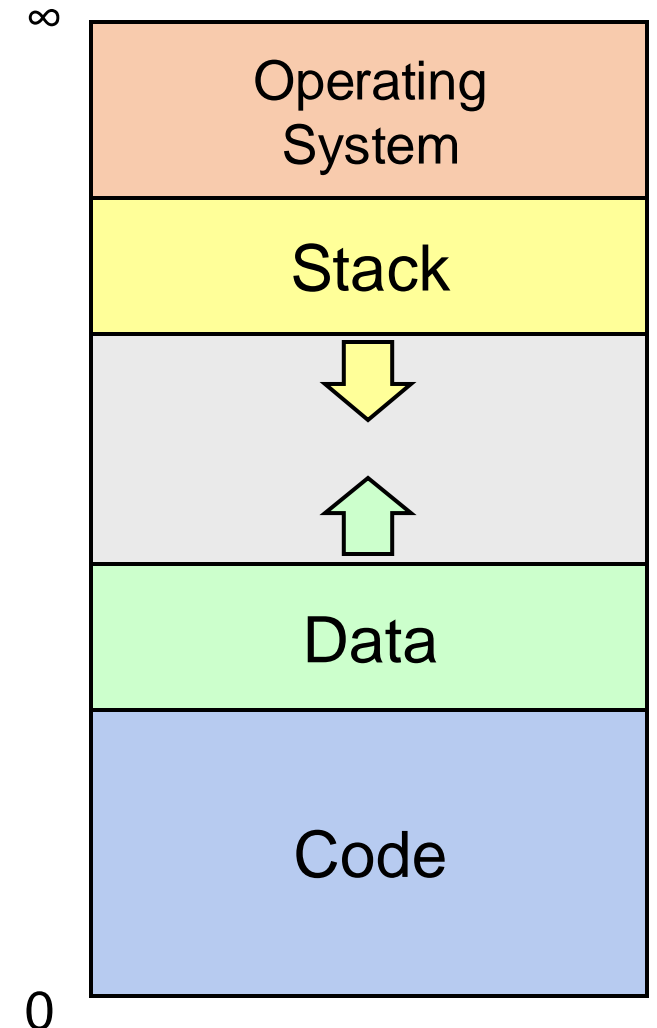
Pre-virtual-memory-idea #1: Let's reserve contiguous blocks in memory for each process.

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 .
```

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?**

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| Operating System |
| Process 3 |
| |
| Process 6 |
| Process 1 |

0
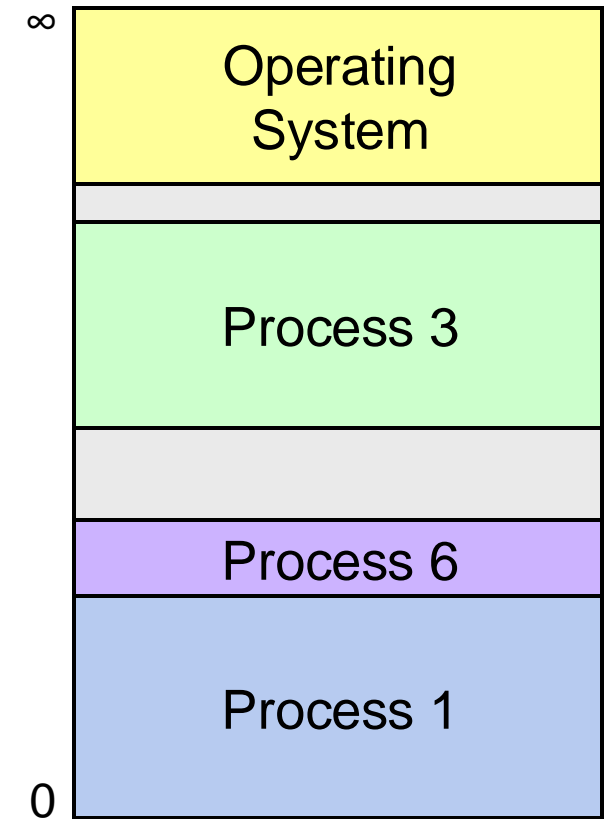
Load-Time Relocation

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

- Can't move once we load the process

- Challenges with allocating memory for new processes – memory fragmentation

- Need to update pointers in executable before running

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Operating System

Process 3

Process 6

Process 1

0
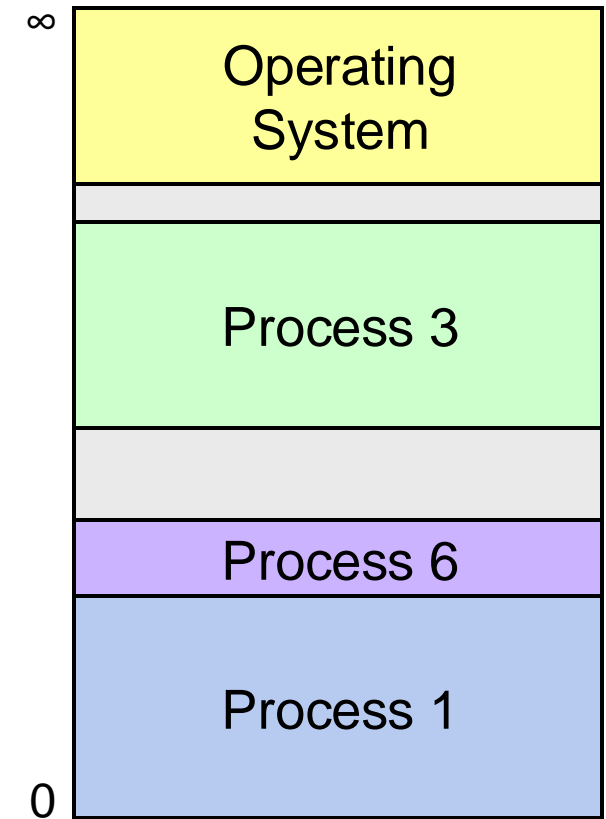
Idea #2: Put every process in its own isolated "virtual world" with "imaginary" (virtual) addresses. Whenever it accesses a virtual address, the OS will translate it to a "real address". Compared to load-time relocation: instead of translating addresses at load-time, we translate <u>on the fly</u>.

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 .
```

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.

- Virtual memory gives the OS *flexibility:*
  - Can map only needed addresses
  - Can give out more memory than there really is! And if we run out of space, can temporarily kick memory contents to disk if needed.   (more later!)

- 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

- 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 .
```

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)

- 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?
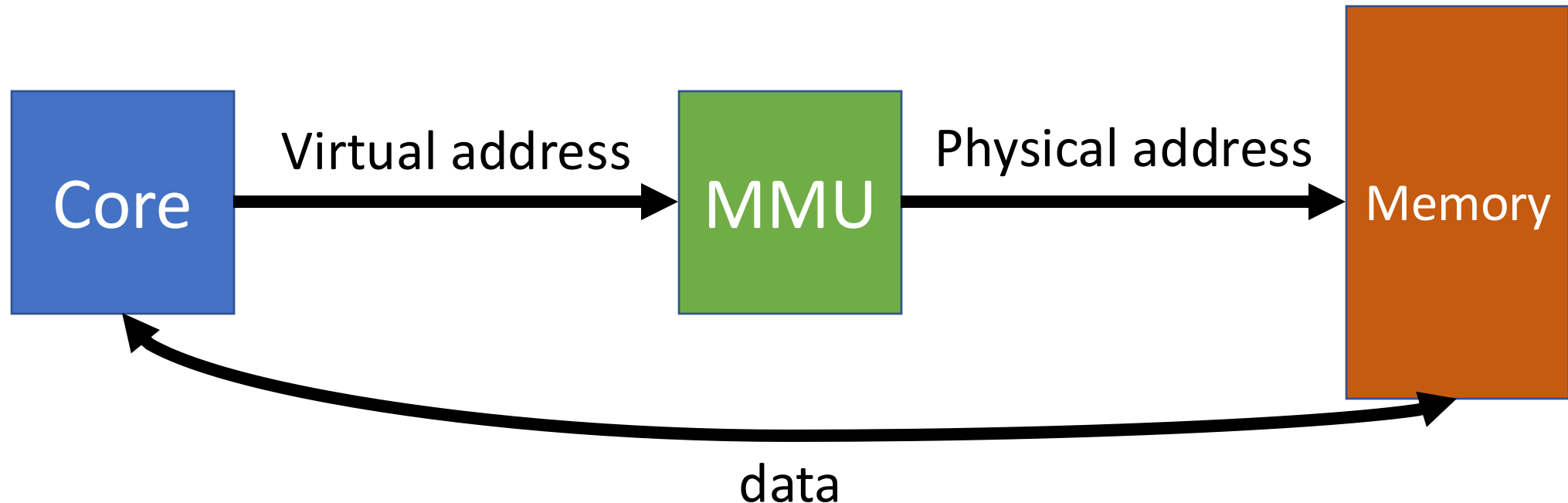
Solution: hardware support

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

Process A Virtual Address Space

∞ Stack
Data
Code
0

Process B Virtual Address Space

∞ Stack
Data
Code
0

Physical Address Space
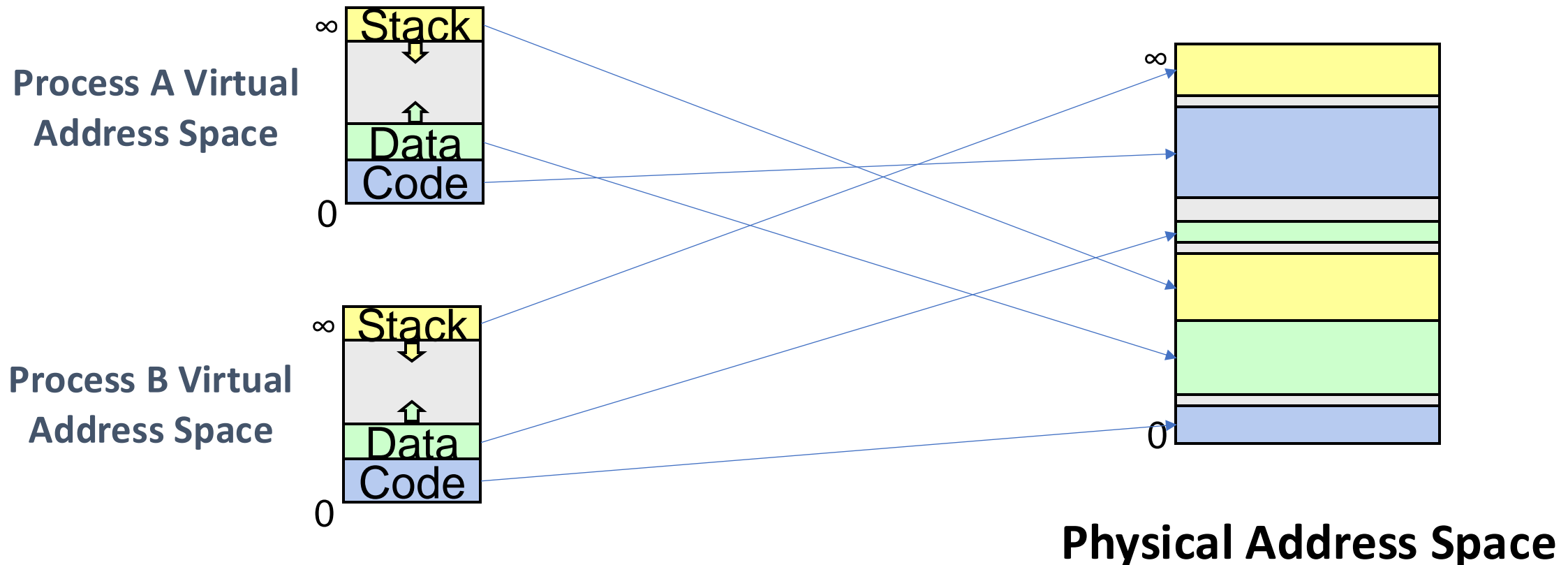
Dynamic Address Translation

- **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
- Load-time relocation
- Introducing virtual memory
- **Dynamic address translation**
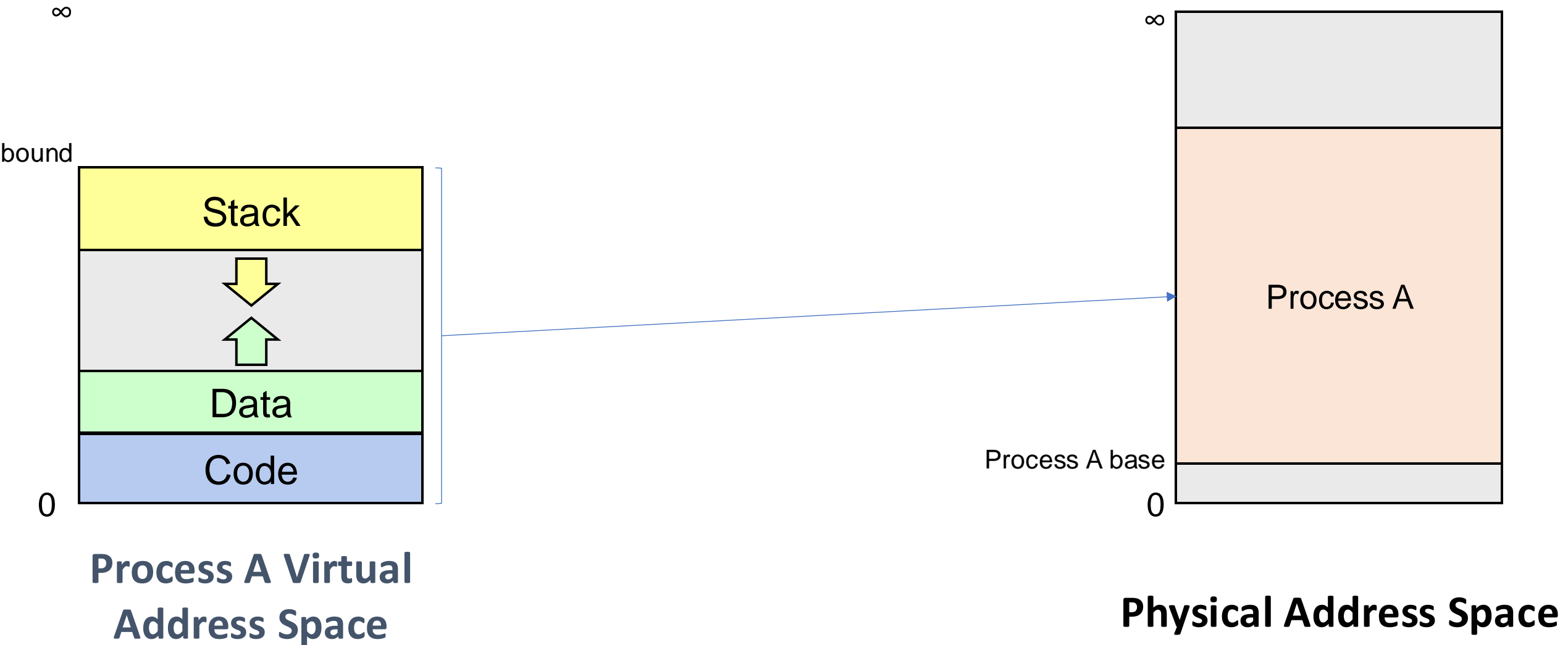 - **Approach #1: Base and bound**

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

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.
  - Base = "how much must we add to the virtual addr. to get the physical addr?"

- 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.
  - Bound = "how high in the virtual address space are we allowed to use?"

- Each process has own base/bound. Stored in PCB and loaded into two registers when running.

Base and Bound

∞

bound

Stack

Data

Code

0

Process A Virtual Address Space

∞

Process A

Process A base

0

Physical Address Space

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

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

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

Accesses 1) physical address 0 and 2) physical address 3000

1) Invalid memory reference and 2) physical address 7000

Gets memory errors for both references

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%

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. Not possible with load-time relocation (since program assumes addresses are fixed), but possible here because program doesn't have the "real" physical addresses.

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.

bound

Stack

Data

Code

0

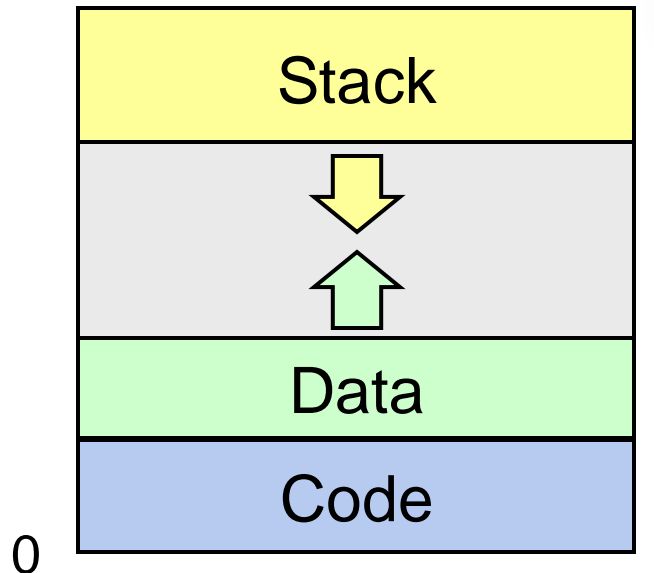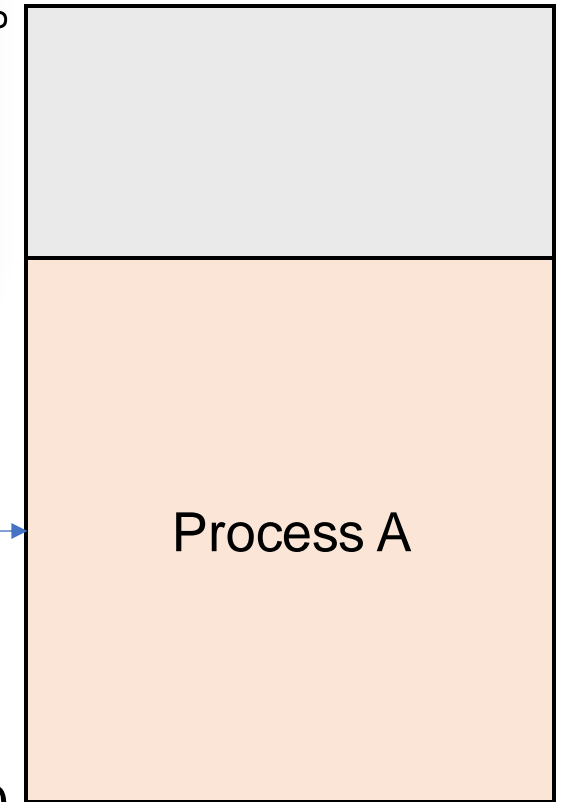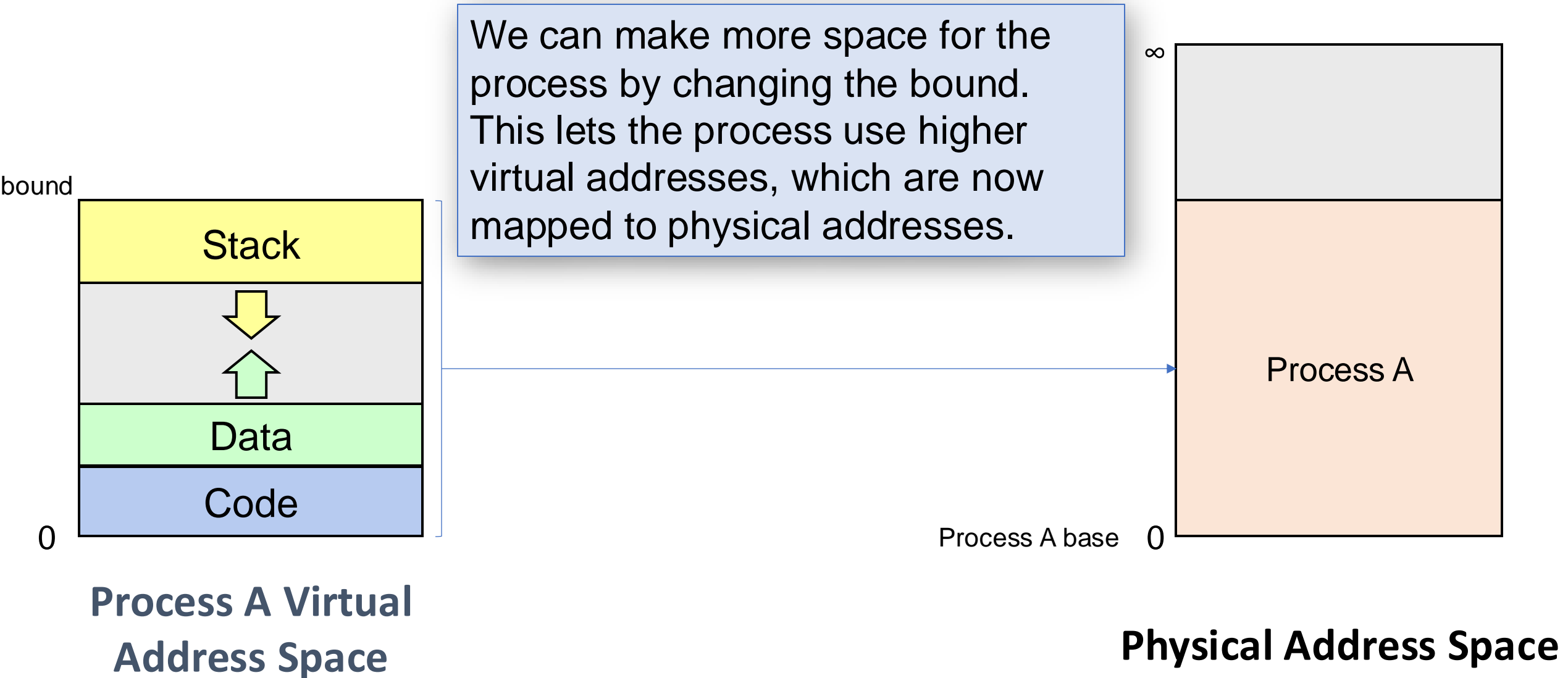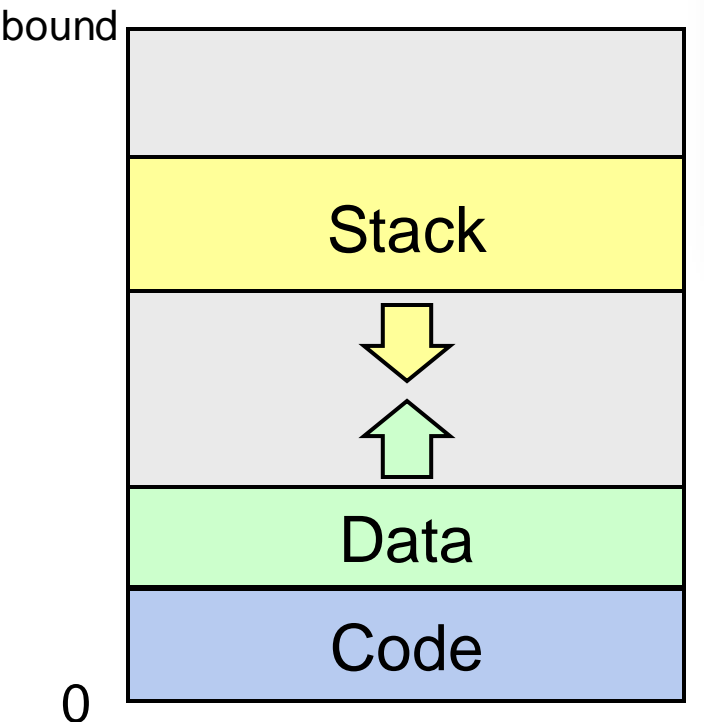**Process A Virtual Address Space**

∞

Process A

Process A base

0

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.

bound

Stack
⬇ ⬆
Data
Code

0

Process A Virtual Address Space

∞

Process A

Process A base   0

Physical Address Space

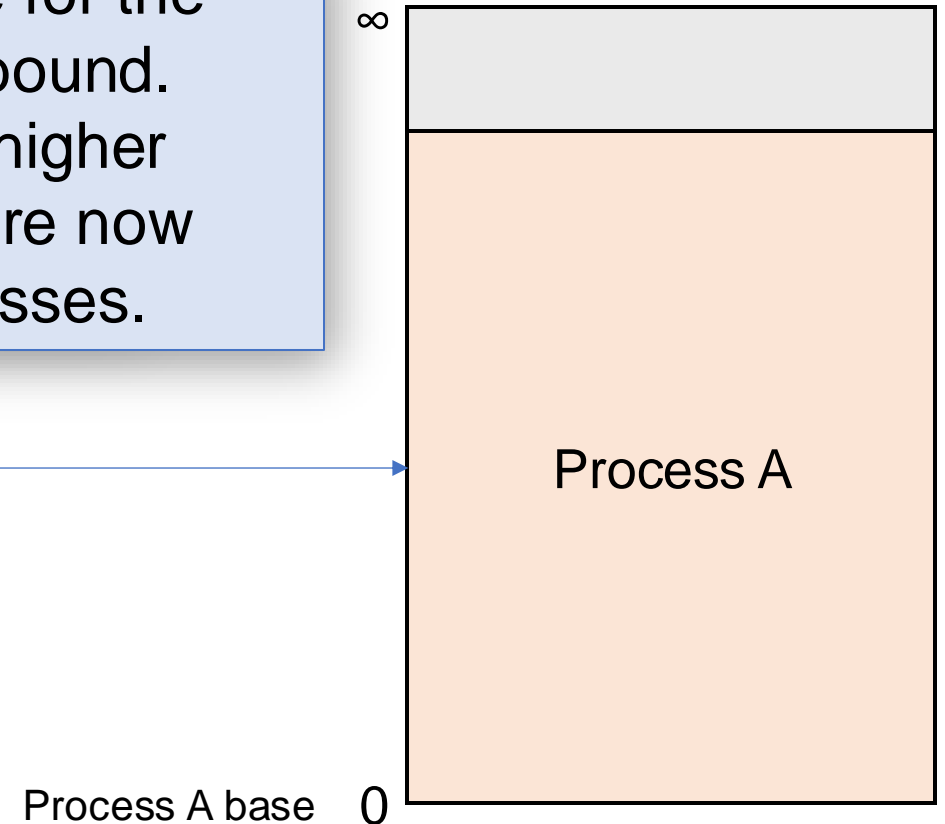# Base and Bound – Changing Bound

We can make more space for the process by changing the bound. This lets the process use higher virtual addresses, which are now mapped to physical addresses.

bound

| Stack |
| Data |
| Code |

0

Process A Virtual Address Space

∞

Process A

Process A base   0

Physical Address Space

Base and Bound — Changing Bound

We can make more space for the process by changing the bound. This lets the process use higher virtual addresses, which are now mapped to physical addresses.
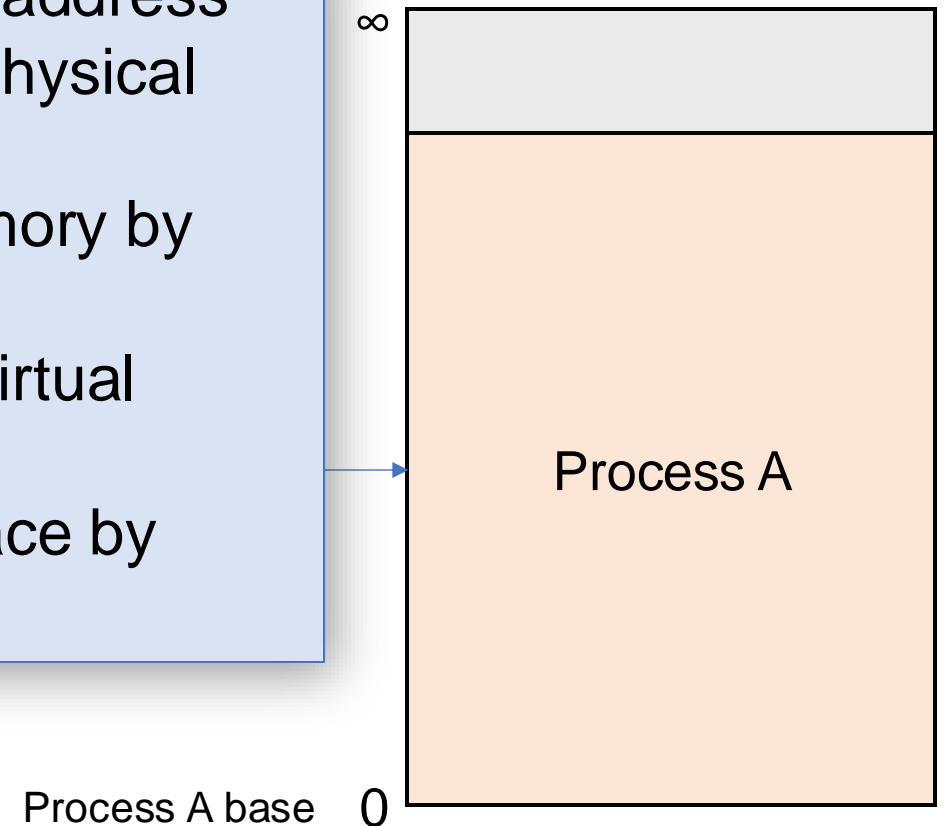
bound

Stack

Data

Code

0

Process A Virtual Address Space

∞

Process A

Process A base   0

Physical Address Space

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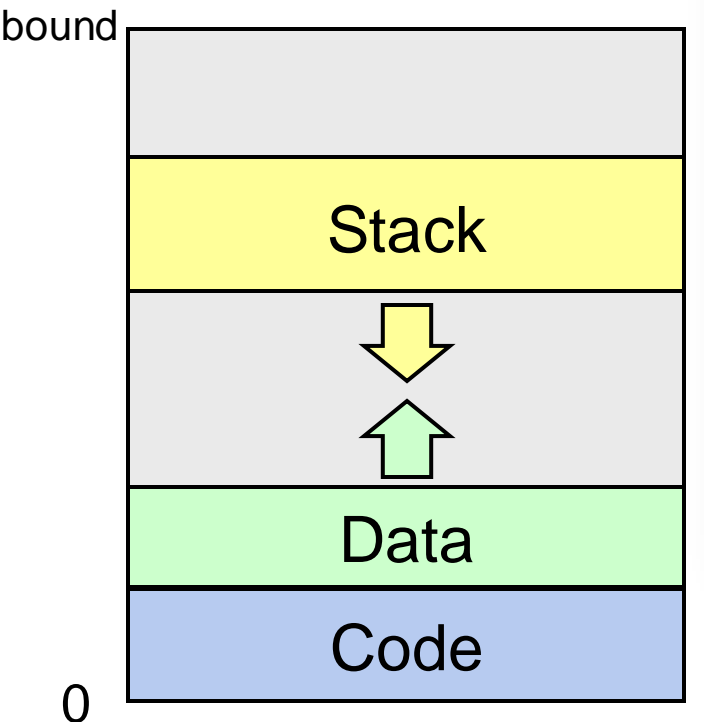
- Must map entire virtual address space contiguously in physical memory.
- Move it in physical memory by modifying the base.
- The base is pinned to virtual address 0.
- Make more upward space by adjusting the bound

bound

Stack

Data

Code

0

Process A Virtual Address Space

∞

Process A

Process A base   0

Physical Address Space

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?

- Must map entire virtual address space contiguously in physical memory.

- Fragmentation

- Growing can only happen upwards with the bound

- Doesn't support read-only regions of memory within a process
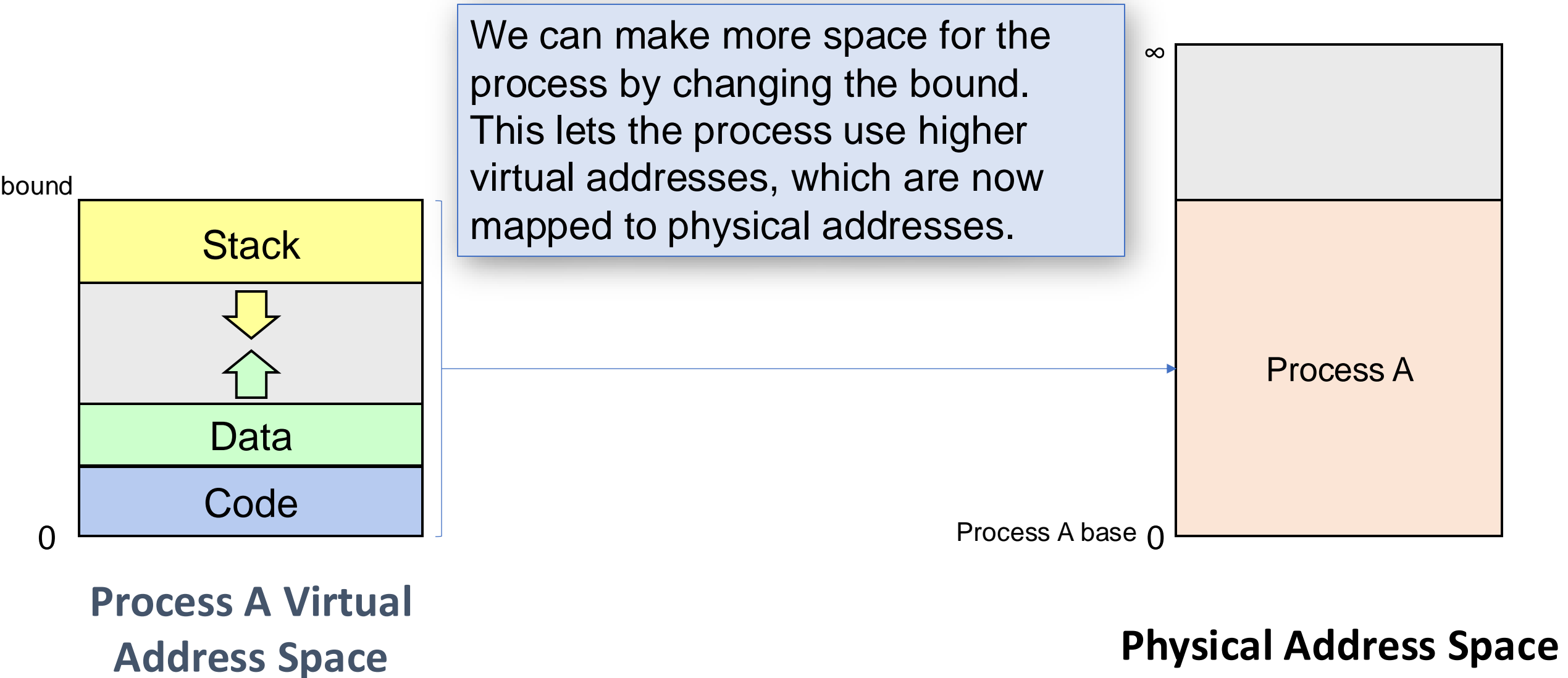
Approach #1: Base and Bound

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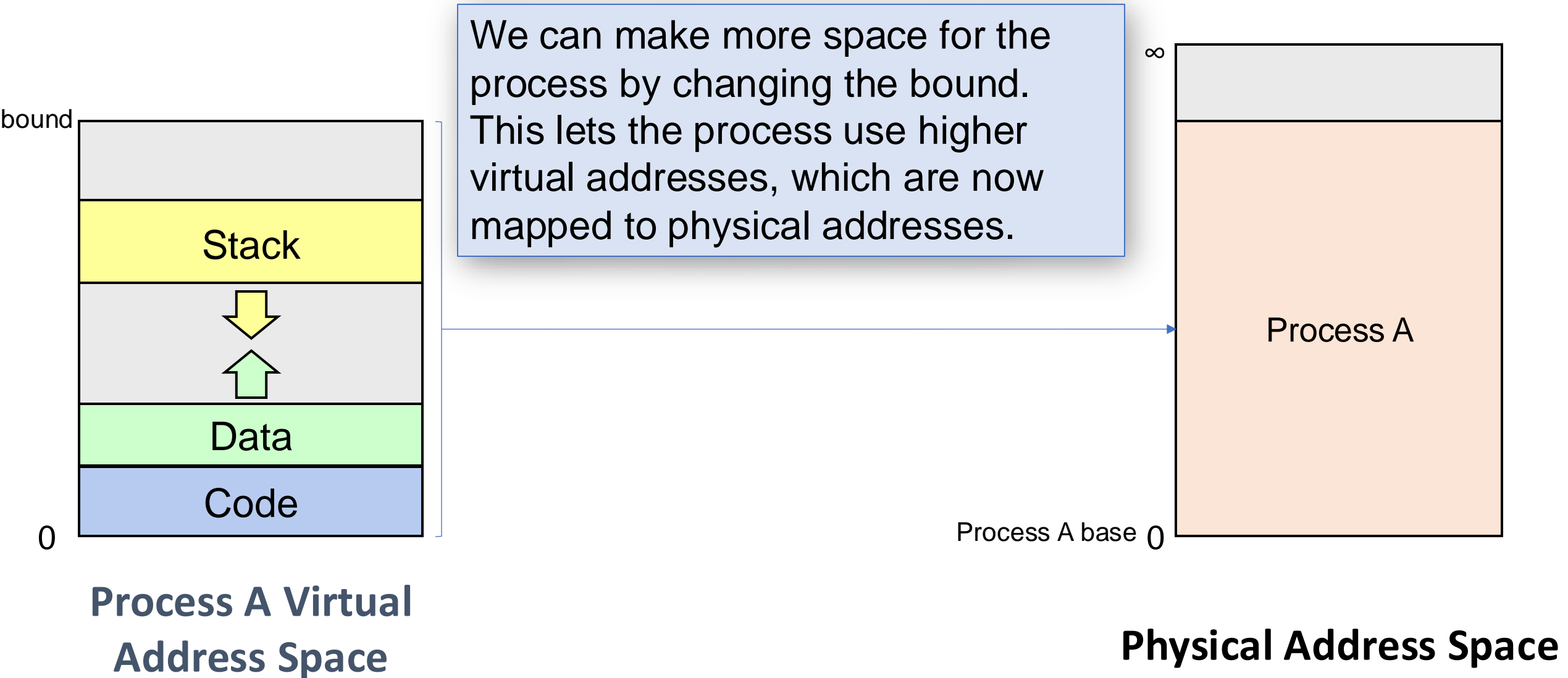
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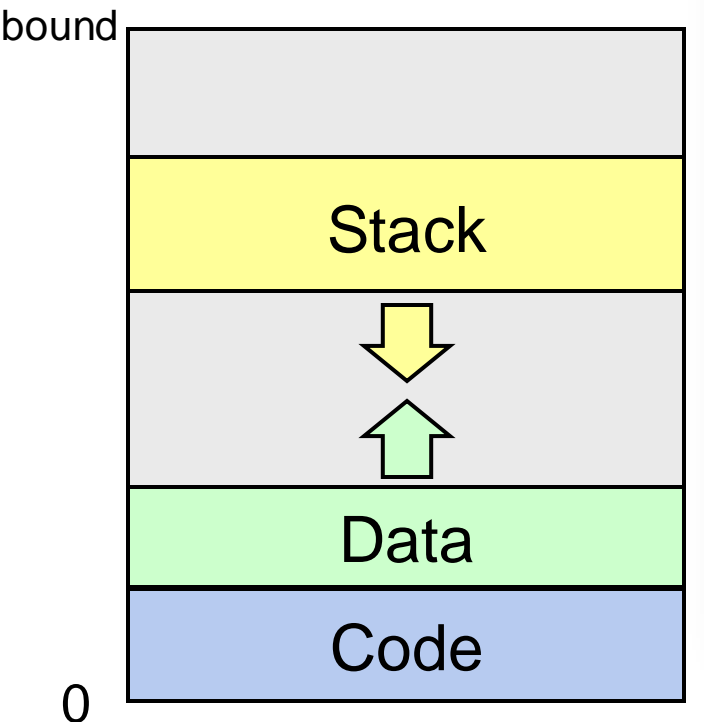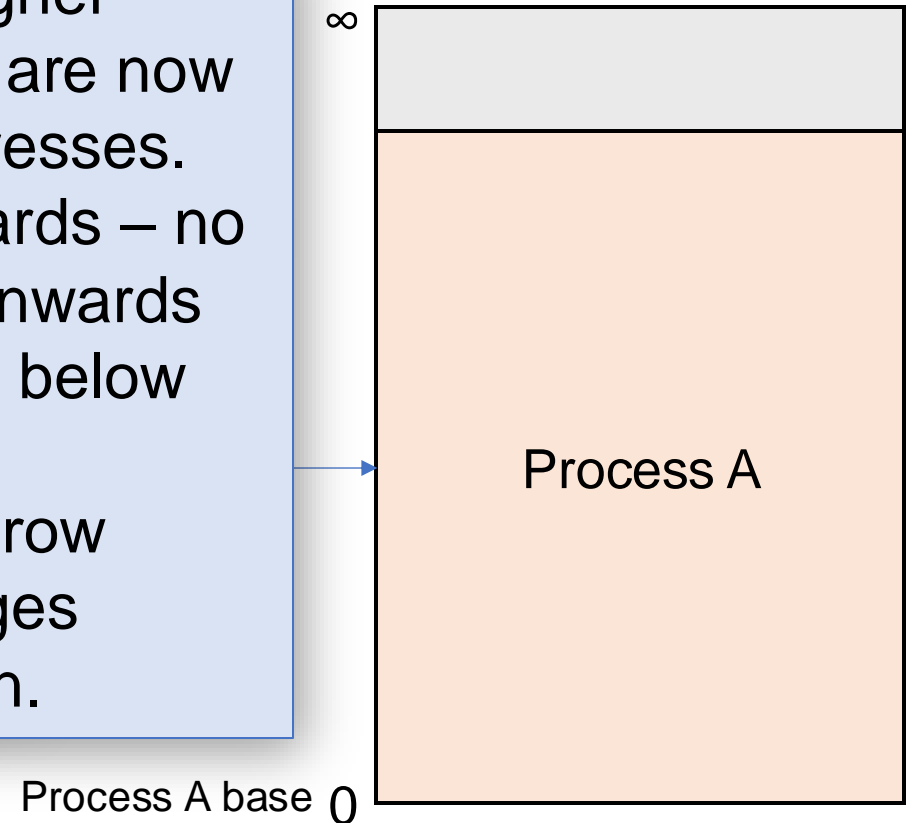
Base and Bound – Changing Bound

We can make more space for the process by changing the bound. This lets the process use higher virtual addresses, which are now mapped to physical addresses.

bound

Stack

Data

Code

0

Process A Virtual Address Space

∞

Process A

Process A base

0

Physical Address Space

Base and Bound – Changing Bound

We can make more space for the process by changing the bound. This lets the process use higher virtual addresses, which are now mapped to physical addresses.

bound

Stack

Data

Code

0

Process A Virtual Address Space

∞

Process A

Process A base

0

Physical Address Space

Base and Bound — Changing Bound

bound

Stack

Data

Code

0

Process A Virtual Address Space

- Process can now use higher virtual addresses, which are now mapped to physical addresses.
- But this only grows upwards – no mechanism to grow downwards (additionally, we can't go below virtual address 0).
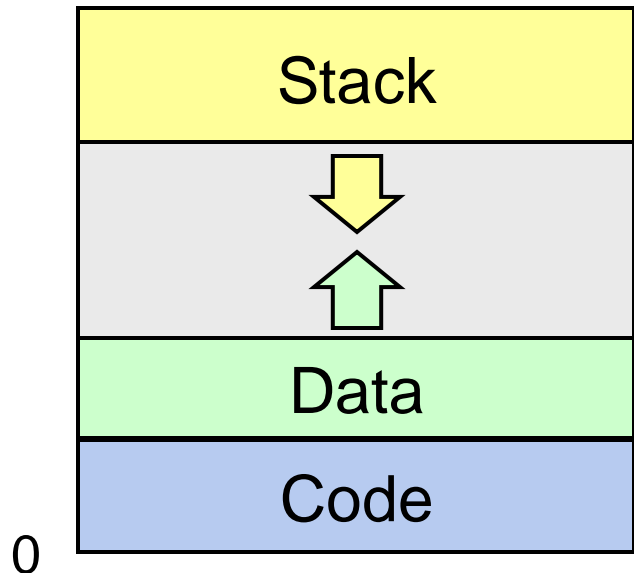- Adjusting base doesn't grow downwards – only changes physical memory location.

∞

Process A

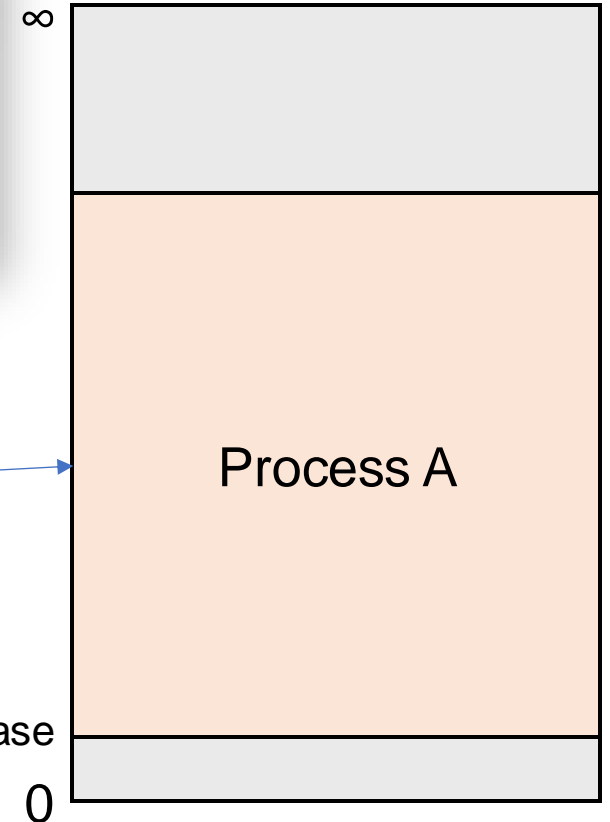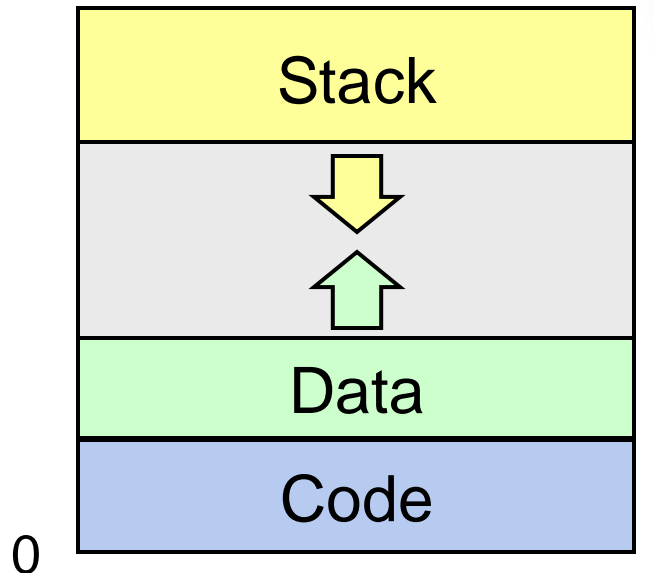Process A base   0

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.

bound

| Stack |
| ⬇ ⬆ |
| Data |
| Code |

0

Process A Virtual Address Space

∞

Process A

Process A base
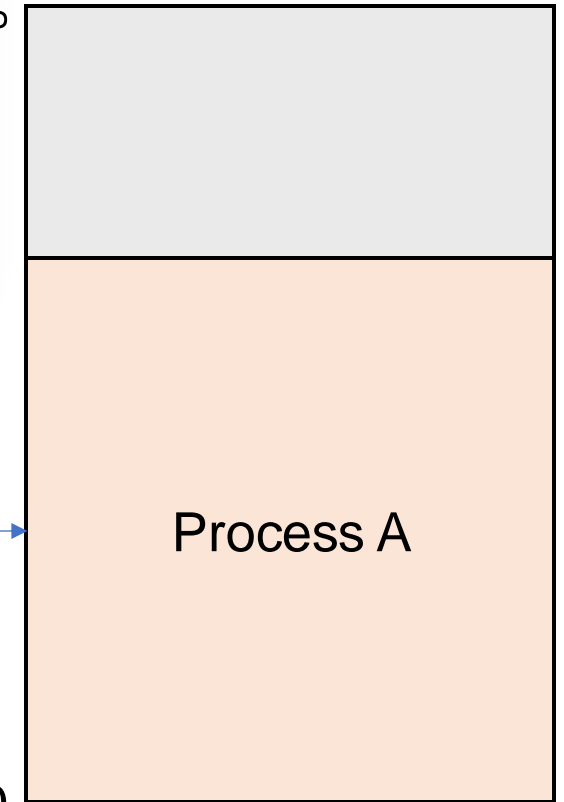
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Physical Address Space

Base and Bound – Changing Base

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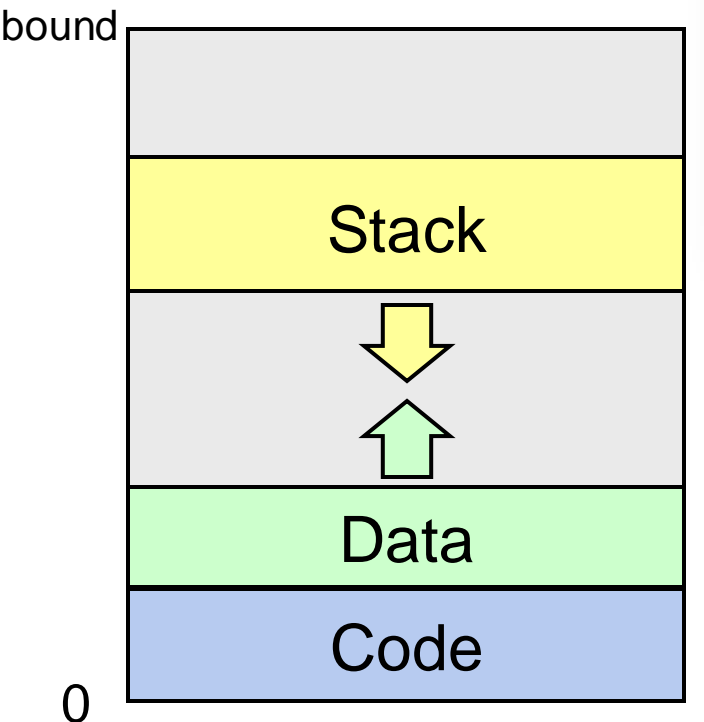
bound

| Stack |
| Data |
| Code |

0

Process A Virtual Address Space

∞

Process A

Process A base   0
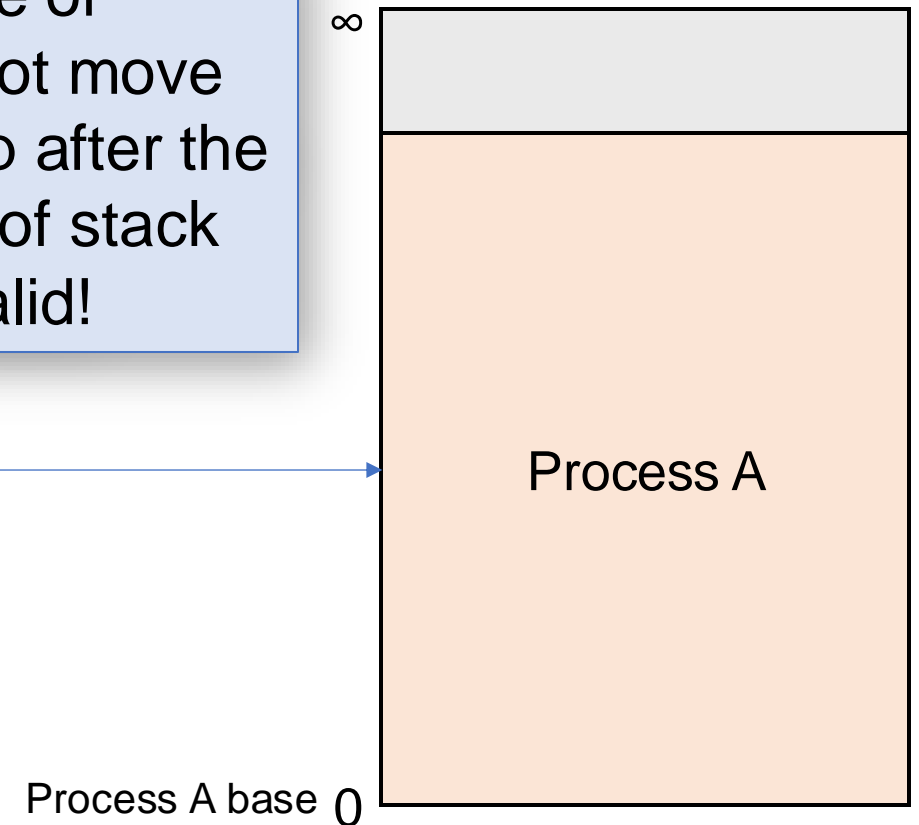
Physical Address Space

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. E.g. array of stack pointers would now be invalid!

bound

| Stack |
| Data |
| Code |

0

Process A Virtual Address Space

∞

Process A

Process A base 0

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.