Memory Management: Address space and Segmentation

CS 571: Operating Systems (Spring 2020)

Lecture 6a

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Some material taken/derived from:
- Wisconsin CS-537 materials created by Remzi Arpaci-Dusseau.

Announcement

- HW1 posted on BB
- Due next Monday, 03/09, 11:59pm

Today's outline

1. Address space

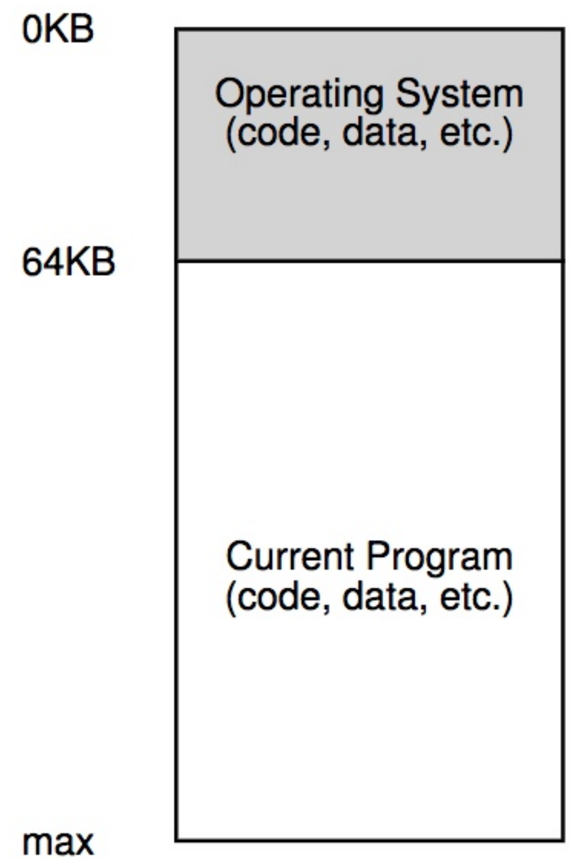
2. Virtual memory accesses

3. Relocation

4. Segmentation

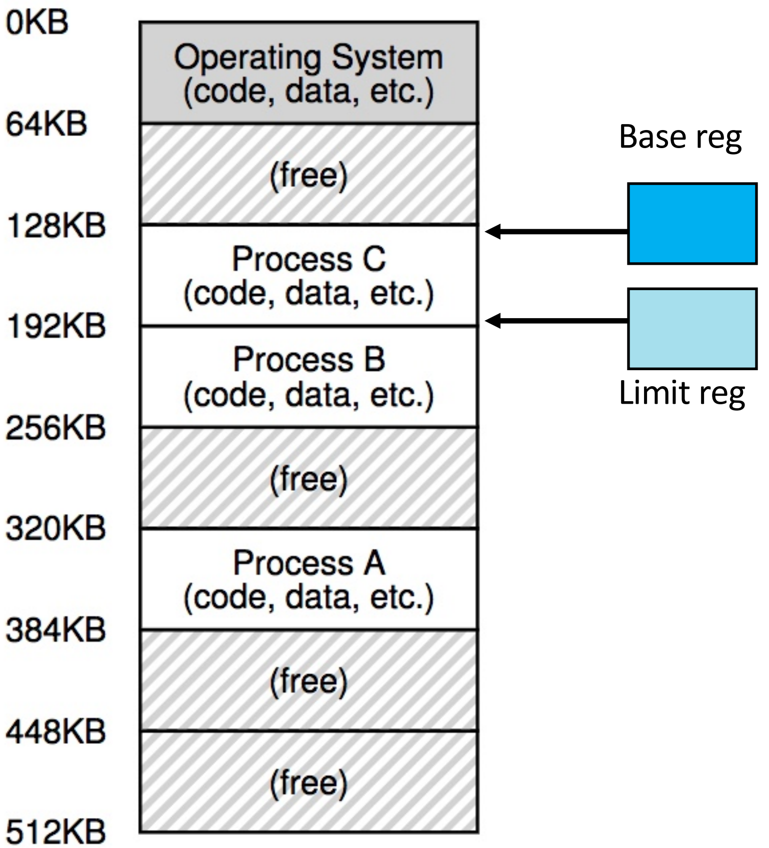
Early Systems

- OS was a set of libraries
- OS sat in memory starting at physical address 0
- The rest was used by running program



Multiprogramming & Time Sharing

- OS makes sure each process is confined to its own address space in memory
- One naïve implementation:
  - <base register & limit register> pair



The Abstraction

- A process has a set of addresses that map to a collection of bytes

- This set is called an address space

- Review: what stuff is in an address space?

Match that Segment!

```
int x;
int main(int argc, char *argv[]) {
    int y;
    int *z = malloc(sizeof(int));
}
```

x	code
main	data
y	heap
z	stack

Match that Segment!

```
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int main(int argc, char *argv[]) {
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}
```

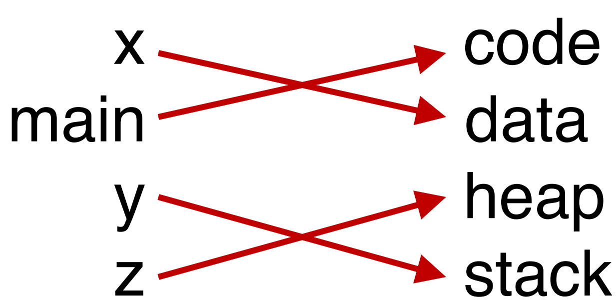

Match that Segment!

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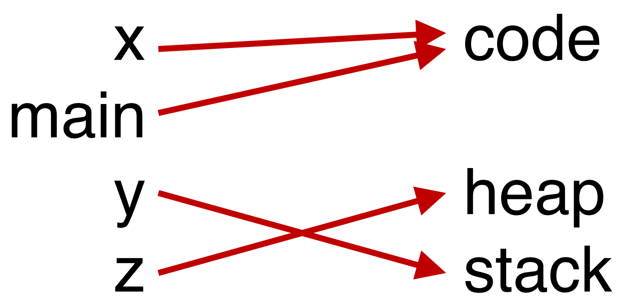
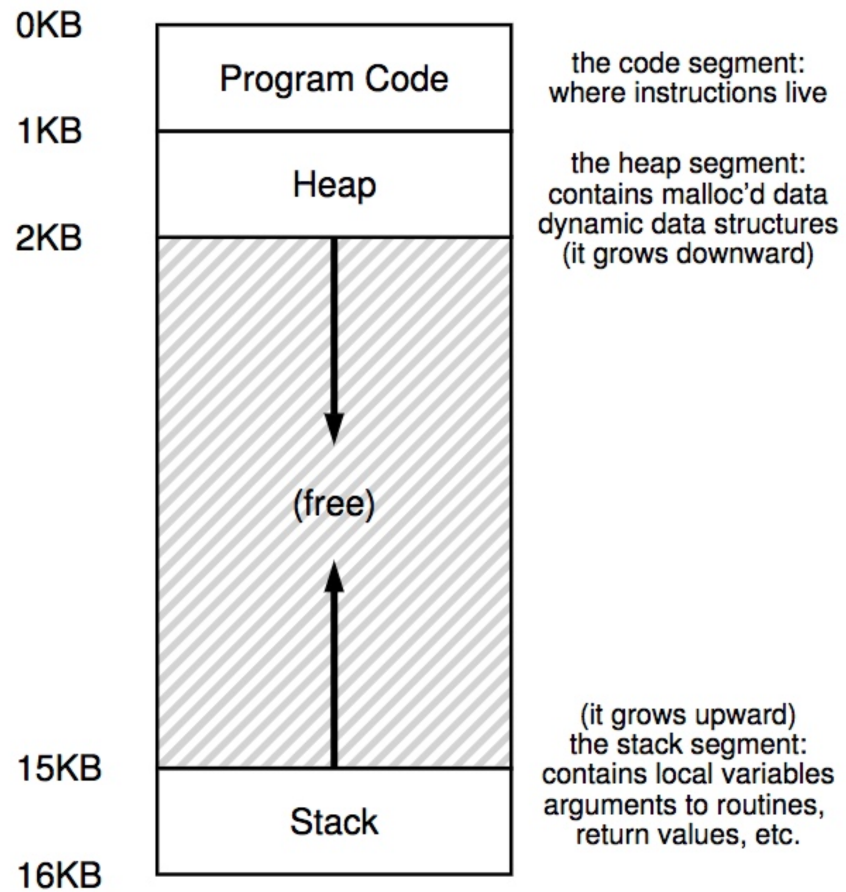


In OSTEP

The Address Space

- Address space
  - An easy-to-use abstraction of physical memory
- The address space is the running program's view of memory in the system
  - Virtual address or logical address
  - Physical address refers to those seen by the memory unit hardware
- The user program generates *logical* addresses; it never sees the real physical addresses



High-level Goals

- Transparency
  - User program behaves as if it has its own private physical memory
- Efficiency
  - Space and time efficient memory virtualization
  - Performance relies on hardware support (e.g., TLBs)
- Protection
  - Isolation property
  - User process shouldn't access or affect anything outside its own address space

All Memory Addresses You See are Virtual

- Any address that a programmer can see is a virtual address

```
#include <stdio.h>
#include <stdlib.h>
int main(int argc, char *argv[]) {
    printf("location of code  : %p\n", (void *) main);
    printf("location of heap  : %p\n", (void *) malloc(1));
    int x = 3;
    printf("location of stack : %p\n", (void *) &x);
    return x;
}
```

Result:

```
location of code  : 0x1095afe50
location of heap  : 0x1096008c0
location of stack : 0x7fff691aea64
```

Virtual Memory Accesses

```c
#include <stdio.h>
#include <stdlib.h>

int main(int argc, char *argv[]) {
    int x;
    x = x + 2;
}
```

```
_main:
0000000100000fa0 pushq %rbp
0000000100000fa1 movq  %rsp, %rbp
0000000100000fa4 xorl  %eax, %eax
0000000100000fa6 movl  %edi, -0x4(%rbp)
0000000100000fa9 movq  %rsi, -0x10(%rbp)
0000000100000fad movl  0x8(%rbp), %edi
0000000100000fb0 addl  $0x2, %edi
0000000100000fb3 movl  %edi, 0x8(%rbp)
0000000100000fb6 popq  %rbp
0000000100000fb7 retq
```

`% otool -tv demo`

(or objdump in Linux)

Virtual Memory Accesses

```c
#include <stdio.h>
#include <stdlib.h>

int main(int argc, char *argv[]) {
    int x;
    x = x + 2;
}
```

```
_main:
0000000100000fa0 pushq %rbp
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0000000100000fb6 popq  %rbp
0000000100000fb7 retq
```

```
% otool -tv demo
```

(or objdump in Linux)

Virtual Memory Accesses

```
%rip = 0x100000fad
%rbp = 0x200
```

Memory accesses:

```
0x100000fad movl 0x8(%rbp), %edi
0x100000fb0 addl $0x2, %edi
0x100000fb3 movl %edi, 0x8(%rbp)
```

Virtual Memory Accesses

```
%rip = 0x100000fad
%rbp = 0x200
```

Memory accesses:
Fetch instr. at addr 0x100000fad

```
0x100000fad movl 0x8(%rbp), %edi
0x100000fb0 addl $0x2, %edi
0x100000fb3 movl %edi, 0x8(%rbp)
```

Virtual Memory Accesses

```
%rip = 0x100000fad
%rbp = 0x200
```

Memory accesses:
Fetch instr. at addr 0x100000fad
Exec, load from addr 0x208

```
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0x100000fb0 addl $0x2, %edi
0x100000fb3 movl %edi, 0x8(%rbp)
```

Virtual Memory Accesses

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%rip = 0x100000fb0
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```

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Virtual Memory Accesses

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%rip = 0x100000fb0
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```

Memory accesses:

Fetch instr. at addr 0x100000fad
Exec, load from addr 0x208

Fetch instr. at addr 0x100000fb0

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0x100000fad movl 0x8(%rbp), %edi
0x100000fb0 addl $0x2, %edi
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Virtual Memory Accesses

```
%rip = 0x100000fb0
%rbp = 0x200
```

```
0x100000fad movl 0x8(%rbp), %edi
0x100000fb0 addl $0x2, %edi
0x100000fb3 movl %edi, 0x8(%rbp)
```

Memory accesses:

Fetch instr. at addr 0x100000fad
Exec, load from addr 0x208

Fetch instr. at addr 0x100000fb0
Exec, no load

Virtual Memory Accesses

```
%rip = 0x100000fb3
%rbp = 0x200
```

```
0x100000fad movl 0x8(%rbp), %edi
0x100000fb0 addl $0x2, %edi
0x100000fb3 movl %edi, 0x8(%rbp)
```

Memory accesses:

Fetch instr. at addr 0x100000fad
Exec, load from addr 0x208

Fetch instr. at addr 0x100000fb0
Exec, no load

Virtual Memory Accesses

```
%rip = 0x100000fb3
%rbp = 0x200
```

```
0x100000fad movl 0x8(%rbp), %edi
0x100000fb0 addl $0x2, %edi
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Memory accesses:

Fetch instr. at addr 0x100000fad
Exec, load from addr 0x208

Fetch instr. at addr 0x100000fb0
Exec, no load

Fetch instr. at addr 0x100000fb3

Virtual Memory Accesses

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%rip = 0x100000fb3
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```

```
0x100000fad movl 0x8(%rbp), %edi
0x100000fb0 addl $0x2, %edi
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Memory accesses:

Fetch instr. at addr 0x100000fad
Exec, load from addr 0x208

Fetch instr. at addr 0x100000fb0
Exec, no load

Fetch instr. at addr 0x100000fb3
Exec, store to addr 0x208

Virtual Memory Accesses

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%rip = 0x100000fb3
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0x100000fad movl 0x8(%rbp), %edi
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Memory accesses:

Fetch instr. at addr 0x100000fad
Exec, load from addr 0x208

Fetch instr. at addr 0x100000fb0
Exec, no load

Fetch instr. at addr 0x100000fb3
Exec, store to addr 0x208

How to relocate the memory access in a way that is transparent to the process?

How to Run Multiple Programs?

- Approaches:
  - Static relocation
  - Dynamic relocation
  - Segmentation

Static Relocation

- Idea: rewrite each program before loading it into memory as a process
- Each rewrite uses different addresses and pointers
- Change jumps, loads, etc.
- Q: Can any addresses be unchanged?

Rewrite for Each New Process

```
0x100010fad movl    0x8(%rbp), %edi
0x100010fb0 addl    $0x2, %edi
0x100010fb3 movl    %edi, 0x8(%rbp)
```

rewrite

```
0x100000fad movl    0x8(%rbp), %edi
0x100000fb0 addl    $0x2, %edi
0x100000fb3 movl    %edi, 0x8(%rbp)
```

rewrite

```
0x100020fad movl    0x8(%rbp), %edi
0x100020fb0 addl    $0x2, %edi
0x100020fb3 movl    %edi, 0x8(%rbp)
```

Rewrite for Each New Process

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rewrite

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0x100010fad movl    0x8(%rbp), %edi
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0x100020fad movl    0x8(%rbp), %edi
0x100020fb0 addl    $0x2, %edi
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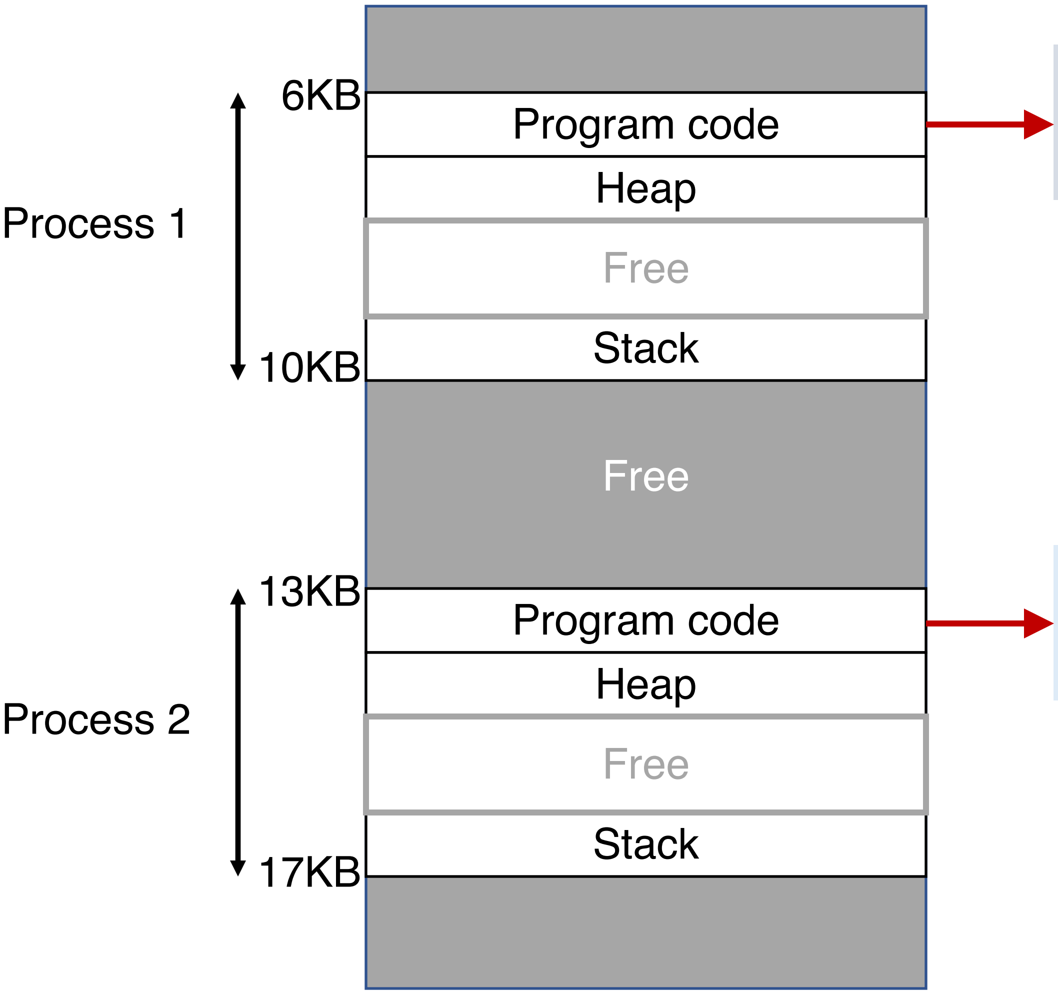
Rewrite for Each New Process

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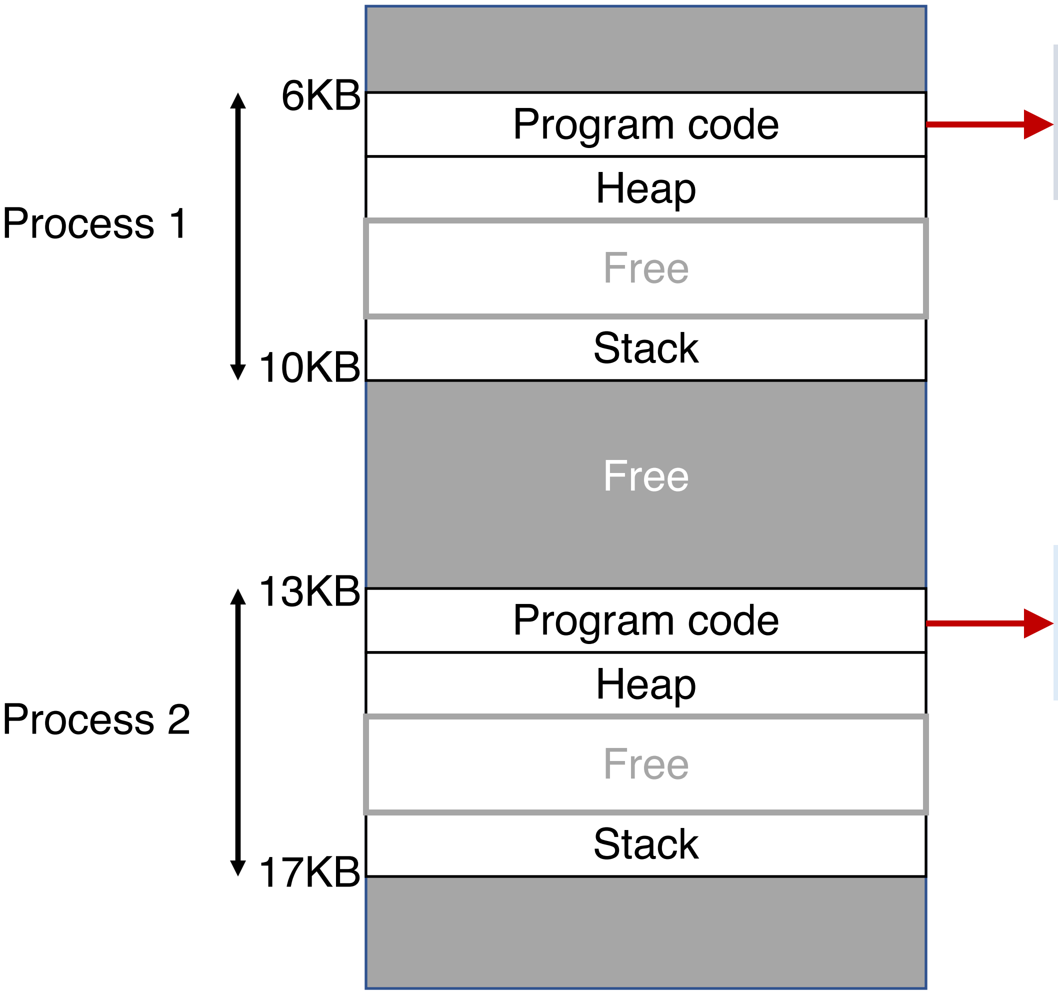
0x100020fb3 movl    %edi, 0x8(%rbp)
```

Rewrite for Each New Process

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0x100020fad movl    0x8(%rbp), %edi
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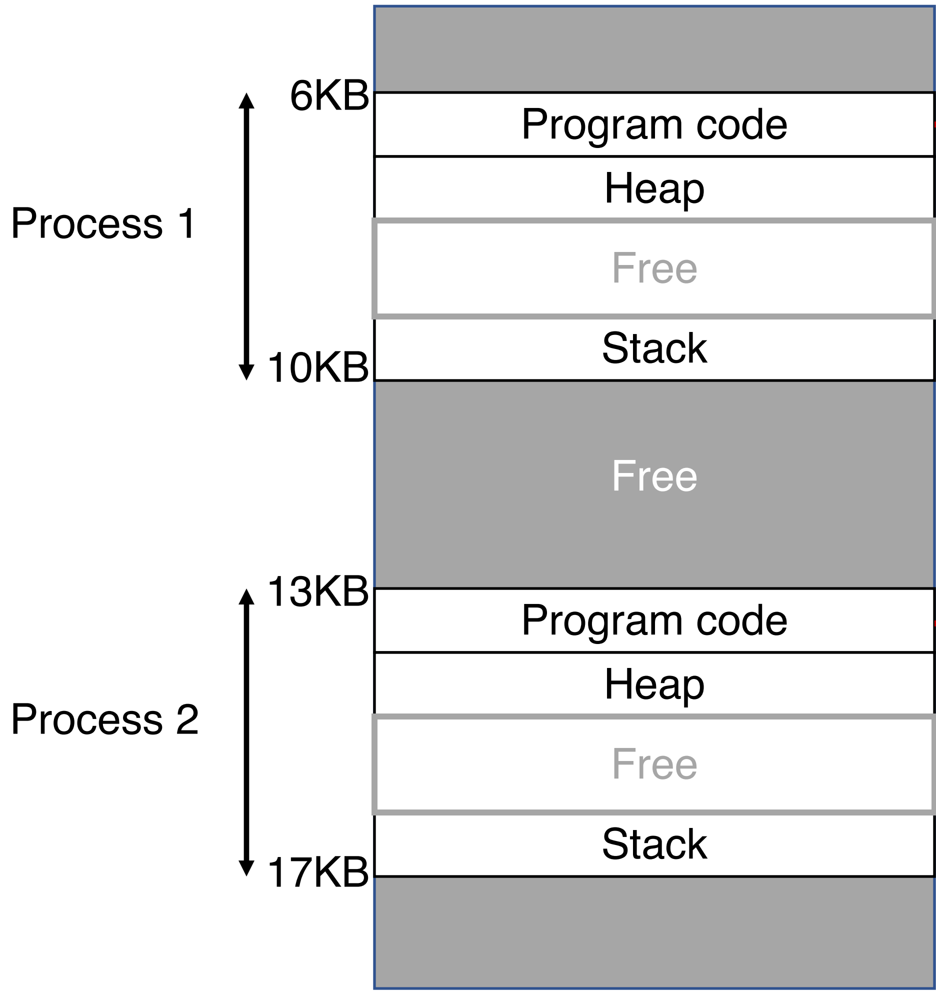
```

Why didn't we have to rewrite the stack addr?

Rewrite for Each New Process

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```

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0x100020fad movl   0x8(%rbp), %edi
0x100020fb0 addl   $0x2, %edi
0x100020fb3 movl   %edi, 0x8(%rbp)
```

Why didn't we have to rewrite the stack addr?

A: `$rbp` is dynamically calculated according to the base addr

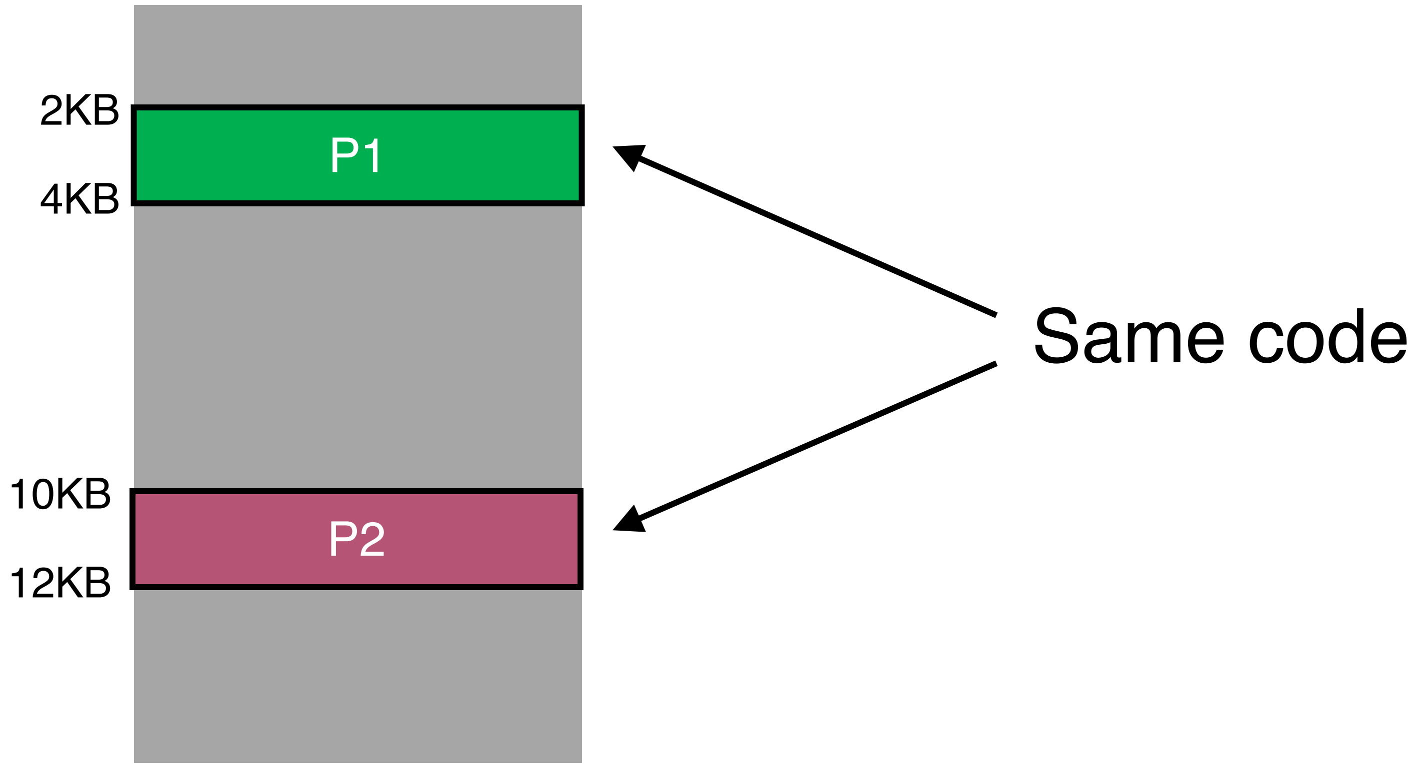
How to Run Multiple Programs?

- Approaches:
  - Static relocation
  - Dynamic relocation
    - Base
    - Base-and-Bounds
  - Segmentation

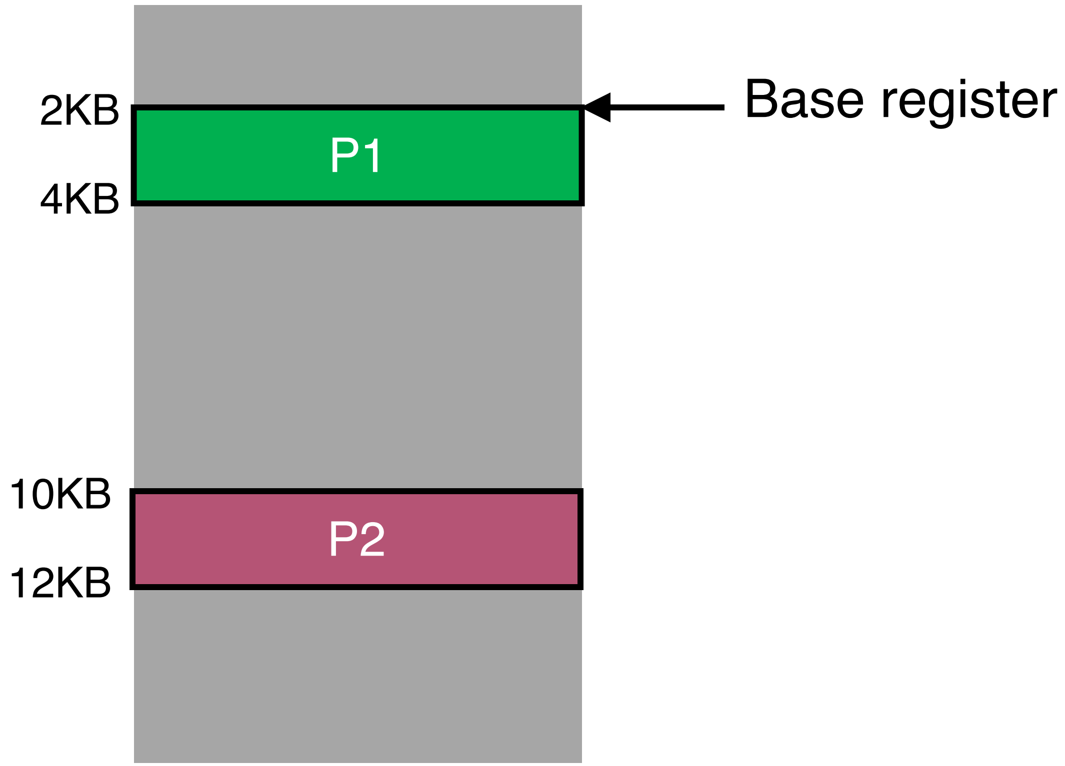
Base

- Idea: translate virtual address to physical by adding an offset each time
- Store base addr in a base register
- Each process has a different value in the base register when running

Base Relocation

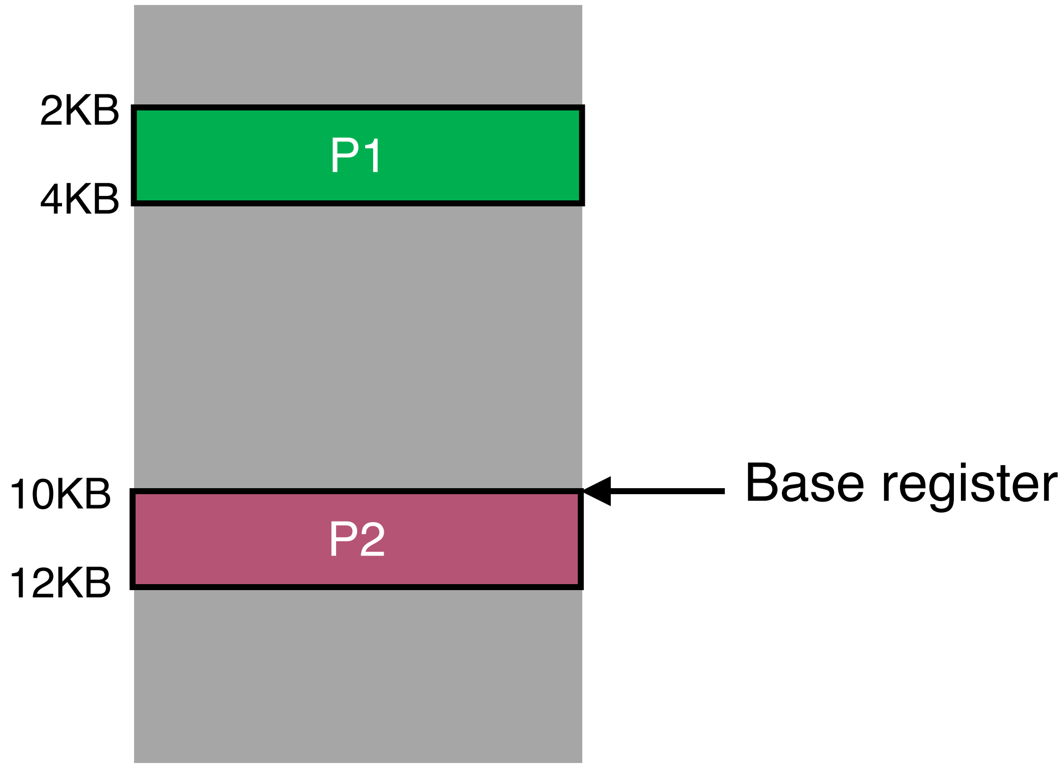


Base Relocation



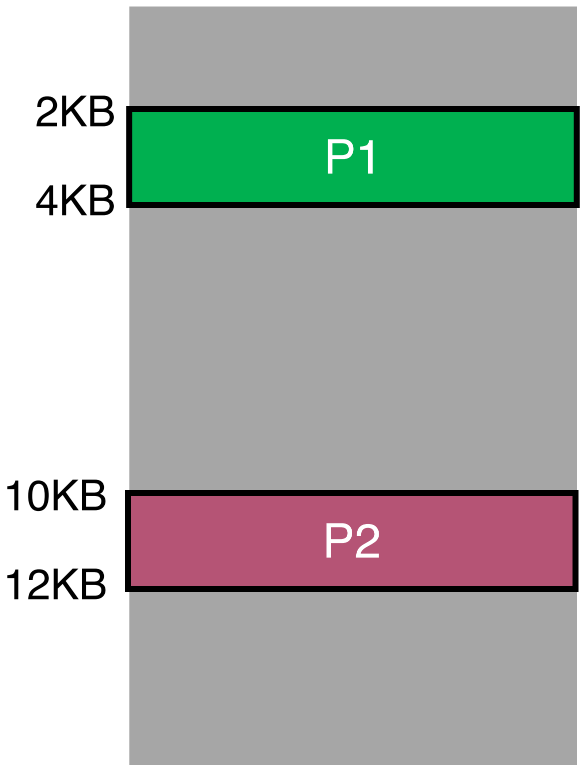
P1 is running …

Base Relocation



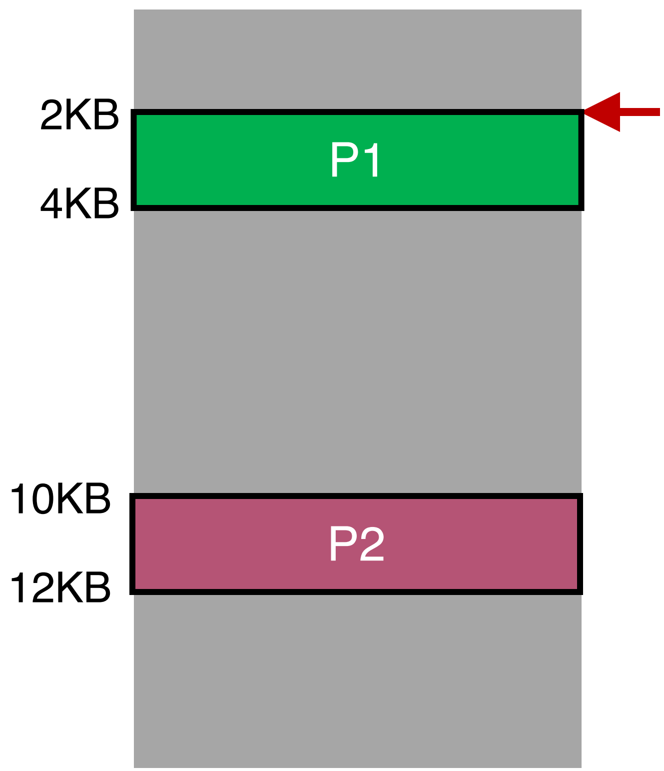
P2 is running …

Base Relocation



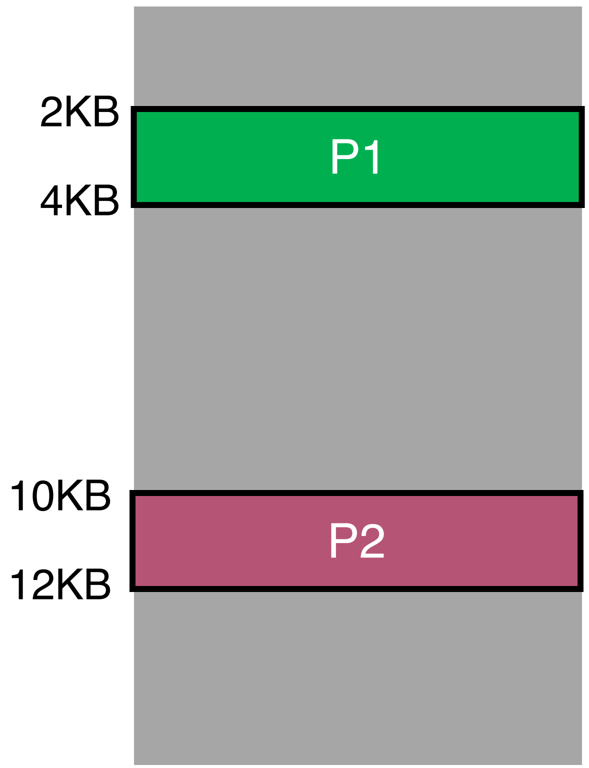
Virtual	Physical
P1: load 100, R1	

Base Relocation



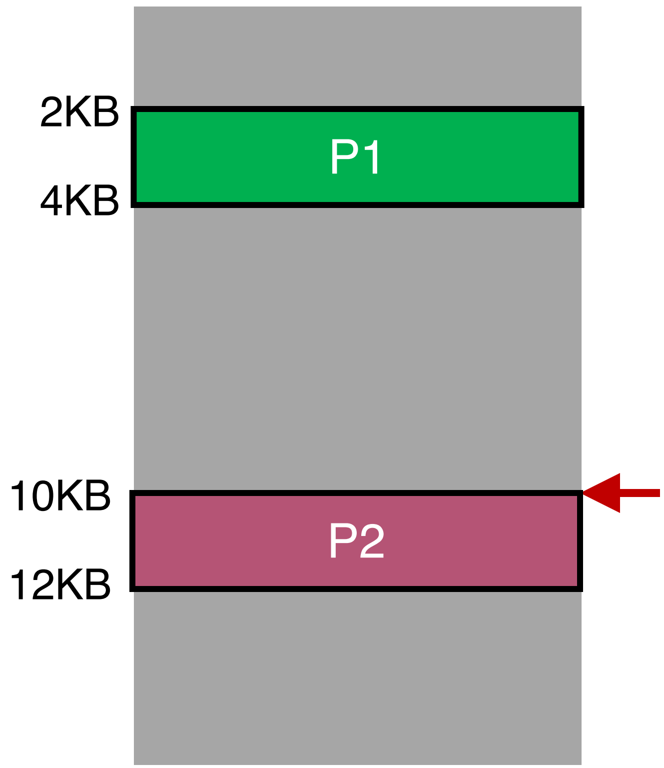
Virtual	Physical
P1: load 100, R1	load 2148, R1

Base Relocation



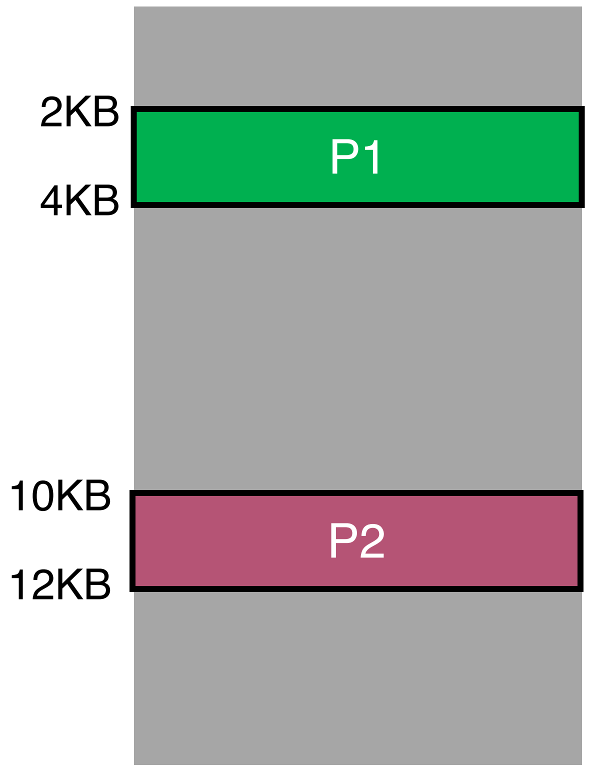
Virtual	Physical
P1: load 100, R1	load 2148, R1
P2: load 100, R1	

Base Relocation



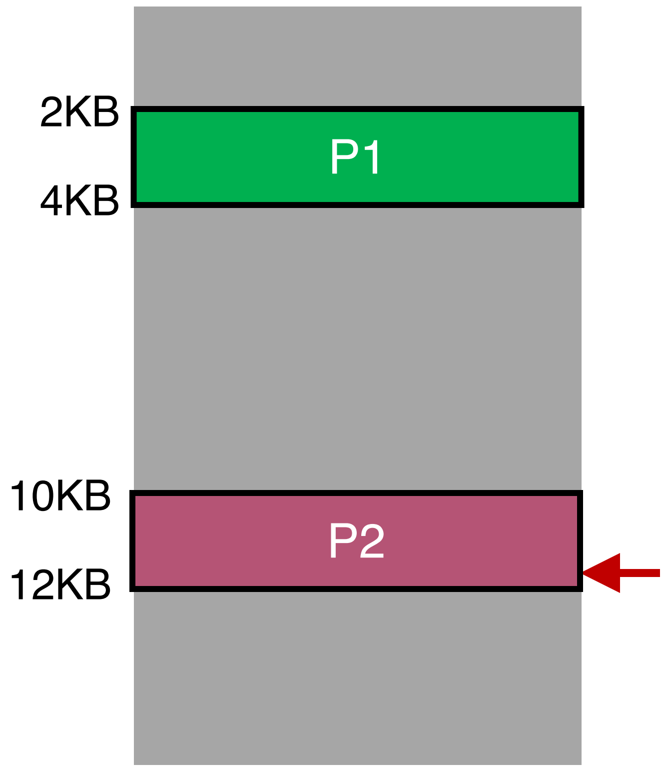
Virtual	Physical
P1: load 100, R1	load 2148, R1
P2: load 100, R1	load 10340, R1

Base Relocation



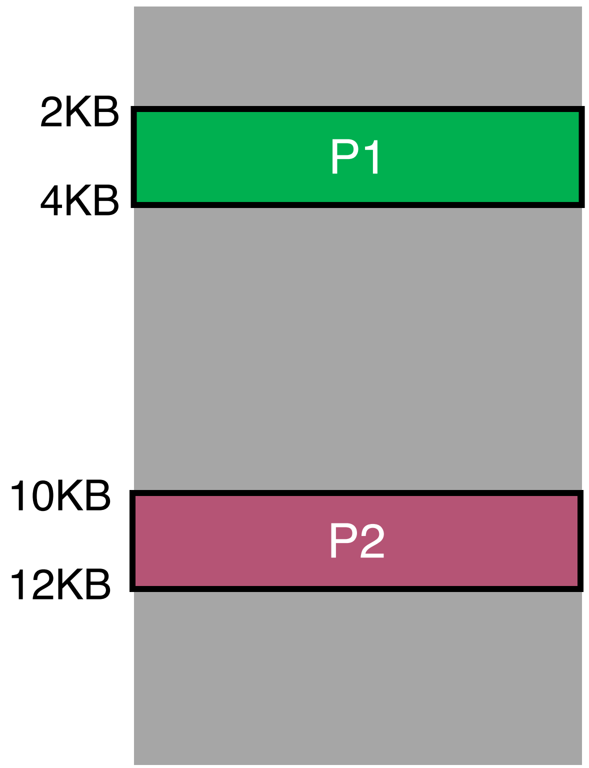
Virtual	Physical
P1: load 100, R1	load 2148, R1
P2: load 100, R1	load 10340, R1
P2: load 2000, R1	

Base Relocation



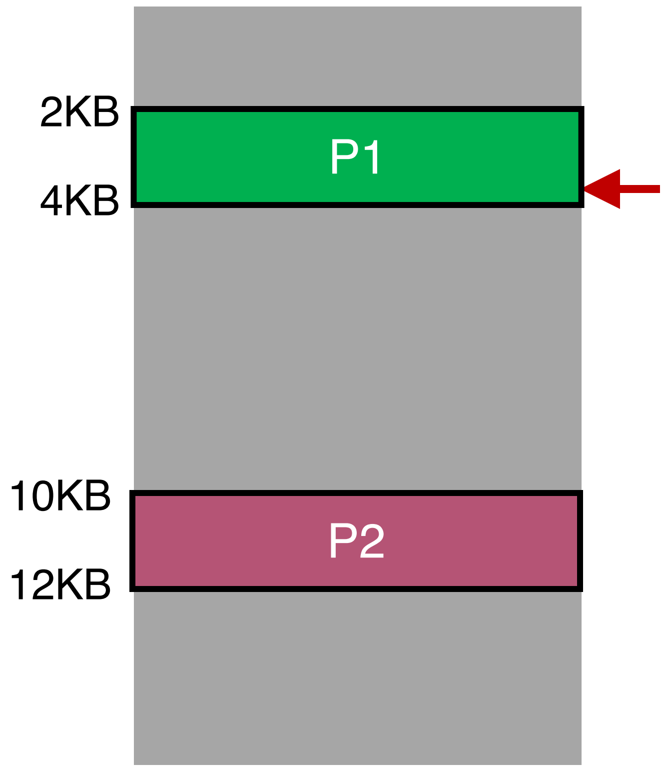
Virtual	Physical
P1: load 100, R1	load 2148, R1
P2: load 100, R1	load 10340, R1
P2: load 2000, R1	load 12240, R1

Base Relocation



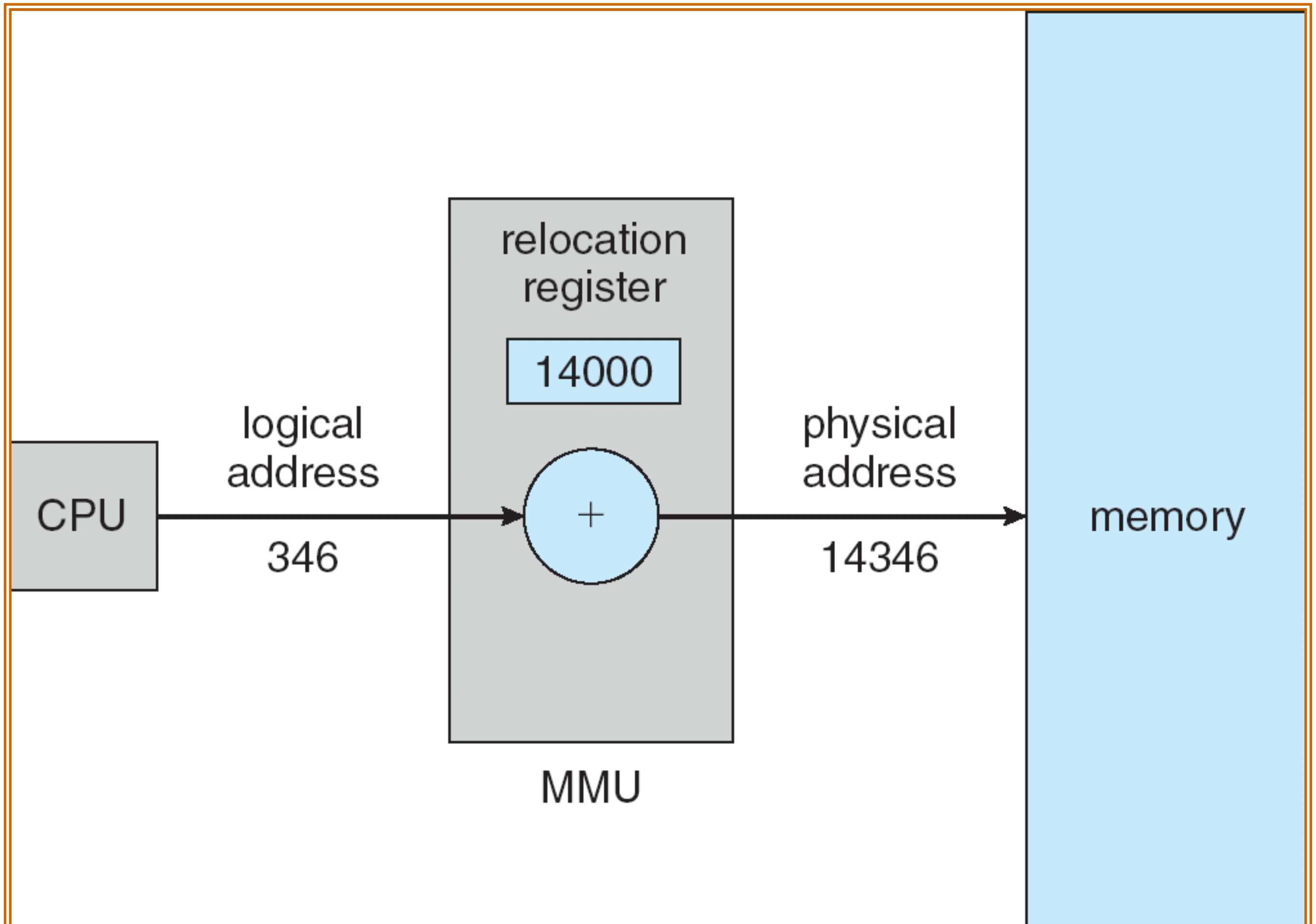
Virtual	Physical
P1: load 100, R1	load 2148, R1
P2: load 100, R1	load 10340, R1
P2: load 2000, R1	load 12240, R1
P1: load 2000, R1	

Base Relocation

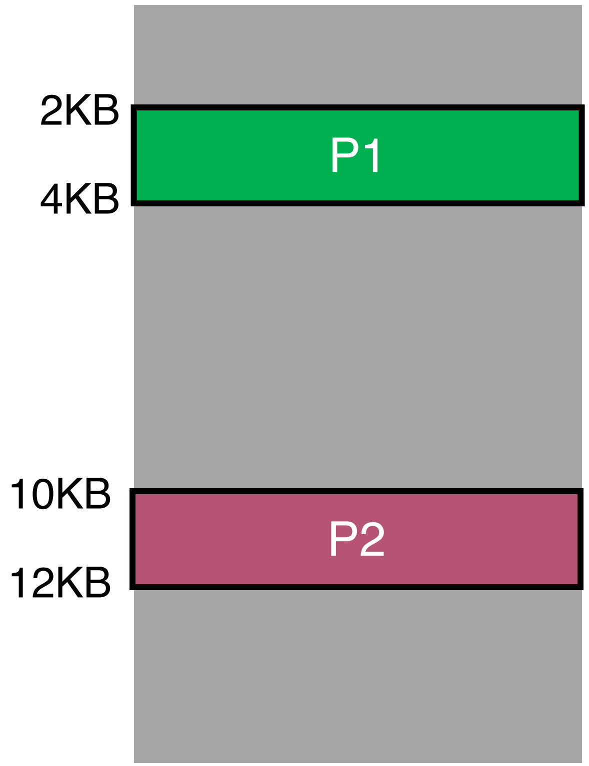


Virtual	Physical
P1: load 100, R1	load 2148, R1
P2: load 100, R1	load 10340, R1
P2: load 2000, R1	load 12240, R1
P1: load 2000, R1	load 4048, R1

Base Relocation Hardware



Base Relocation



Virtual	Physical
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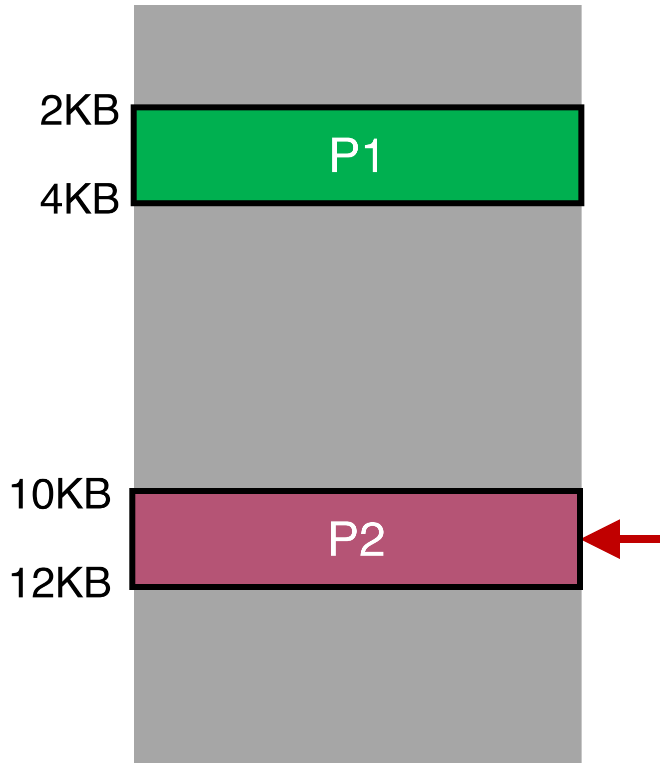
P2: load 100, R1	load 10340, R1
P2: load 2000, R1	load 12240, R1
P1: load 2000, R1	load 4048, R1

Can P1 hurt P2?
Can P2 hurt P1?

Base Relocation



Virtual	Physical
P1: load 100, R1	load 2148, R1
P2: load 100, R1	load 10340, R1
P2: load 2000, R1	load 12240, R1
P1: load 2000, R1	load 4048, R1
P1: store 9241, R1	**store 11289, R1**

Can P1 hurt P2?
Can P2 hurt P1?

Overflow!

How to Run Multiple Programs?

- Approaches:
  - Static relocation
  - Dynamic relocation
    - Base
    - Base-and-Bounds
  - Segmentation

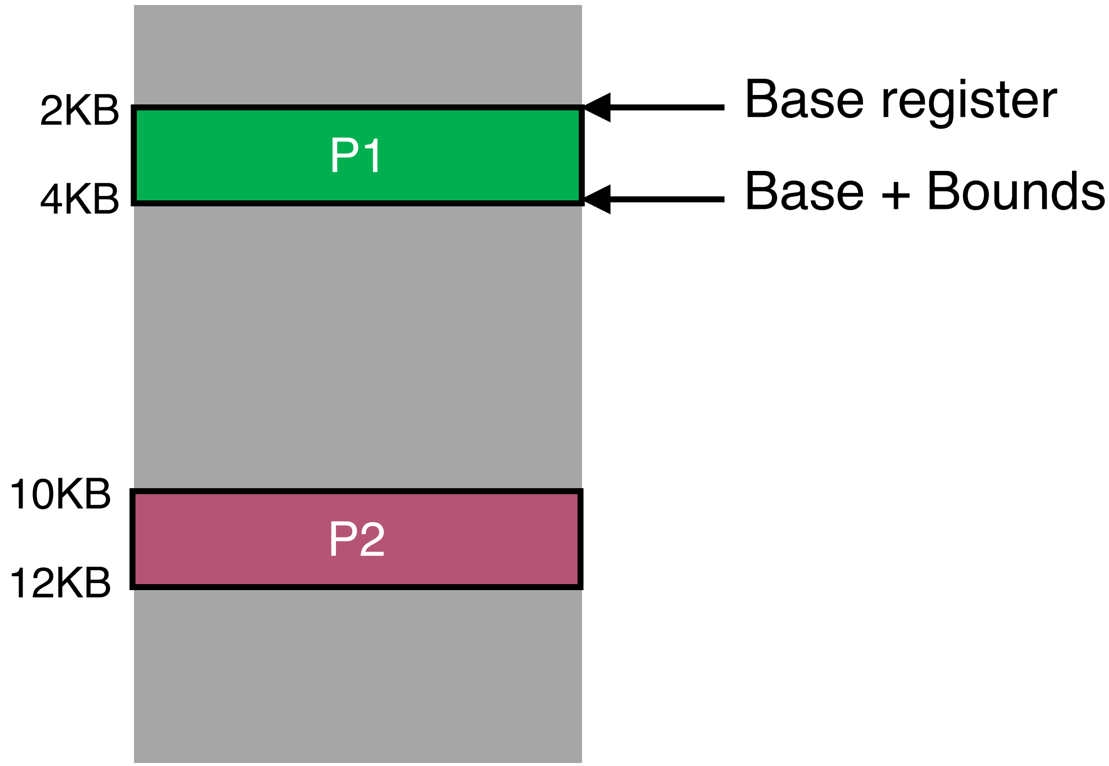
Base-and-Bounds

- Idea: add bound register to avoid "overflow"
- Two CPU registers
  - Base register
  - Bounds register (or limit register)

```
physical addr = virtual addr + base
```

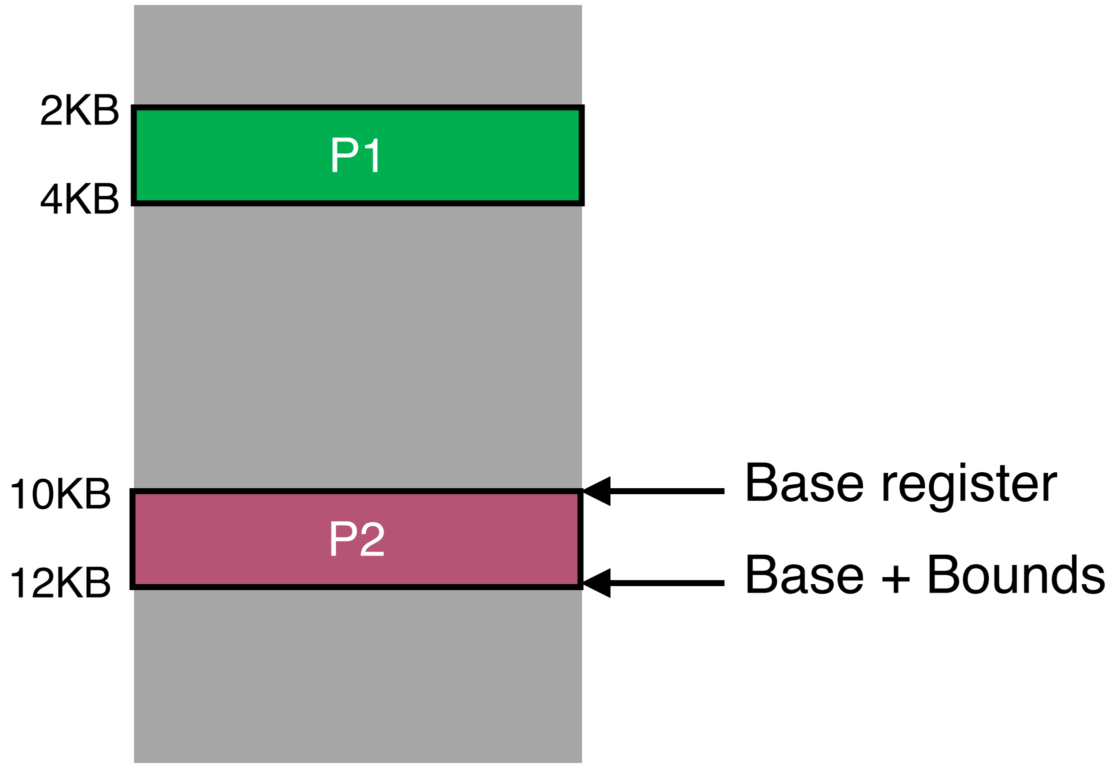
- The base-and-bounds hardware referred to as Memory Management Unit (MMU)
- Protection: The hardware provides special instructions to modify the base and bounds register
  - Allowing OS to change them when different processes run
  - Privileged (only in kernel mode)

Base-and-Bounds



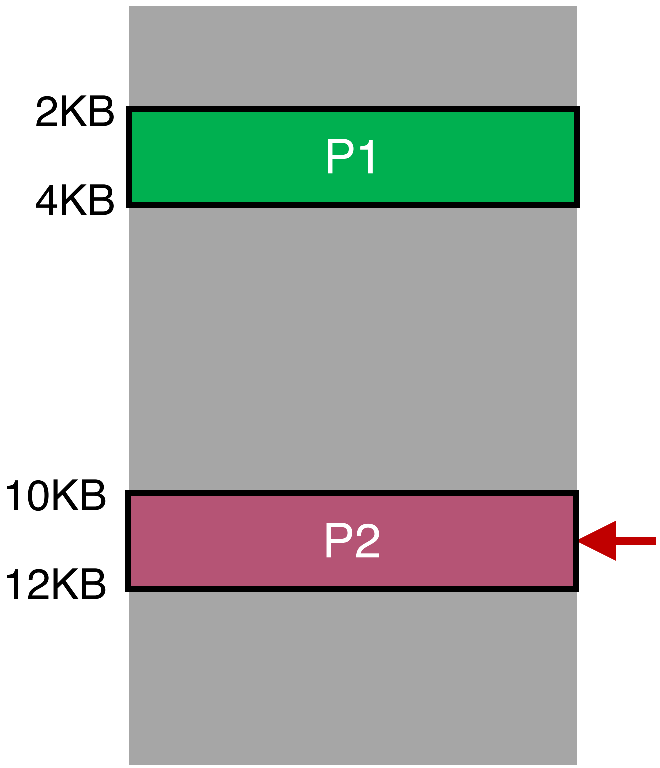
P1 is running …

Base-and-Bounds



P2 is running …

Base-and-Bounds



Virtual	Physical
P1: load 100, R1	load 2148, R1
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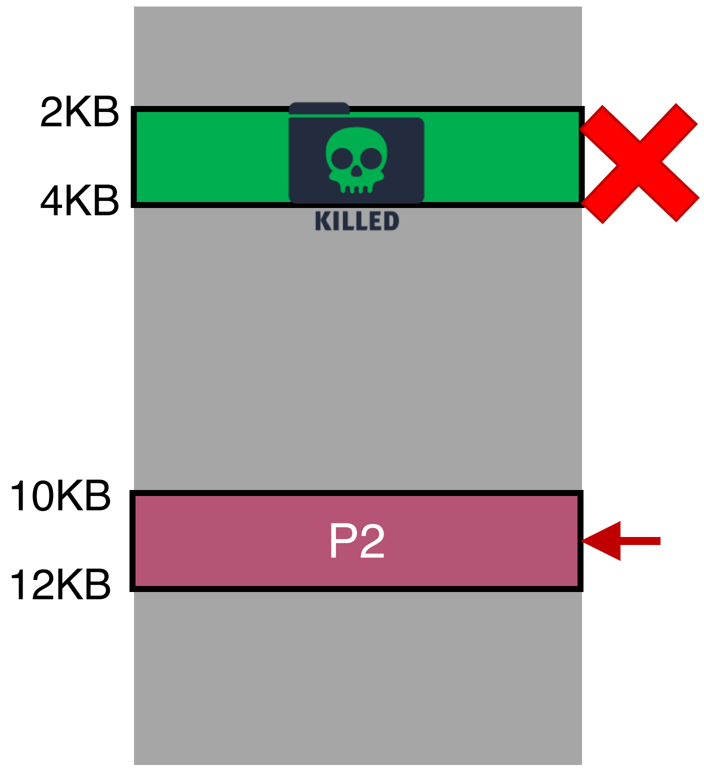
P1: load 2000, R1	load 4048, R1
P1: store 9241, R1	

Can P1 hurt P2?

Base-and-Bounds



Virtual	Physical
P1: load 100, R1	load 2148, R1
P2: load 100, R1	load 10340, R1
P2: load 2000, R1	load 12240, R1
P1: load 2000, R1	load 4048, R1
P1: store 9241, R1	**Interrupt!**

Can P1 hurt P2?

Base-and-Bounds Pros/Cons

- Pros?
  - Fast + simple
  - Little bookkeeping overhead (2 registers)

- Cons?
  - Not flexible
  - Wastes memory for large memory addresses

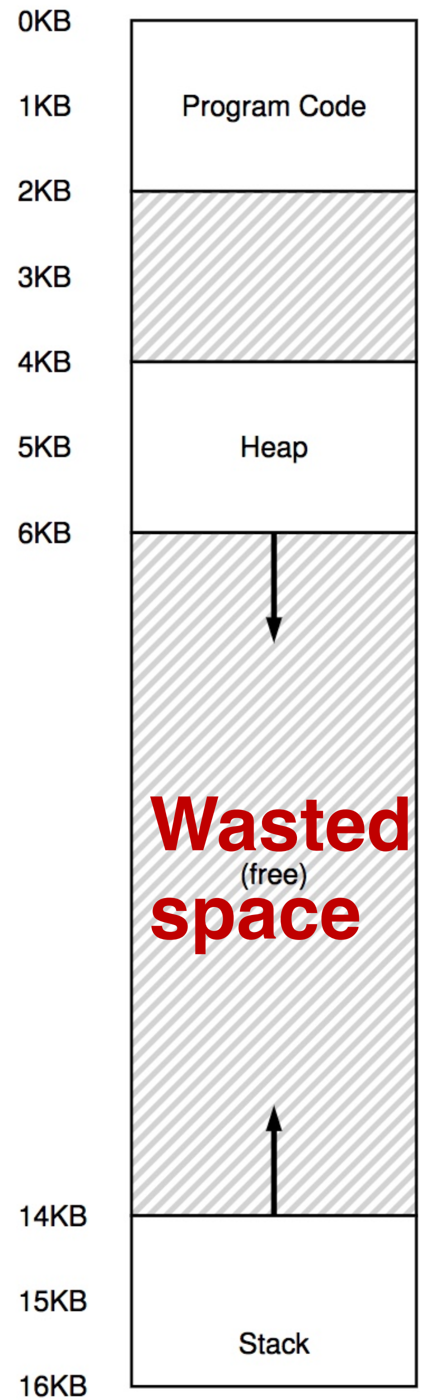
Base-and-Bounds Pros/Cons

- Pros?
  - Fast + simple
  - Little bookkeeping overhead (2 registers)

- Cons?
  - Not flexible
  - Wastes memory for large memory addresses

Problems with Base-and-Bounds?

- Simple base-and-bounds approach wastes a chunk of “free” space between stack and heap
- Impossible to run a program when its entire address space is greater than the memory capacity



How to Run Multiple Programs?

- Approaches:
  - Static relocation
  - Dynamic relocation
    - Base
    - Base-and-Bounds
  - Segmentation

Segmentation

- Idea: generalize base-and-bounds
- Each base+bounds pair is a segment
- Use different segments for heap and memory
  - Requires more registers
- Resize segments as needed

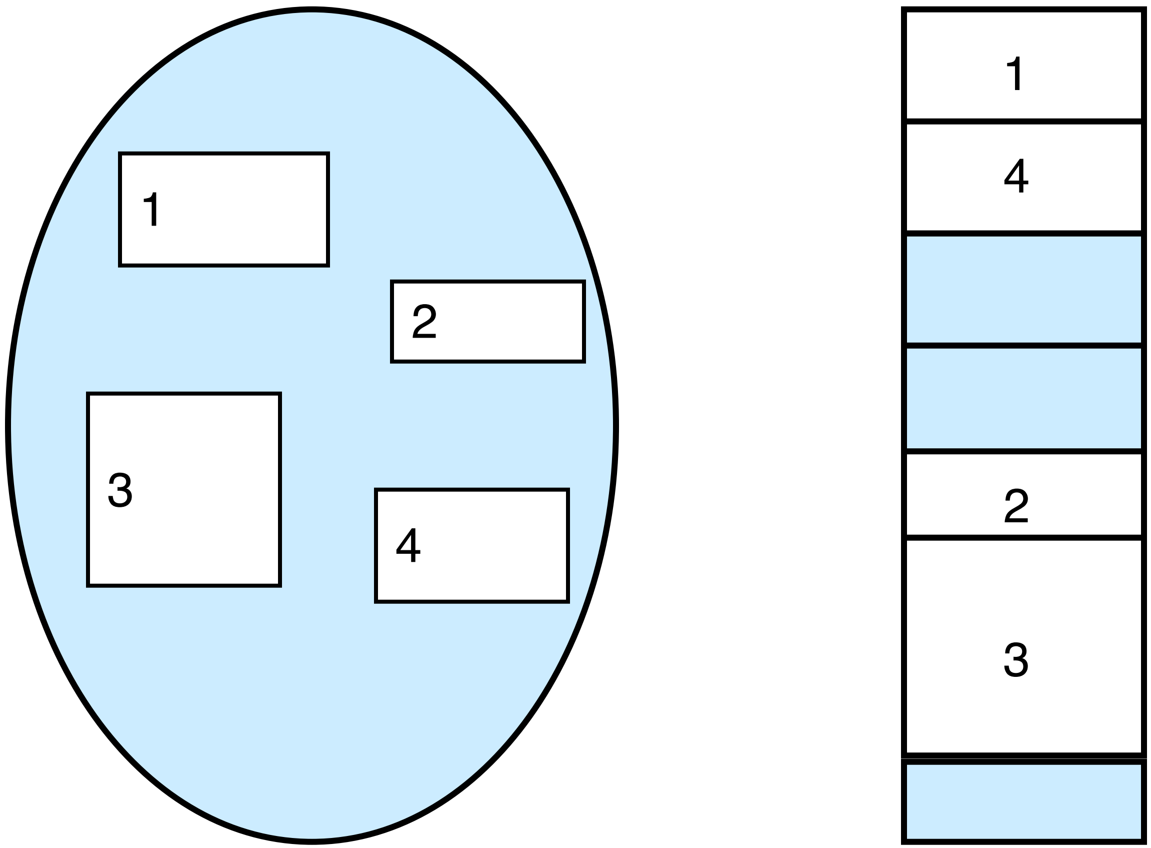
Segmentation (cont.)

- A segment is a contiguous portion of the address space

- A program is a collection of segments

- A segment can be a logical unit:
  - E.g., *main program, procedure, function, object, local variables, global variables, common block, stack, heap, symbol table, or arrays, etc.*

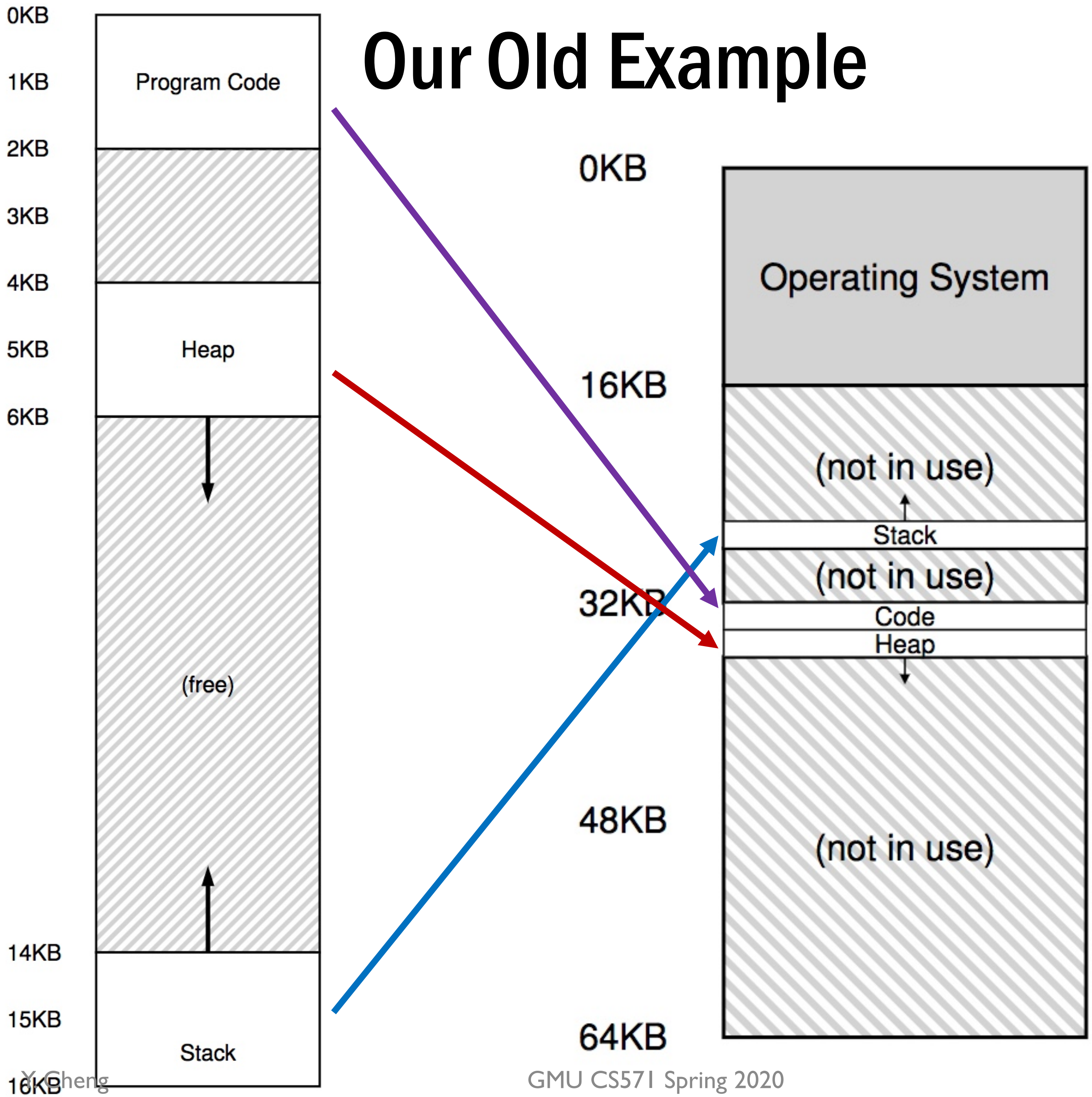
Logical View of Segmentation



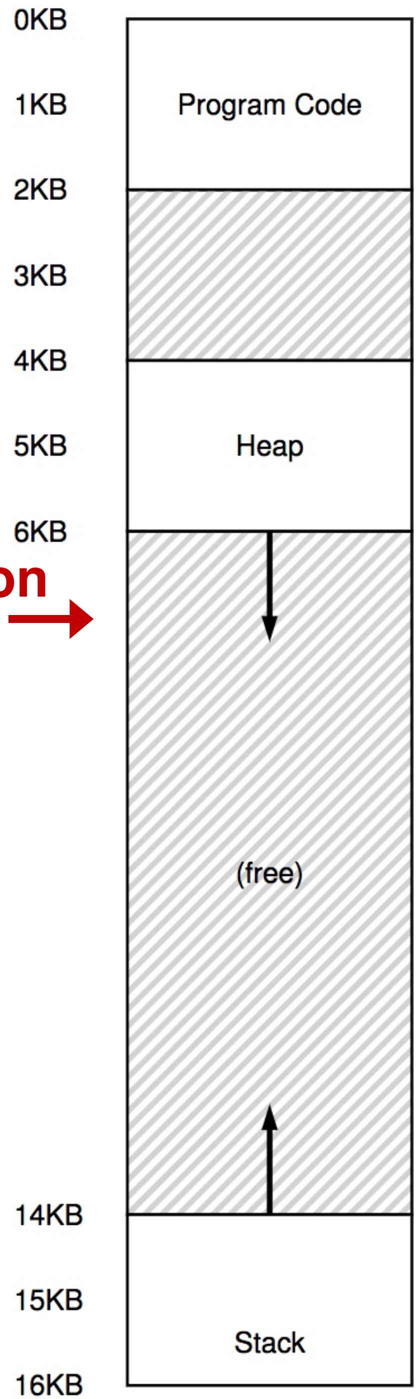
Virtual address space of a process

physical memory

Our Old Example



Segfault!



Segmentation fault →

Access to the address 7KB …

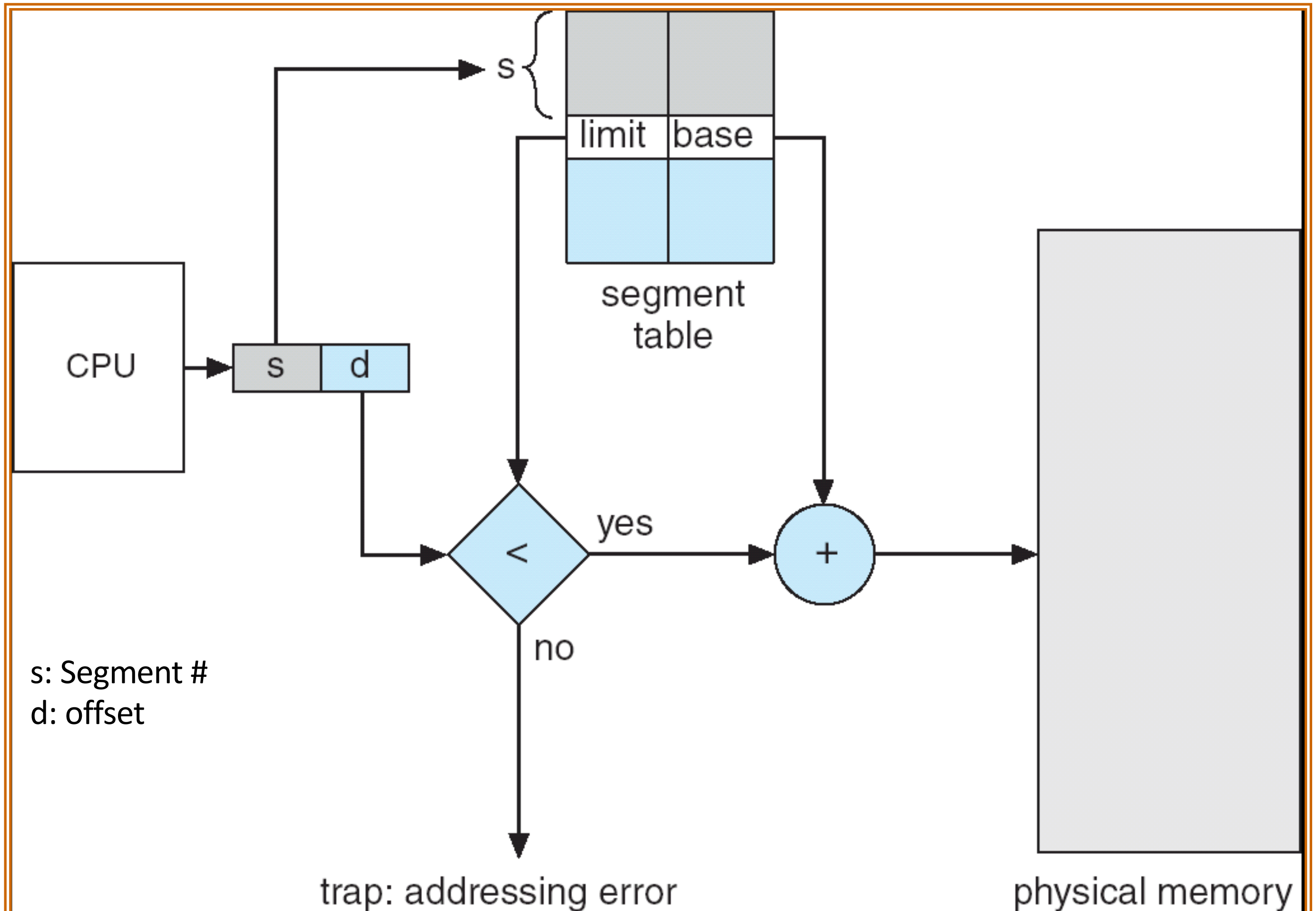
Segmentation Architecture

- Logical address consists of a pair:

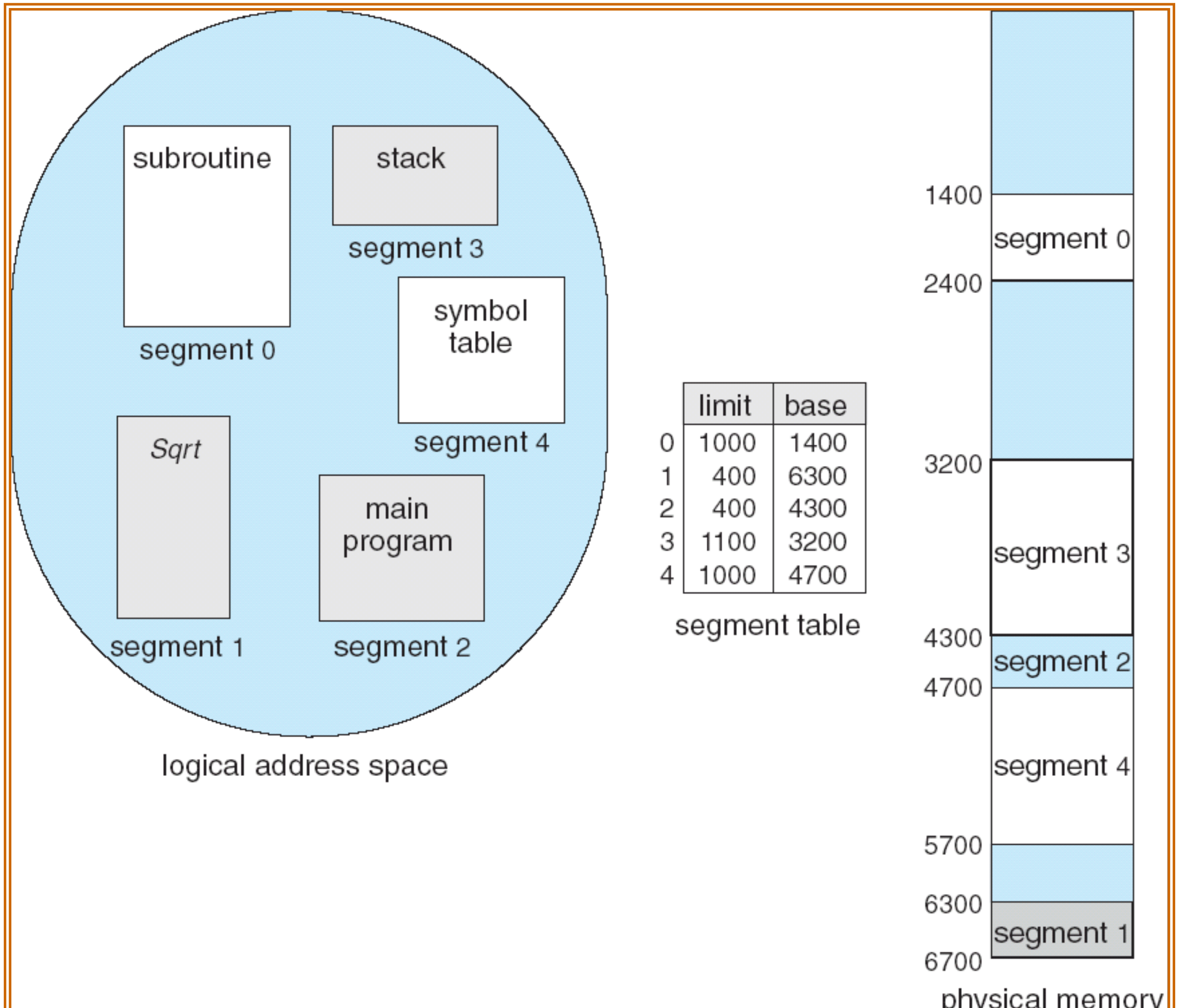
  `<segment-number, offset>`

- *Segment table* – maps two-dimensional physical addresses. Each table entry has:
  - *base* – contains the starting physical address where the segments reside in memory
  - *limit* – specifies the length of the segment (or bound)
- *Segment-table base register (STBR)* points to the segment table's location in memory
- *Segment-table length register (STLR)* indicates number of segments used by a process
  - segment number *s* is legal if $s <$ STLR

Segmentation Hardware



Example of Segmentation



	limit	base
0	1000	1400
1	400	6300
2	400	4300
3	1100	3200
4	1000	4700

Worksheet