# Scheduling Policy: Review

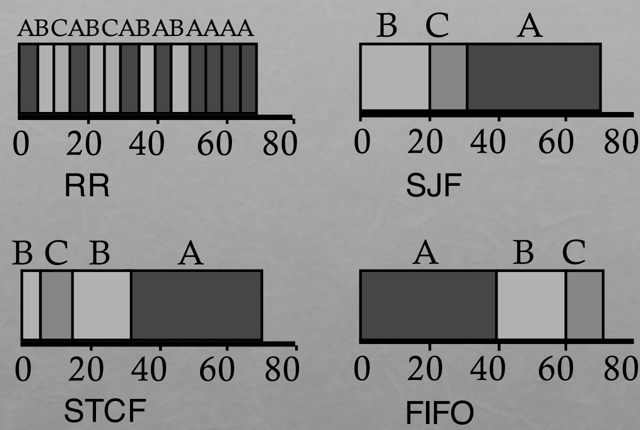
Workload

| JOB | arrival | run |
|---|---|---|
| A | 0 | 40 |
| B | 0 | 20 |
| C | 5 | 10 |

**Schedulers**:

FIFO
SJF
STCF
RR

Timelines




UNIVERSITY of WISCONSIN-MADISON
Computer Sciences Department

CS 537
Introduction to Operating Systems

Andrea C. Arpaci-Dusseau
Remzi H. Arpaci-Dusseau

# Memory Virtualization:

**Questions answered in this lecture:**

What is in the address space of a process (review)?

What are the different ways that that OS can virtualize memory?

Time sharing, static relocation, dynamic relocation

(base, base + bounds, segmentation)

What hardware support is needed for dynamic relocation?

# Announcements

- Switching discussion sections unofficially
- Project 1
  - Handin directories now available
  - Some test scripts available
  - Due next Friday, 5pm
- Lots of Office Hours

# More Virtualization

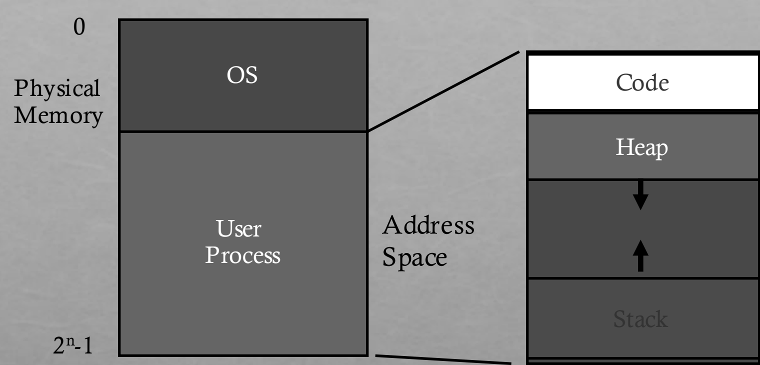
1st part of course: Virtualization

Virtual CPU: *illusion* of **private CPU registers**
- 2 lectures (mechanism + policy)

Virtual RAM: *illusion* of **private memory**
- 5 lectures

# Motivation for Virtualizing Memory

Uniprogramming: One process runs at a time




Disadvantages:

- Only one process runs at a time
- Process can destroy OS

# Multiprogramming Goals for Memory

Transparency

- Processes are not aware that memory is shared
- Works regardless of number and/or location of processes

Protection

- Cannot corrupt OS or other processes
- Privacy: Cannot read data of other processes

Efficiency

- Do not waste memory resources (minimize fragmentation)

Sharing

- Cooperating processes can share portions of address space

# Abstraction: Address Space

Address space: Each process has set of addresses

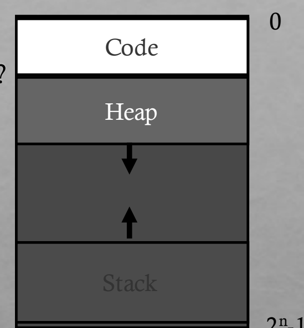
Problem:

How can OS provide illusion of private address space to each process?

Review: What is in an address space?

Address space has static and dynamic components

- Static: Code and some global variables
- Dynamic: Stack and Heap




# Motivation for Dynamic Memory

Why do processes need dynamic allocation of memory?

- Do not know amount of memory needed at compile time
- Must be pessimistic when allocate memory statically
    - Allocate enough for worst possible case; Storage is used inefficiently

Recursive procedures

- Do not know how many times procedure will be nested

Complex data structures: lists and trees

- `struct my_t *p = (struct my_t *)malloc(sizeof(struct my_t));`

Two types of dynamic allocation

- Stack
- Heap

# Stack Organization

Definition: Memory must be freed in opposite order from allocation

```
alloc(A);
alloc(B);
alloc(C);
free(C);
alloc(D);
free(D);
free(B);
free(A);
```

Simple and efficient implementation:
Pointer separates allocated and freed space

- Allocate: Increment pointer
- Free: Decrement pointer

No fragmentation

# Where are stacks used?

OS uses stack for procedure call frames (local variables and parameters)

```
main () {
      int A = 0;
      foo (A);
      printf("A: %d\n", A);
}

void foo (int Z) {
      int A = 2;
      Z = 5;
      printf("A: %d Z: %d\n", A, Z);
}
```

# Heap Organization

Definition: Allocate from any random location: malloc(), new()

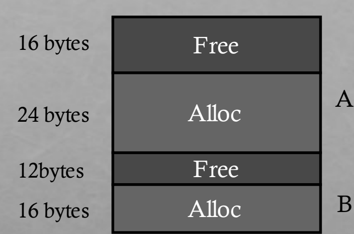
- Heap memory consists of allocated areas and free areas (holes)
- Order of allocation and free is unpredictable

Advantage

- Works for all data structures

Disadvantages

- Allocation can be slow
- End up with small chunks of free space - fragmentation
- Where to allocate 12 bytes? 16 bytes? 24 bytes??




- What is OS's role in managing heap?
  - OS gives big chunk of free memory to process; library manages individual allocations

# Quiz: Match that Address Location

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

Possible segments: static data, code, stack, heap

What if no static data segment?

| Address | Location |
|---|---|
| x | Static data → Code |
| main | Code |
| y | Stack |
| z | Stack |
| *z | Heap |

# Memory Accesses

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

int main(int argc, char *argv[]) {
  int x;
  x = x + 3;
}
```

```
0x10:  movl 0x8(%rbp), %edi
0x13:  addl $0x3, %edi
0x19:  movl %edi, 0x8(%rbp)
```

`otool –tv demo1.o`
(or objdump on Linux)

%**rbp** is the base pointer:
points to base of current stack frame

# Quiz: Memory Accesses?

Initial %rip = 0x10
%rbp = 0x200

```
0x10:  movl  0x8(%rbp),  %edi
0x13:  addl  $0x3,  %edi
0x19:  movl  %edi,  0x8(%rbp)
```

%**rbp** is the base pointer:
points to base of current stack frame

**%rip** is instruction pointer (or program counter, PC)

**Memory Accesses to what addresses?**

1) Fetch instruction at addr 0x10
Exec:

2) load from addr 0x208

3) Fetch instruction at addr 0x13
Exec:

no memory access

4) Fetch instruction at addr 0x19
Exec:

5) store to addr 0x208

# How to Virtualize Memory?

Problem: How to run multiple processes simultaneously?

Addresses are "hardcoded" into process binaries

How to avoid collisions across different processes?

Possible Solutions for Mechanisms (covered today):

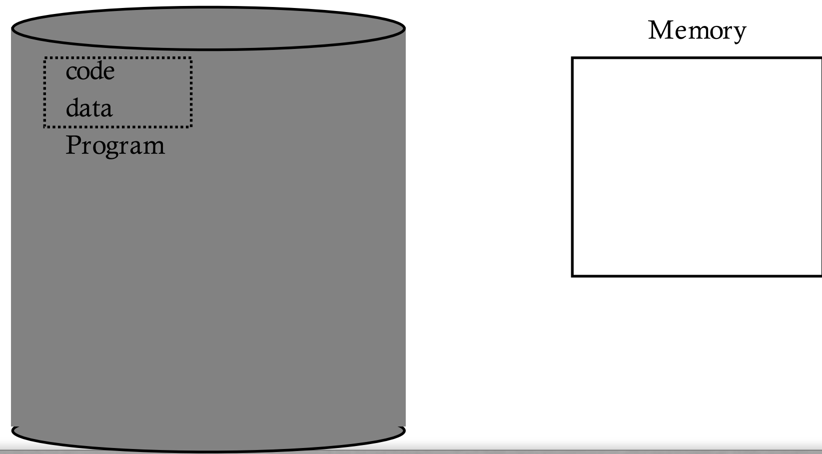
1. Time Sharing
2. Static Relocation
3. Base
4. Base+Bounds
5. Segmentation

# 1) Time Sharing of Memory

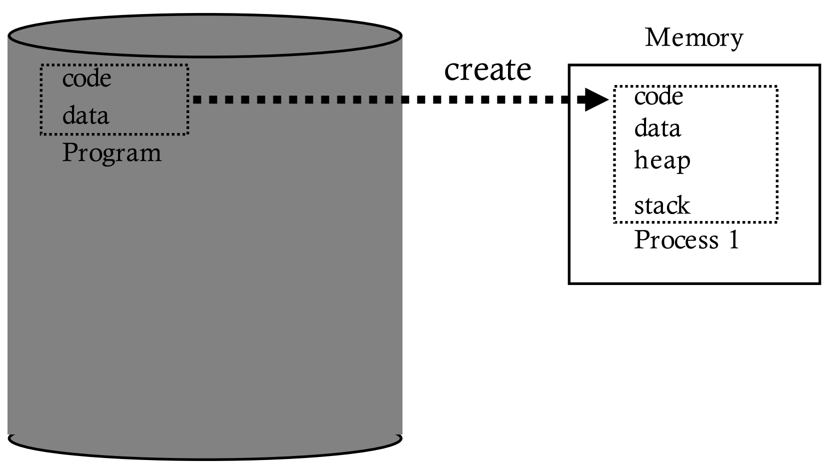
Try similar approach to how OS virtualizes CPU

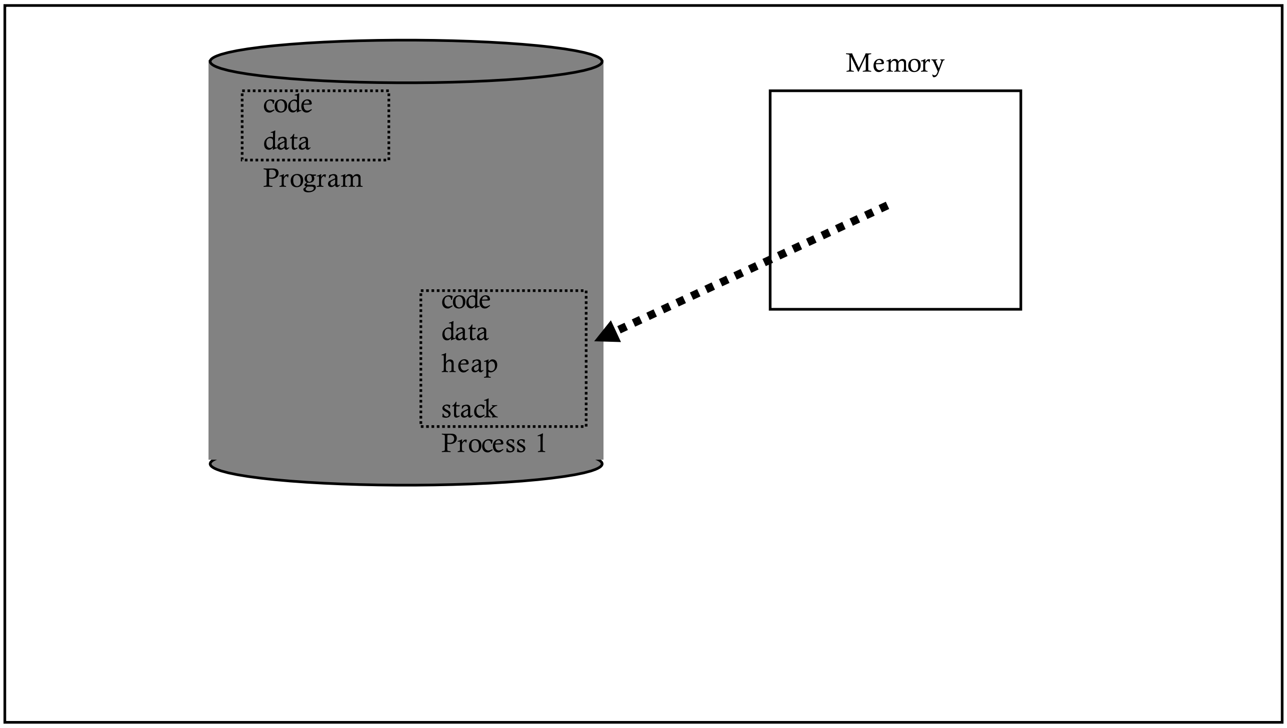
Observation:
OS gives illusion of many virtual CPUs by saving **CPU registers** to **memory** when a process isn't running

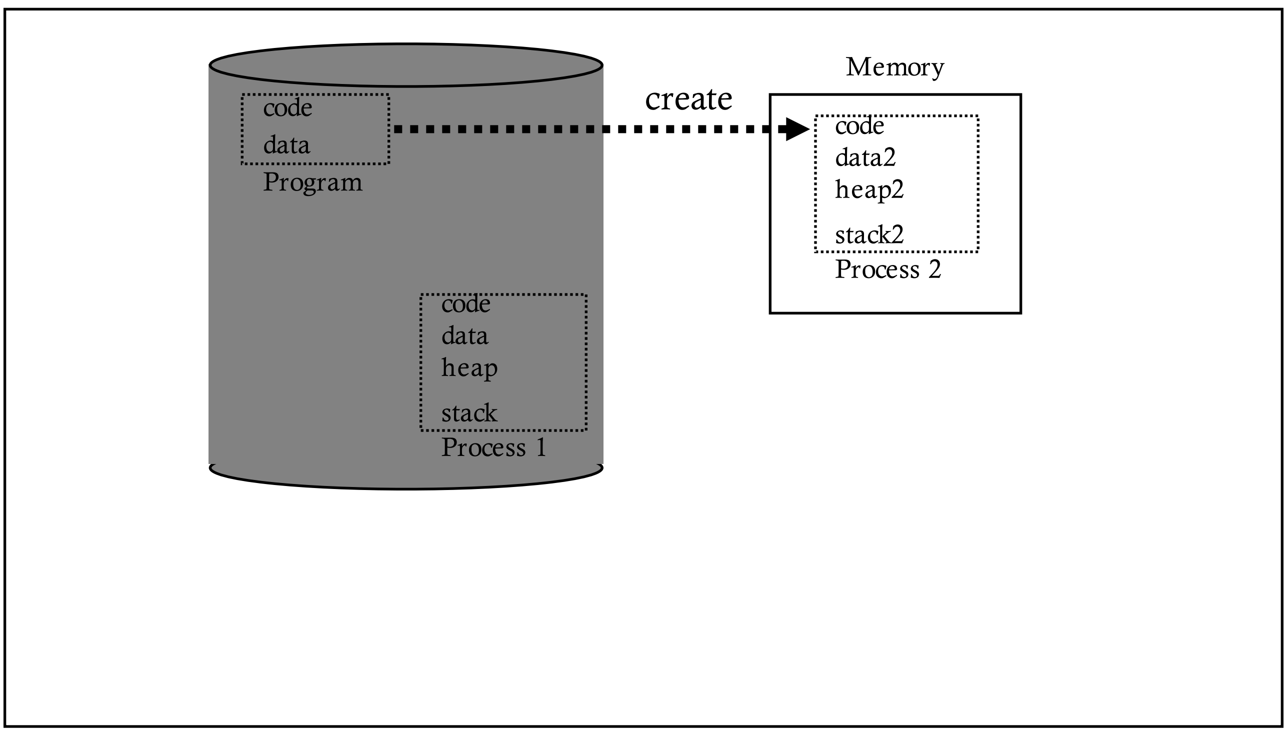
Could give illusion of many virtual memories by saving **memory** to **disk** when process isn't running

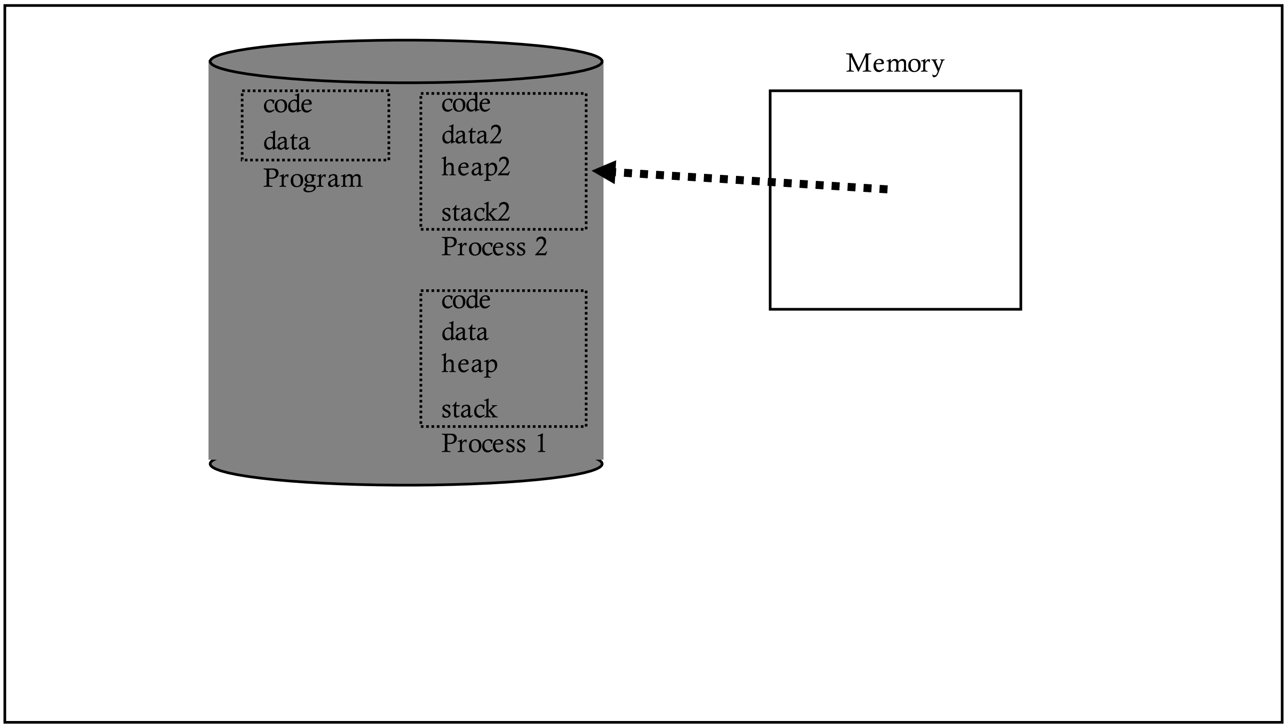


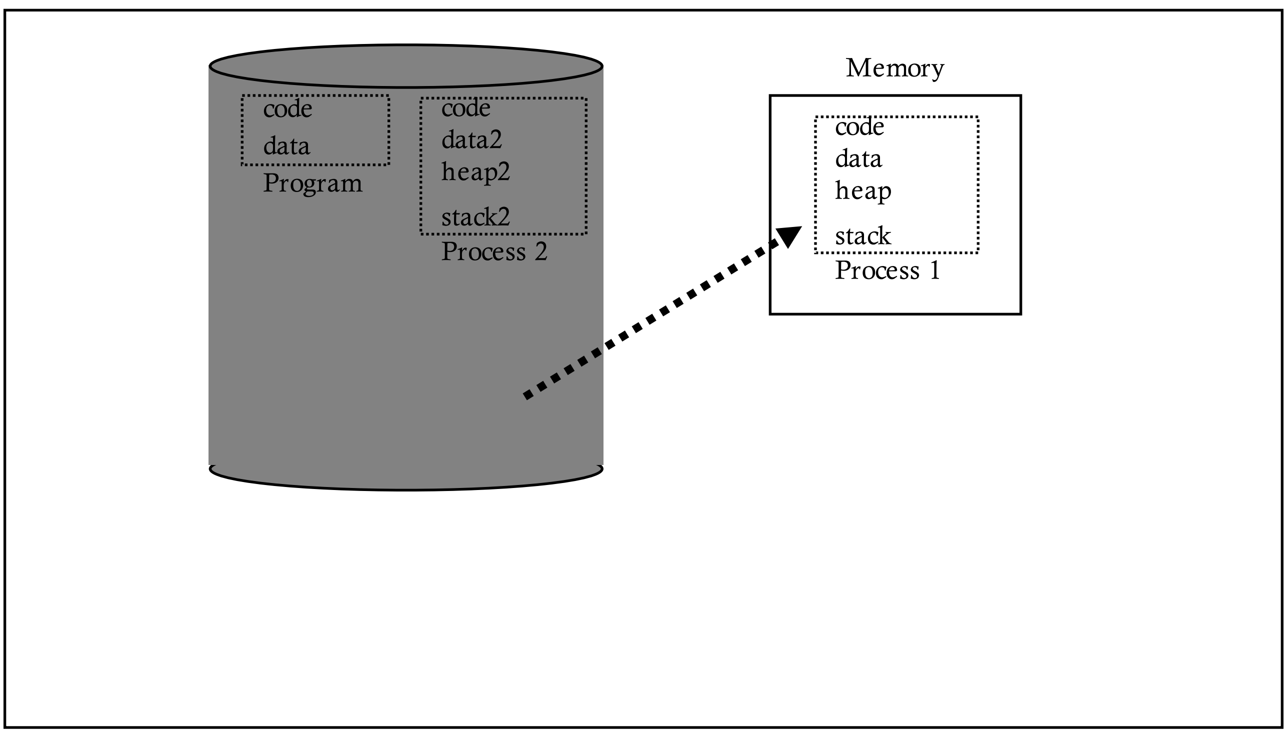

# Time Share Memory: Example




Memory
code
data
Program
code
data
heap
stack
Process 1


Memory
create
code
data
Program
code
data2
heap2
stack2
Process 2
code
data
heap
stack
Process 1


Memory
code
data
Program
code
data2
heap2
stack2
Process 2
code
data
heap
stack
Process 1


Memory
code
data
Program
code
data2
heap2
stack2
Process 2
code
data
heap
stack
Process 1

# Problems with Time Sharing Memory

Problem: Ridiculously poor performance

Better Alternative: **space sharing**

- At same time, space of memory is divided across processes

Remainder of solutions all use space sharing

# Repeat: How to Virtualize Memory?

Problem: How to run multiple processes simultaneously?

Addresses are "hardcoded" into process binaries

How to avoid collisions across different processes?

Possible Solutions for Mechanisms (covered today):

1. ~~Time Sharing~~
2. Static Relocation
3. Base
4. Base+Bounds
5. Segmentation

# 2) Static Relocation

Idea: OS rewrites each program before loading it as a process in memory

Each rewrite for different process uses different addresses and pointers

Change jumps, loads of static data

- 0x10: movl0x8(%rbp), %edi
- 0x13: addl$0x3, %edi
- 0x19: movl%edi, 0x8(%rbp)

rewrite

```
0x1010: movl  0x8(%rbp), %edi
0x1013: addl  $0x3, %edi
0x1019: movl  %edi, 0x8(%rbp)
```

rewrite

```
0x3010: movl  0x8(%rbp), %edi
0x3013: addl  $0x3, %edi
0x3019: movl  %edi, 0x8(%rbp)
```

# How to Virtualize Memory?

Problem: How to run multiple processes simultaneously?

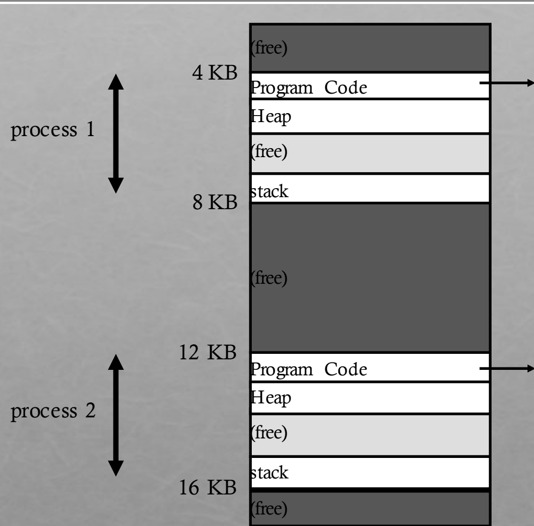
Addresses are "hardcoded" into process binaries

How to avoid collisions across different processes?

Possible Solutions for Mechanisms (covered today):

1. ~~Time Sharing~~
2. Static Relocation
3. Base
4. Base+Bounds
5. Segmentation

# Static: Layout in Memory




```
0x1010: movl  0x8(%rbp), %edi
0x1013: addl  $0x3, %edi
0x1019: movl  %edi, 0x8(%rbp)
```

```
0x3010: movl  0x8(%rbp), %edi
0x3013: addl  $0x3, %edi
0x3019: movl  %edi, 0x8(%rbp)
```

Why didn't OS rewrite stack addr?

# Static Relocation: Disadvantages

No protection

- Process can destroy OS or other processes
- No privacy

Cannot move address space after it has been placed

- May not be able to allocate new process

# Repeat: How to Virtualize Memory?

Problem: How to run multiple processes simultaneously?

Addresses are "hardcoded" into process binaries

How to avoid collisions across different processes?

Possible Solutions for Mechanisms (covered today):

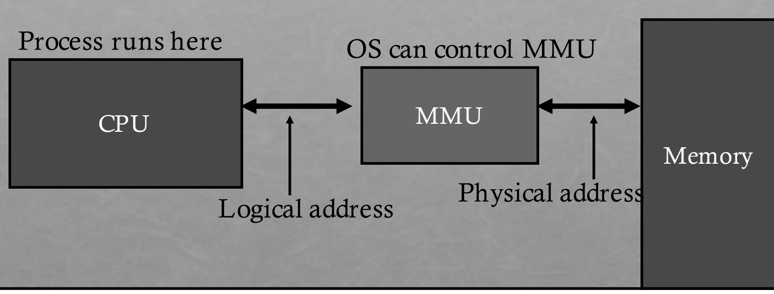
1. ~~Time Sharing~~
2. ~~Static Relocation~~
3. Dynamic Relocation: Base
4. Base+Bounds
5. Segmentation

# 3) Dynamic Relocation

Goal: Protect processes from one another

Requires hardware support
- Memory Management Unit (MMU)

MMU dynamically changes process address at every memory reference
- Process generates logical or virtual addresses (in their address space)
- Memory hardware uses physical or real addresses



# Hardware Support for Dynamic Relocation

Two operating modes

- Privileged (protected, kernel) mode: OS runs
  - When enter OS (trap, system calls, interrupts, exceptions)
  - Allows certain instructions to be executed
    - **Can manipulate contents of MMU**
  - **Allows OS to access all of physical memory**
- User mode: User processes run
  - **Perform translation of logical address to physical address**

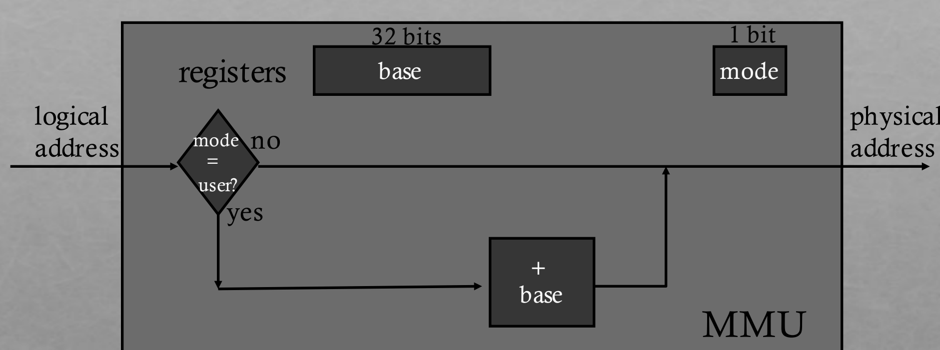
Minimal MMU contains **base register** for translation

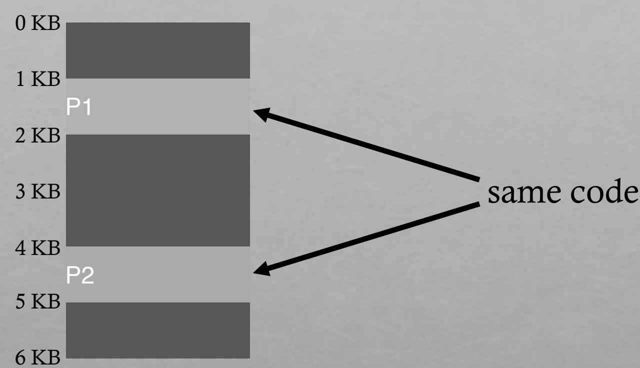
- base: start location for address space

# Implementation of Dynamic Relocation: Base Reg

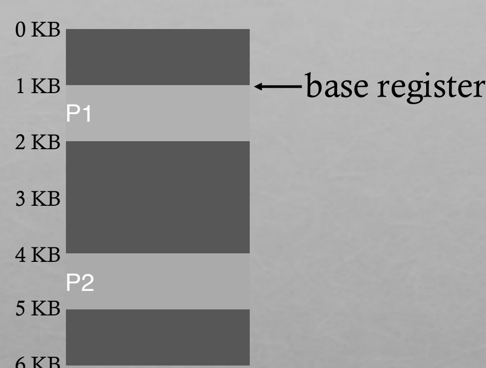
Translation on every memory access of user process

- MMU adds base register to logical address to form physical address
- Each process has different value in base register

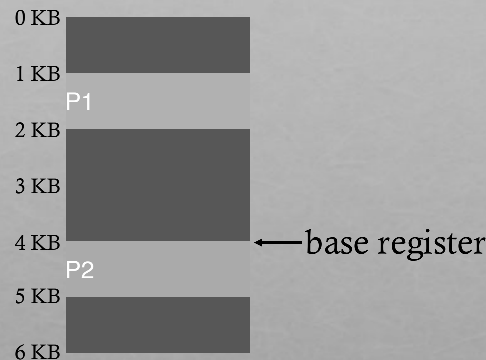





# Visual Example of Dynamic Relocation: Base Register

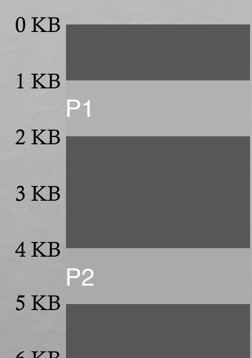



P1 is running

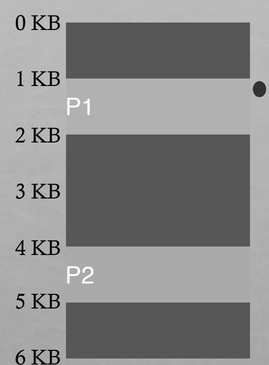



P2 is running

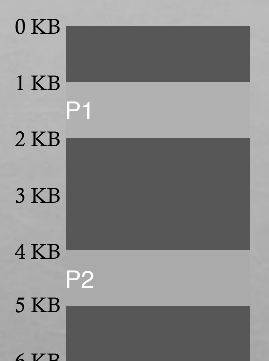
(Decimal notation)



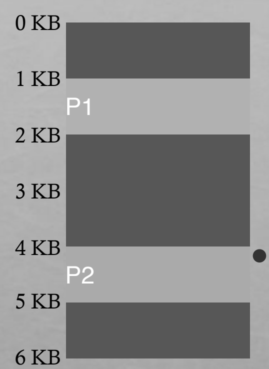

| Virtual | Physical |
|---|---|
| P1: load 100, R1 | |



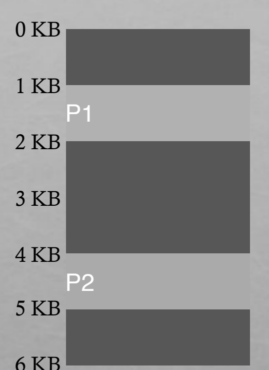

| Virtual | Physical | |
|---|---|---|
| P1: load 100, R1 | load 1124, R1 | (1024 + 100) |



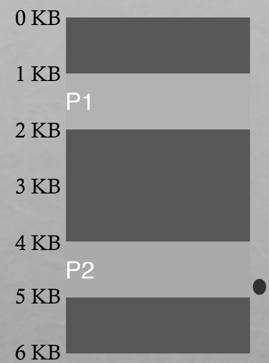

| Virtual | Physical |
|---|---|
| P1: load 100, R1 | load 1124, R1 |
| P2: load 100, R1 | |



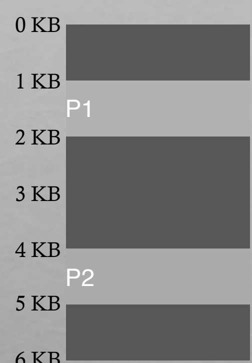

| Virtual | Physical | |
|---|---|---|
| P1: load 100, R1 | load 1124, R1 | |
| P2: load 100, R1 | load 4196, R1 | (4096 + 100) |



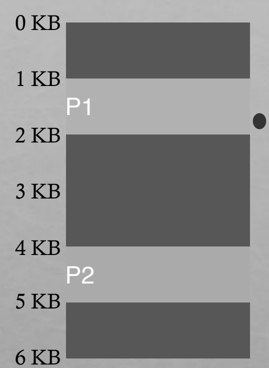

| Virtual | Physical |
|---|---|
| P1: load 100, R1 | load 1124, R1 |
| P2: load 100, R1 | load 4196, R1 |
| P2: load 1000, R1 | |




| Virtual | Physical |
|---|---|
| P1: load 100, R1 | load 1124, R1 |
| P2: load 100, R1 | load 4196, R1 |
| P2: load 1000, R1 | load 5196, R1 |




| Virtual | Physical |
|---|---|
| P1: load 100, R1 | load 1124, R1 |
| P2: load 100, R1 | load 4196, R1 |
| P2: load 1000, R1 | load 5196, R1 |
| P1: load 1000, R1 | |

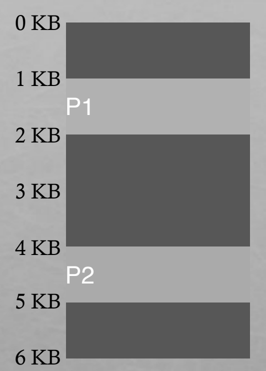



| Virtual | Physical |
|---|---|
| P1: load 100, R1 | load 1124, R1 |
| P2: load 100, R1 | load 4196, R1 |
| P2: load 1000, R1 | load 5196, R1 |
| P1: load 1000, R1 | load 2024, R1 |

# Quiz: Who Controls the Base Register?

What entity performs translation of addresses using base register?
(1) process, (2) OS, or (3) HW

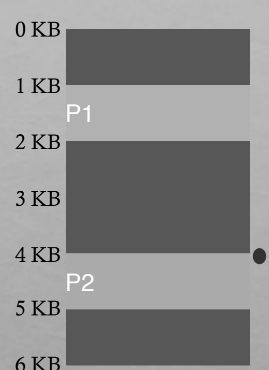
What entity controls the contents and modifies the base register?
(1) process, (2) OS, or (3) HW




| Virtual | Physical |
|---|---|
| P1: load 100, R1 | load 1124, R1 |
| P2: load 100, R1 | load 4196, R1 |
| P2: load 1000, R1 | load 5196, R1 |
| P1: load 1000, R1 | load 2024, R1 |

Can P2 hurt P1?
Can P1 hurt P2?

How well does dynamic relocation do with base register for protection?




| Virtual | Physical | |
|---|---|---|
| P1: load 100, R1 | load 1124, R1 | |
| P2: load 100, R1 | load 4196, R1 | |
| P2: load 1000, R1 | load 5196, R1 | |
| P1: load 100, R1 | load 2024, R1 | |
| P1: store 3072, R1 | store 4096, R1 | (3072 + 1024) |

Can P2 hurt P1?
Can P1 hurt P2?

How well does dynamic relocation do with base register for protection?

# Break!

Ask your neighbors…

How is Project 1 coming along? What do they think about the discussion videos? Have they run any of the tests for P1a yet? What seems to be the hardest aspect?

# 4) Dynamic with Base+Bounds

Idea: limit the address space with a bounds register

Base register: smallest physical addr (or starting location)

Bounds register: size of this process's virtual address space

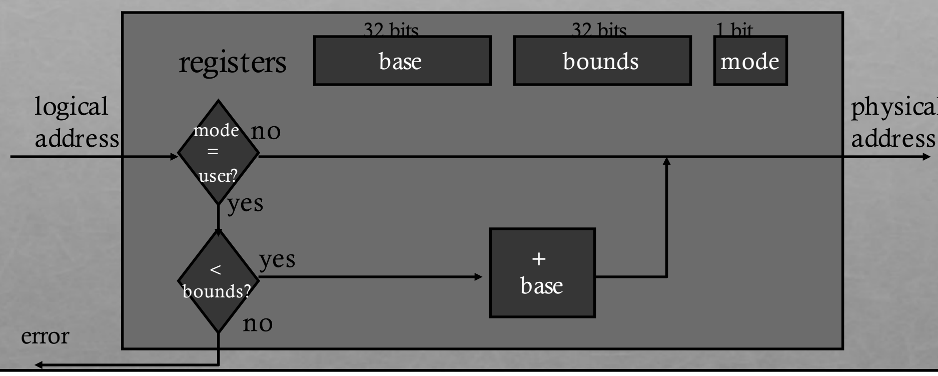
- Sometimes defined as largest physical address (base + size)

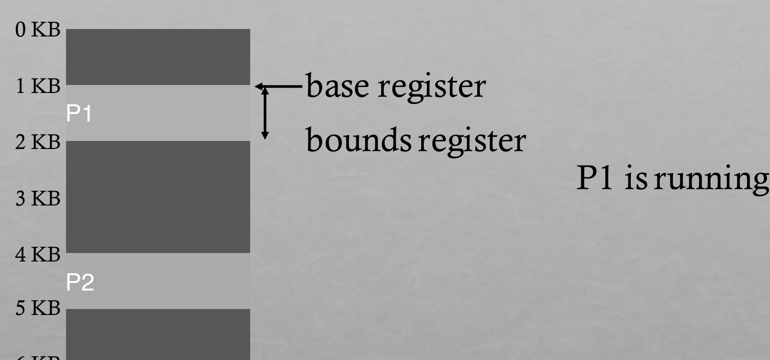
OS kills process if process loads/stores beyond bounds

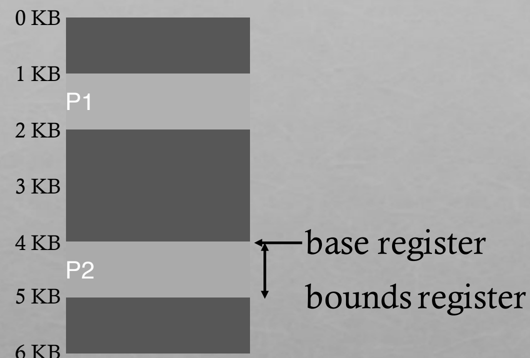
# Implementation of Base+Bounds

Translation on every memory access of user process

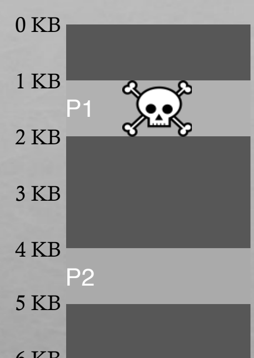
- MMU compares logical address to bounds register
  - if logical address is greater, then generate error
- MMU adds base register to logical address to form physical address






P2 is running




| Virtual | Physical | |
|---|---|---|
| P1: load 100, R1 | load 1124, R1 | |
| P2: load 100, R1 | load 4196, R1 | |
| P2: load 1000, R1 | load 5196, R1 | |
| P1: load 100, R1 | load 2024, R1 | |
| P1: store 3072, R1 | interrupt OS! | 3072 > 1024 |

Can P1 hurt P2?

# Managing Processes with Base and Bounds

Context-switch

- Add base and bounds registers to PCB
- Steps
  - Change to privileged mode
  - Save base and bounds registers of old process
  - Load base and bounds registers of new process
  - Change to user mode and jump to new process

What if don't change base and bounds registers when switch? Threads!

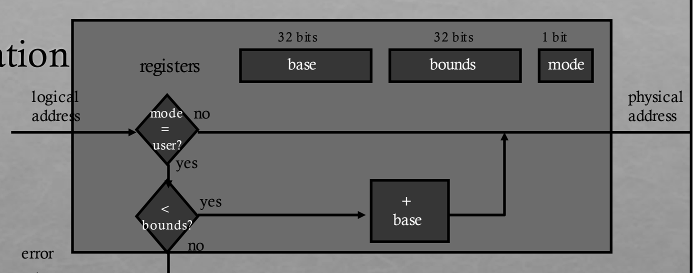
Protection requirement

- User process cannot change base and bounds registers
- User process cannot change to privileged mode

# Base and Bounds Advantages

Advantages

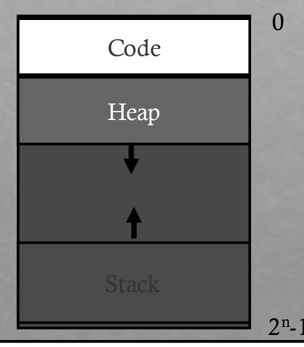
- Provides protection (both read and write) across address spaces
- Supports dynamic relocation
  - Can place process at different locations initially and also move address spaces
- Simple, inexpensive implementation
  - Few registers, little logic in MMU
- Fast
  - Add and compare in parallel



# Base and Bounds Disadvantages

Disadvantages

- Each process must be allocated contiguously in physical memory
  - Must allocate memory that may not be used by process
- No partial sharing: Cannot share limited parts of address space



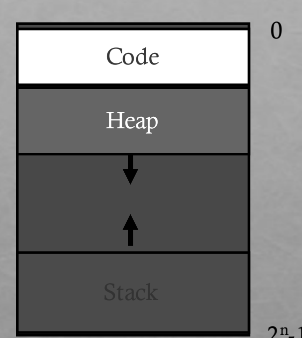

# 5) Segmentation

Divide address space into logical segments

- Each segment corresponds to logical entity in address space
  - code, stack, heap

Each segment can independently:

- be placed separately in physical memory
- grow and shrink
- be protected (separate read/write/execute bits)



# Segmented Addressing

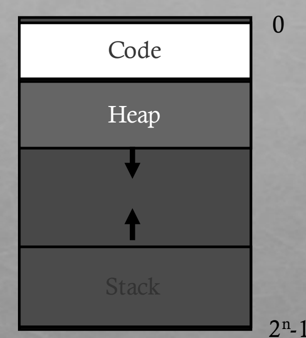
Process now specifies segment and offset within segment

How does process designate a particular segment?

- Use part of logical address
  - Top bits of logical address select segment
  - Low bits of logical address select offset within segment

What if small address space, not enough bits?

- Implicitly by type of memory reference
- Special registers




# Segmentation Implementation

MMU contains Segment Table (for currently running process)

- Each segment has own base and bounds, protection bits
- Example: 14 bit logical address, 4 segments; how many bits for segment? How many bits for offset?

| Segment | Base | Bounds | R W |
|---|---|---|---|
| 0 | 0x2000 | 0x6ff | 1 0 |
| 1 | 0x0000 | 0x4ff | 1 1 |
| 2 | 0x3000 | 0xfff | 1 1 |
| 3 | 0x0000 | 0x000 | 0 0 |

remember:
1 hex digit->4 bits

# Quiz: Address Translations with Segmentation

MMU contains Segment Table (for currently running process)

- Each segment has own base and bounds, protection bits
- Example: 14 bit logical address, 4 segments; how many bits for segment? How many bits for offset?

| Segment | Base | Bounds | R W |
|---|---|---|---|
| 0 | 0x2000 | 0x6ff | 1 0 |
| 1 | 0x0000 | 0x4ff | 1 1 |
| 2 | 0x3000 | 0xfff | 1 1 |
| 3 | 0x0000 | 0x000 | 0 0 |

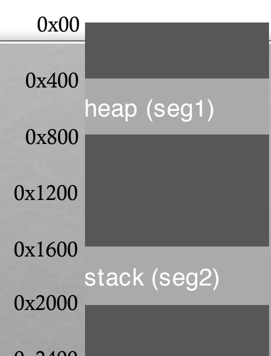
remember:
1 hex digit->4 bits

Translate logical addresses (in hex) to physical addresses

`0x0240:` 0x2240
`0x1108:` 0x0108
`0x265c:` 0x365c
`0x3002:` ERROR!

# Visual Interpretation

Physical memory




| Virtual (hex) | Physical |
|---|---|
| load 0x2010, R1 | |

Segment numbers:
0: code+data
1: heap
2: stack

Physical memory


| Virtual (hex) | Physical |
|---|---|
| load 0x2010, R1 | 0x1600 + 0x010 = 0x1610 |

Segment numbers:
- 0: code+data
- 1: heap
- 2: stack

Physical memory


| Virtual (hex) | Physical |
|---|---|
| load 0x2010, R1 | 0x1600 + 0x010 = 0x1610 |
| load 0x1010, R1 | |

Segment numbers:
- 0: code+data
- 1: heap
- 2: stack

Physical memory


| Virtual (hex) | Physical |
| --- | --- |
| load 0x2010, R1 | 0x1600 + 0x010 = 0x1610 |
| load 0x1010, R1 | 0x400 + 0x010 = 0x410 |

Segment numbers:
0: code+data
1: heap
2: stack

Physical memory


| Virtual | Physical |
| --- | --- |
| load 0x2010, R1 | 0x1600 + 0x010 = 0x1610 |
| load 0x1010, R1 | 0x400 + 0x010 = 0x410 |
| load 0x1100, R1 | |

Segment numbers:
0: code+data
1: heap
2: stack

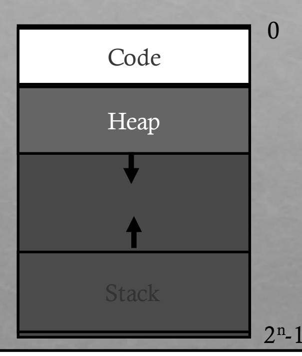
Physical memory


| Virtual | Physical |
|---|---|
| load 0x2010, R1 | 0x1600 + 0x010 = 0x1610 |
| load 0x1010, R1 | 0x400 + 0x010 = 0x410 |
| load 0x1100, R1 | 0x400 + 0x100 = 0x500 |

Segment numbers:
- 0: code+data
- 1: heap
- 2: stack

# Advantages of Segmentation

- Enables sparse allocation of address space
  - Stack and heap can grow independently
  - Heap: If no data on free list, dynamic memory allocator requests more from OS (e.g., UNIX: malloc calls sbrk())
  - Stack: OS recognizes reference outside legal segment, extends stack implicitly
- Different protection for different segments
  - Read-only status for code
- Enables sharing of selected segments
- Supports dynamic relocation of each segment



# Disadvantages of Segmentation

Each segment must be allocated contiguously

- May not have sufficient physical memory for large segments

Fix in next lecture with paging…

# Conclusion

HW+OS work together to virtualize memory

- Give illusion of private address space to each process

Add MMU registers for base+bounds so translation is fast

- OS not involved with every address translation, only on context switch or errors

Dynamic relocation with segments is good building block

- Next lecture: Solve fragmentation with paging