Roadmap

C:

```
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Java:

```
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg =
    c.getMPG();
```

Assembly language:

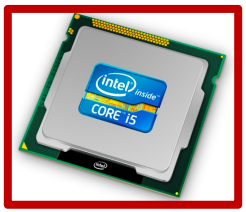
```
get_mpg(car*):
        lw      a5,0(a0)
        lw      a4,4(a0)
        divw    a5,a5,a4
        fcvt.s.w        fa0,a5
        ret
```

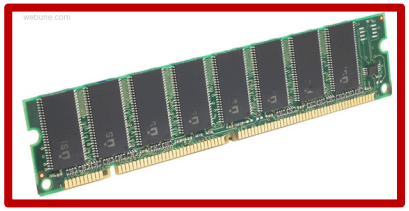
Machine code:

```
0111010000011000
10001101000010000000010
1000100111000010
11000001111110100011111
```

OS:

Computer system:





Memory & data
Arrays & structs
Integers & floats
RISC V assembly
Procedures & stacks
Executables
Memory & caches
Processor Pipeline
Performance
Parallelism

Virtual Memory (VM*)

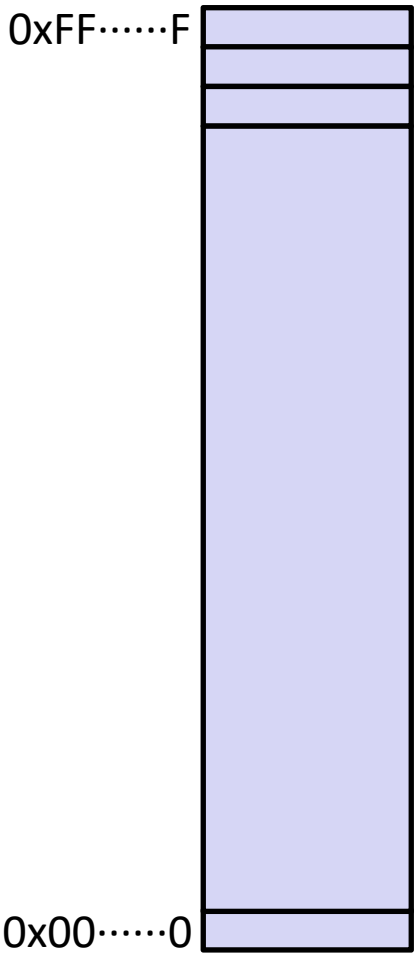
- **Overview and motivation**
- **VM as a tool for caching**
- Address translation
- VM as a tool for memory management
- VM as a tool for memory protection

Warning: Virtual memory is pretty complex, but crucial for understanding how processes work and for debugging performance

**Not to be confused with "Virtual Machine" which is a whole other thing.*

Memory as we know it so far… is *virtual!*

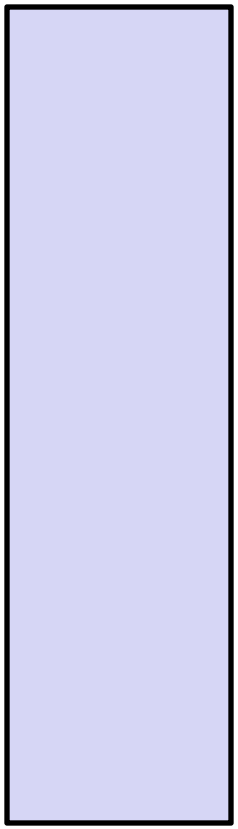
- Programs refer to virtual memory addresses
  - `movq (%rdi),%rax`
  - Conceptually memory is just a very large array of bytes
  - System provides private address space to each process
- Allocation: Compiler and run-time system
  - Where different program objects should be stored
  - All allocation within single virtual address space
- But…
  - We *probably* don't have 2^w bytes of physical memory
  - We *certainly* don't have 2^w bytes of physical memory ***for every process***
  - Processes should not interfere with one another
    - Except in certain cases where they want to share code or data



Problem 1: How Does Everything Fit?

64-bit virtual addresses can address several exabytes (18,446,744,073,709,551,616 bytes)

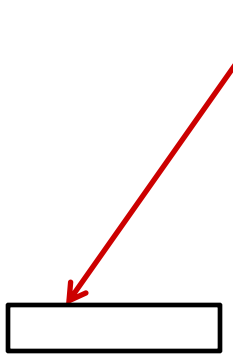
16 EiB



?

Physical main memory offers a few gigabytes (*e.g.* 8,589,934,592 bytes)

8 GiB

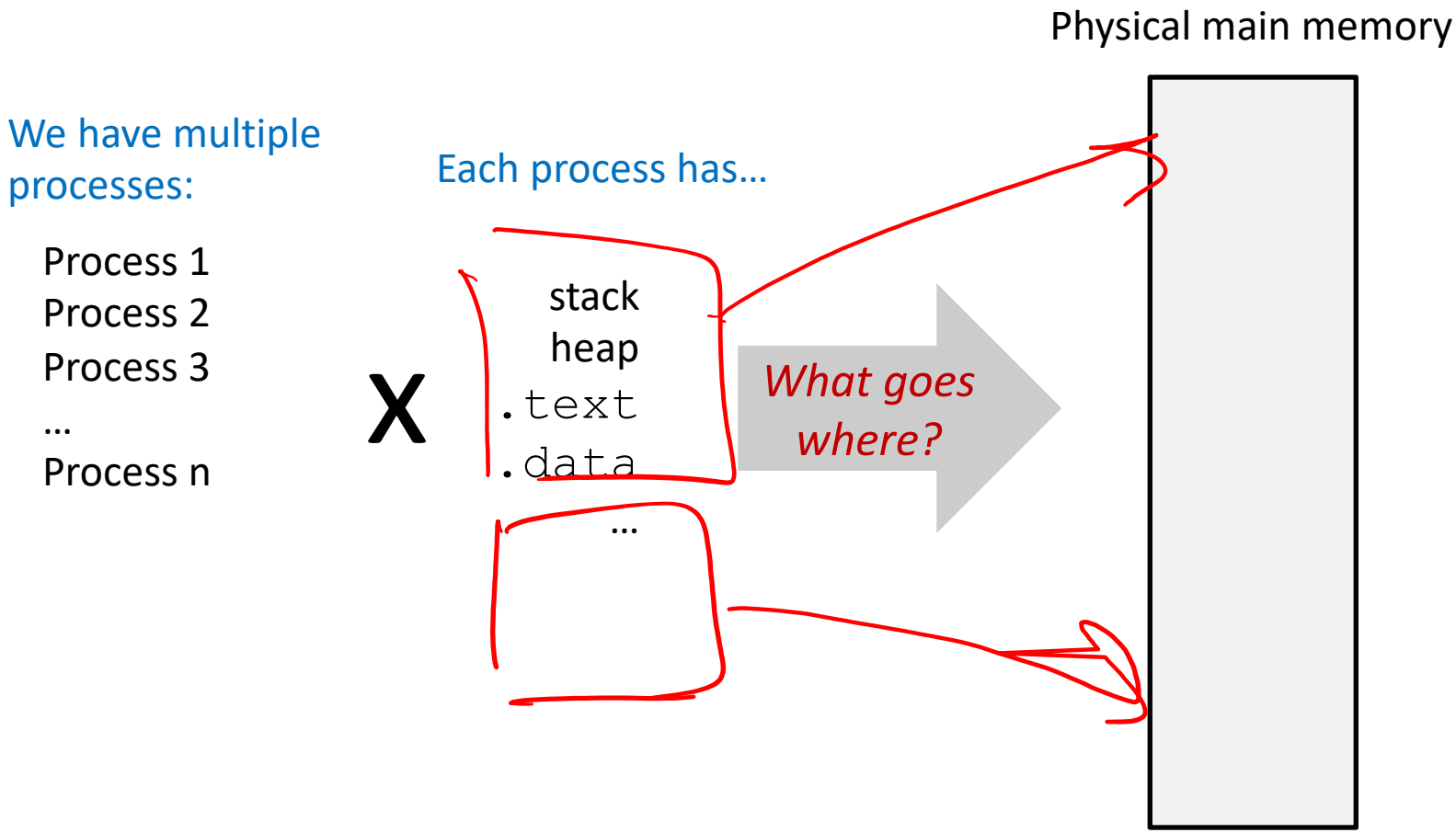


(Not to scale; physical memory would be smaller than the period at the end of this sentence compared to the virtual address space.)

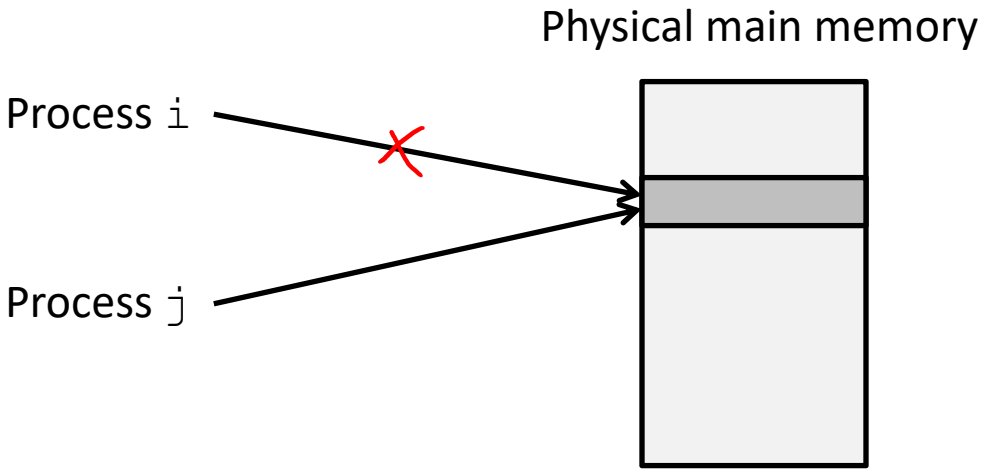
smaller than this!

1 virtual address space per process, with many processes…

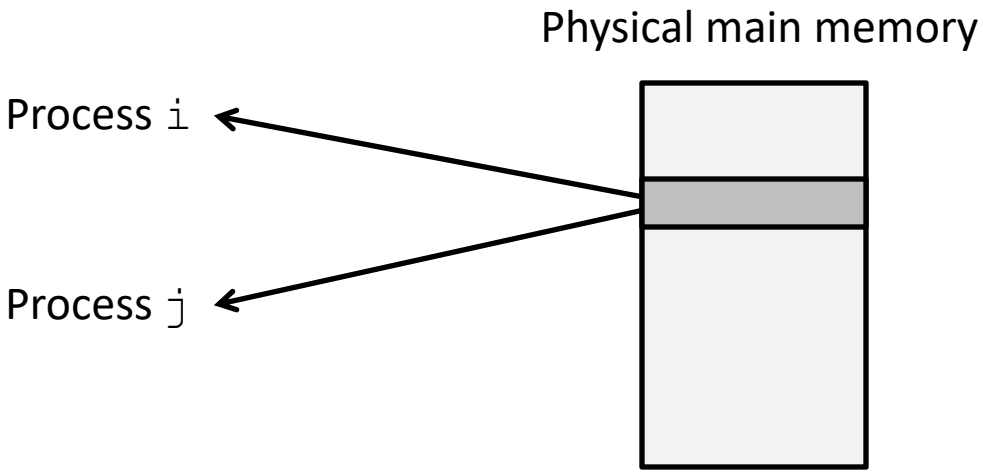
Problem 2: Memory Management



Problem 3: How To Protect



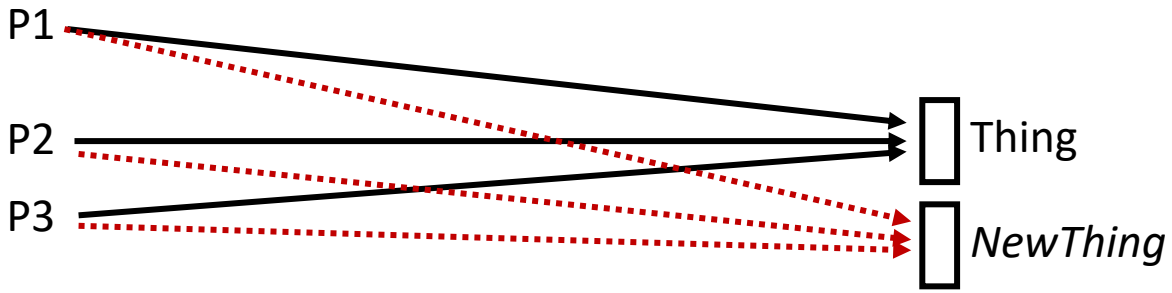
Problem 4: How To Share?



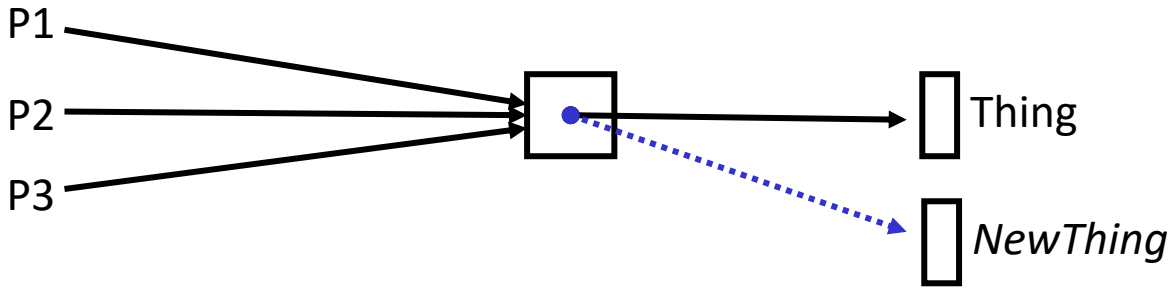
How can we solve these problems?

- "Any problem in computer science can be solved by adding another level of **indirection**." *– David Wheeler, inventor of the subroutine*

- Without Indirection



- With Indirection

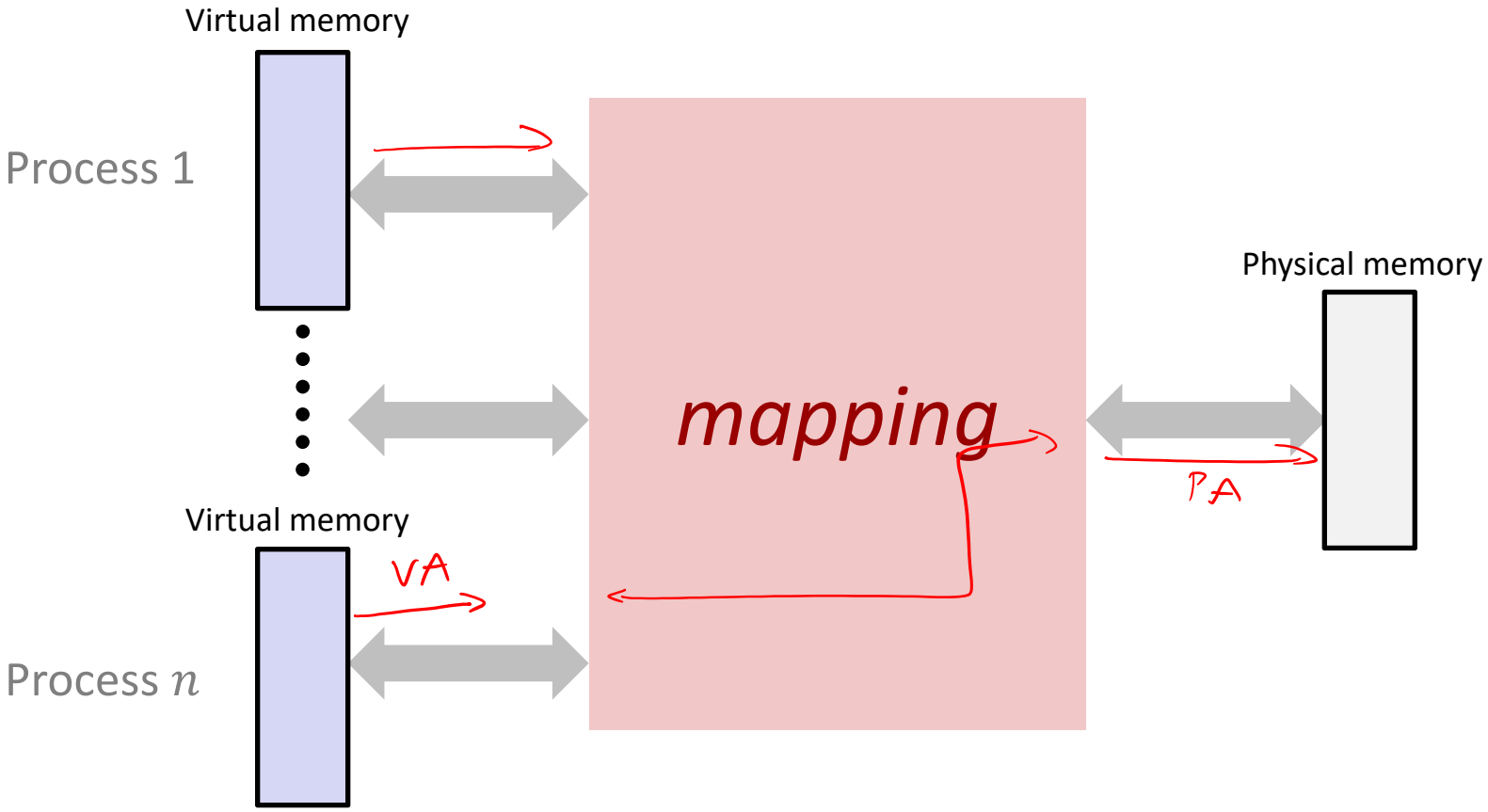


What if I want to move Thing?

Indirection

- *Indirection*: The ability to reference something using a name, reference, or container instead of the value itself. A flexible mapping between a name and a thing allows changing the thing without notifying holders of the name.
  - Adds some work (now have to look up 2 things instead of 1)
  - But don't have to track all uses of name/address (single source!)
- Examples:
  - **Phone system:** cell phone number portability
  - **Domain Name Service (DNS):** translation from name to IP address
  - **Call centers:** route calls to available operators, etc.
  - **Dynamic Host Configuration Protocol (DHCP):** local network address assignment

Indirection in Virtual Memory



- Each process gets its own private virtual address space
- Solves the previous problems!

Address Spaces

bits $n = \lceil \log_2 N \rceil$ ceiling function (round up)

- Virtual address space: Set of $N = 2^n$ virtual addr
  - {0, 1, 2, 3, …, N-1}

bytes $m = \lceil \log_2 M \rceil$

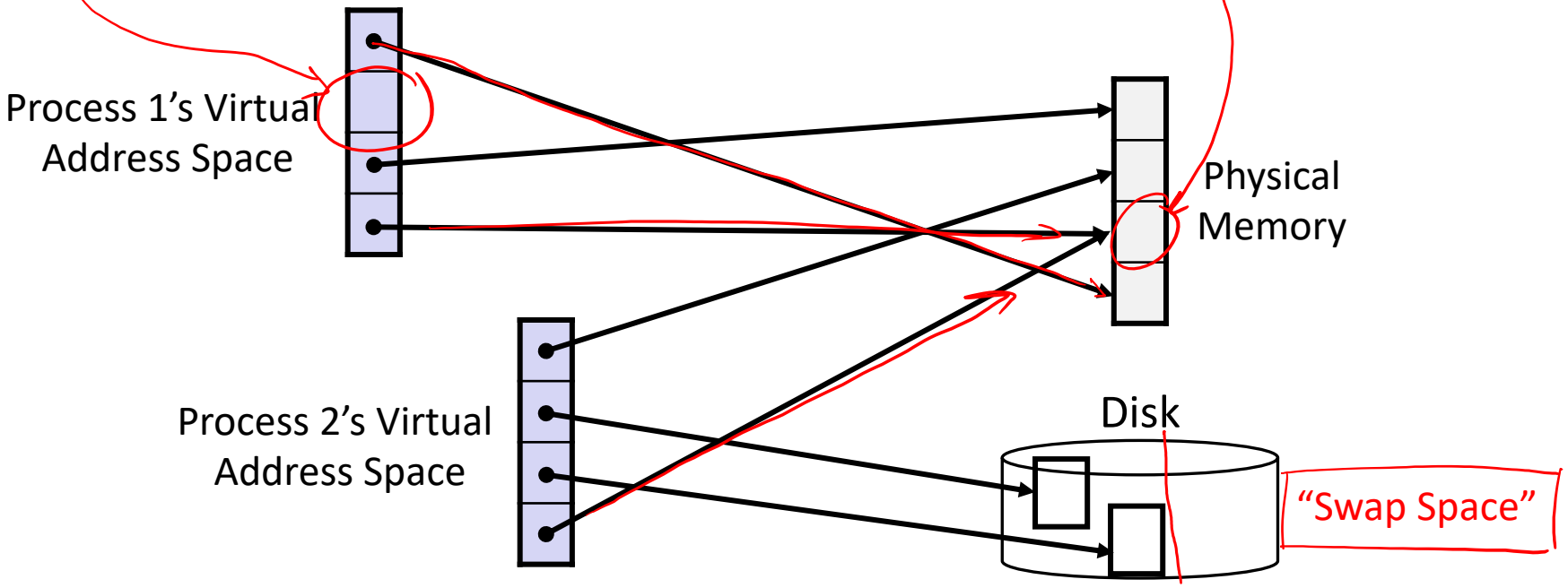
- Physical address space: Set of $M = 2^m$ physical addr
  - {0, 1, 2, 3, …, M-1}

- Every byte in main memory has:
  - one physical address (PA)
  - zero, one, *or more* virtual addresses (VAs)

unused — used by one process — used by many processes

Mapping

- A virtual address (VA) can be mapped to either physical memory or disk
  - Unused VAs may not have a mapping
  - VAs from *different* processes may map to same location in memory/disk



Summary

- Virtual memory provides:
  - Ability to use limited memory (RAM) across multiple processes
  - Illusion of contiguous virtual address space for each process
  - Protection and sharing amongst processes