CSCI 2410 Systems Programming

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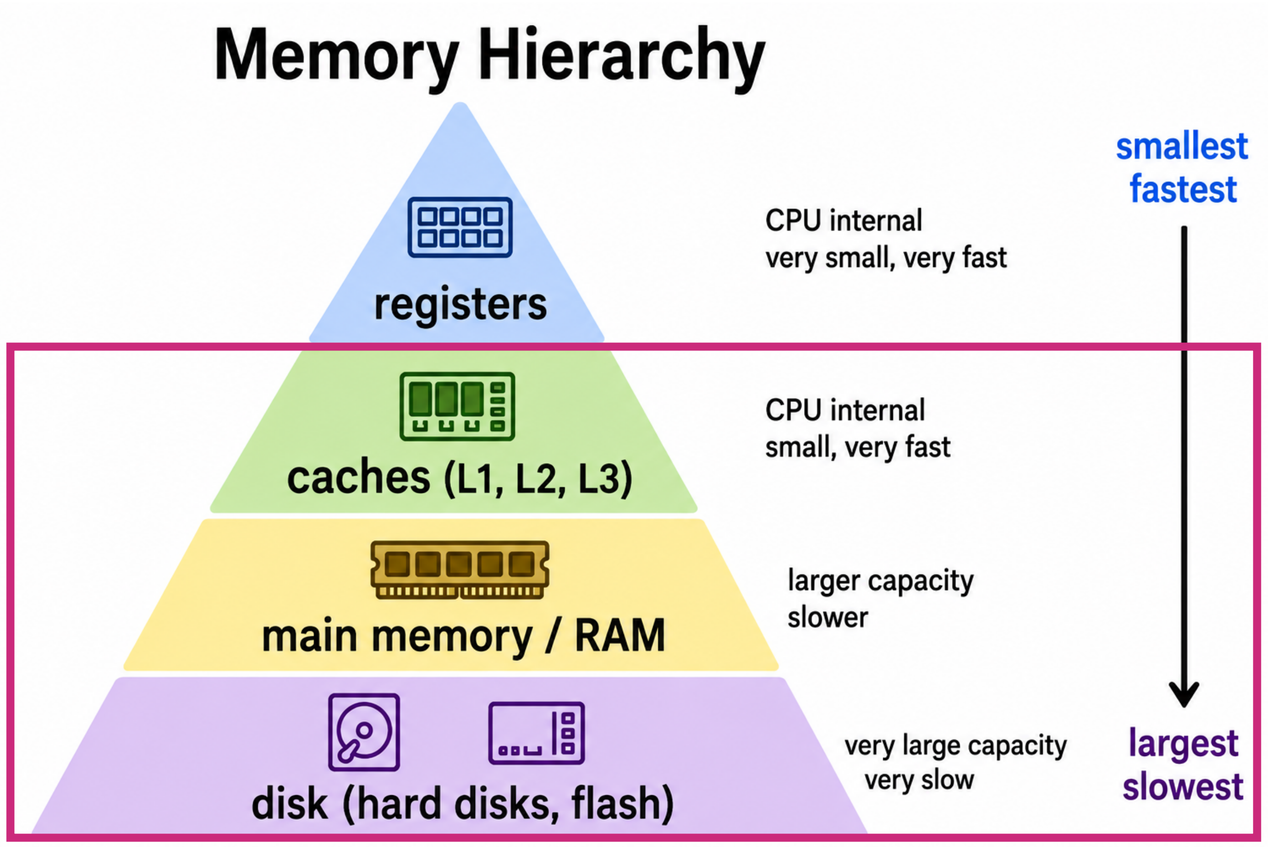
Slides materials are mostly credited to Sibin Mohan and Gabriel Parmer at GWU.

Memory Hierarchy



Why do we need so many layers?

- Registers are expensive!
- So are caches.
- Also, registers and caches are volatile.
- Speed vs. size: The faster the memory, the more expensive.

Registers

- Fastest form of memory
- Part of CPUs; what CPU uses for computing
- Each CPU has a set of registers.
- e.g., `a = b + 3;`
  - b is loaded into a register
  - a is computed and the result stored in another register or the same register used by b, if b is not used anymore.

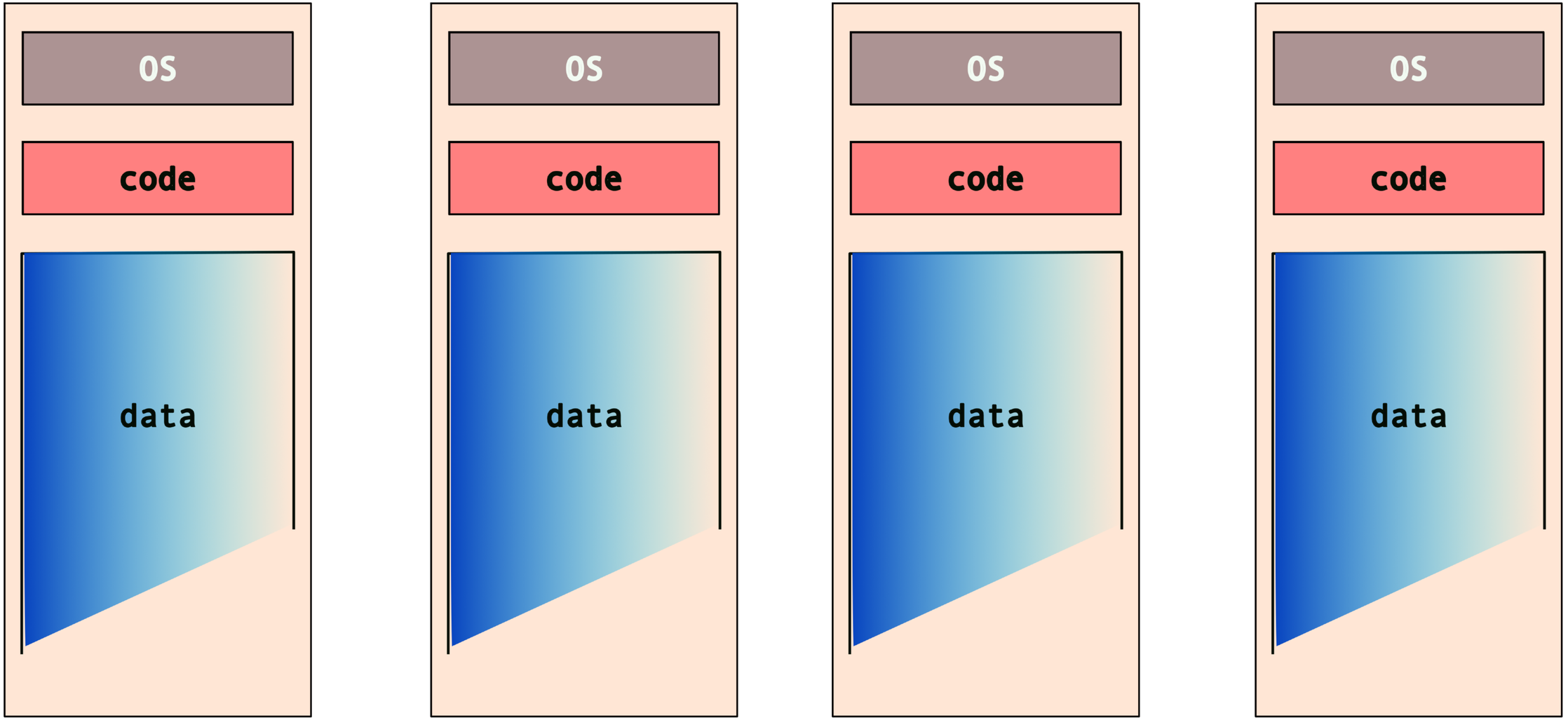
Caches

- Fast, on-chip, volatile memory
- (Largely) Transparent to programs and programmers
- Used by CPU to improve performance
- Typical sizes, hundreds of KBs to hundreds of MBs

Main Memory

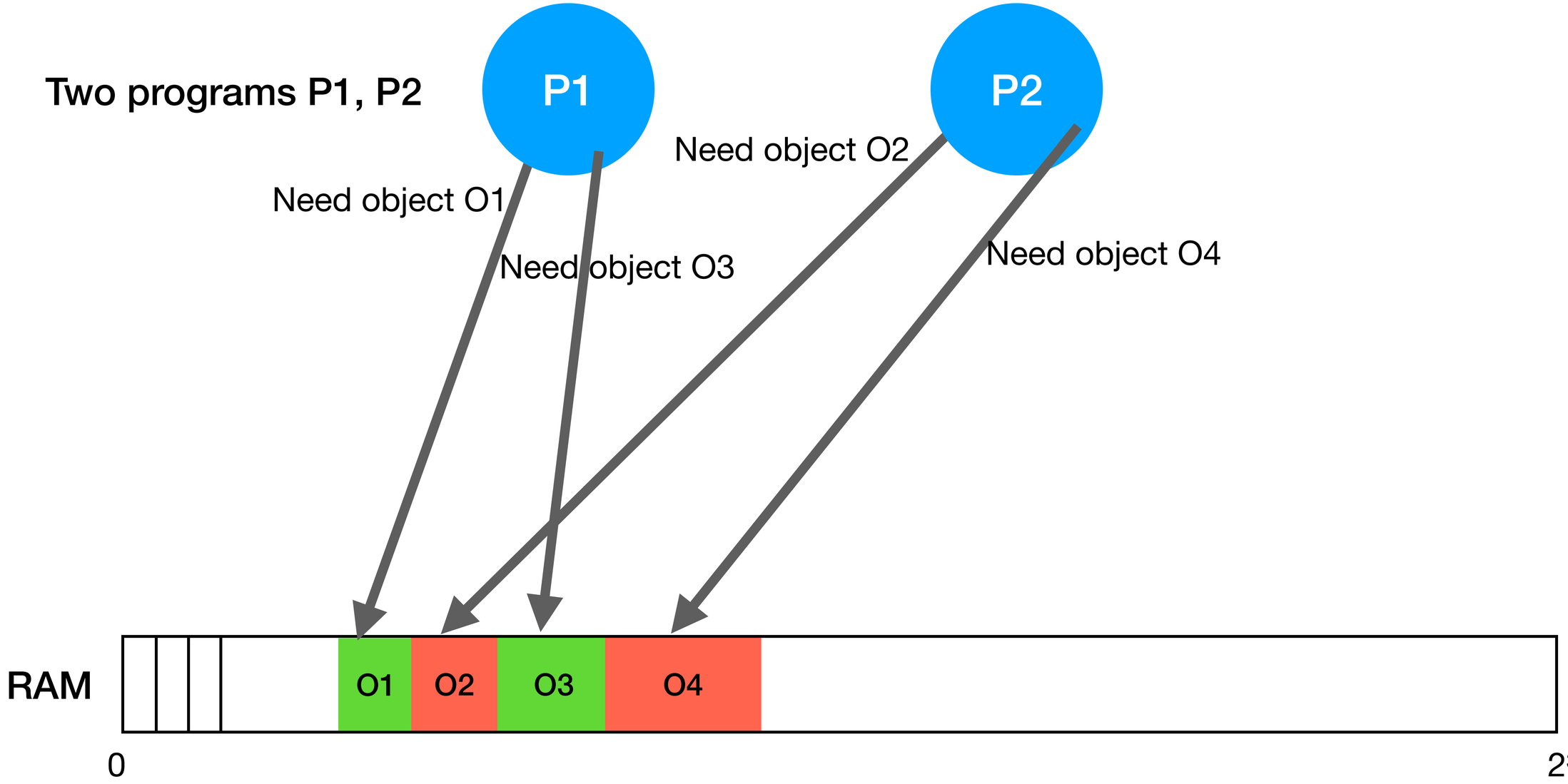
- Random Access Memory (RAM), also known as DRAM
- Typical sizes, GB range
- Limited by “width” of CPU
  - e.g., 32-bit CPU —> 4 GB of memory (generally)
- Memory is divided into many units, and each unit has its *address*.
- In mainstream systems, memory is *byte-addressable.*

Virtual Memory

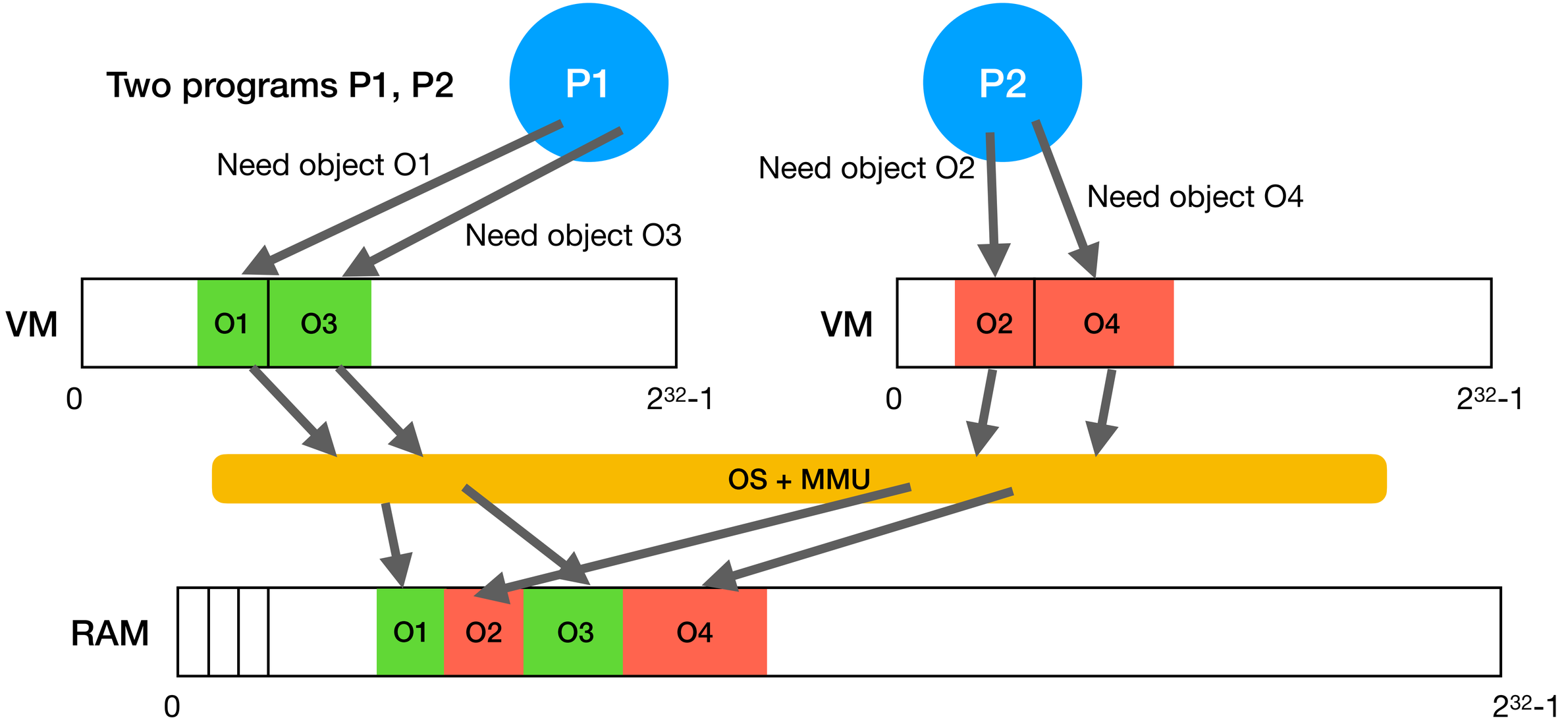


Or, at least the programs “think” so!

Using Main Memory Directly

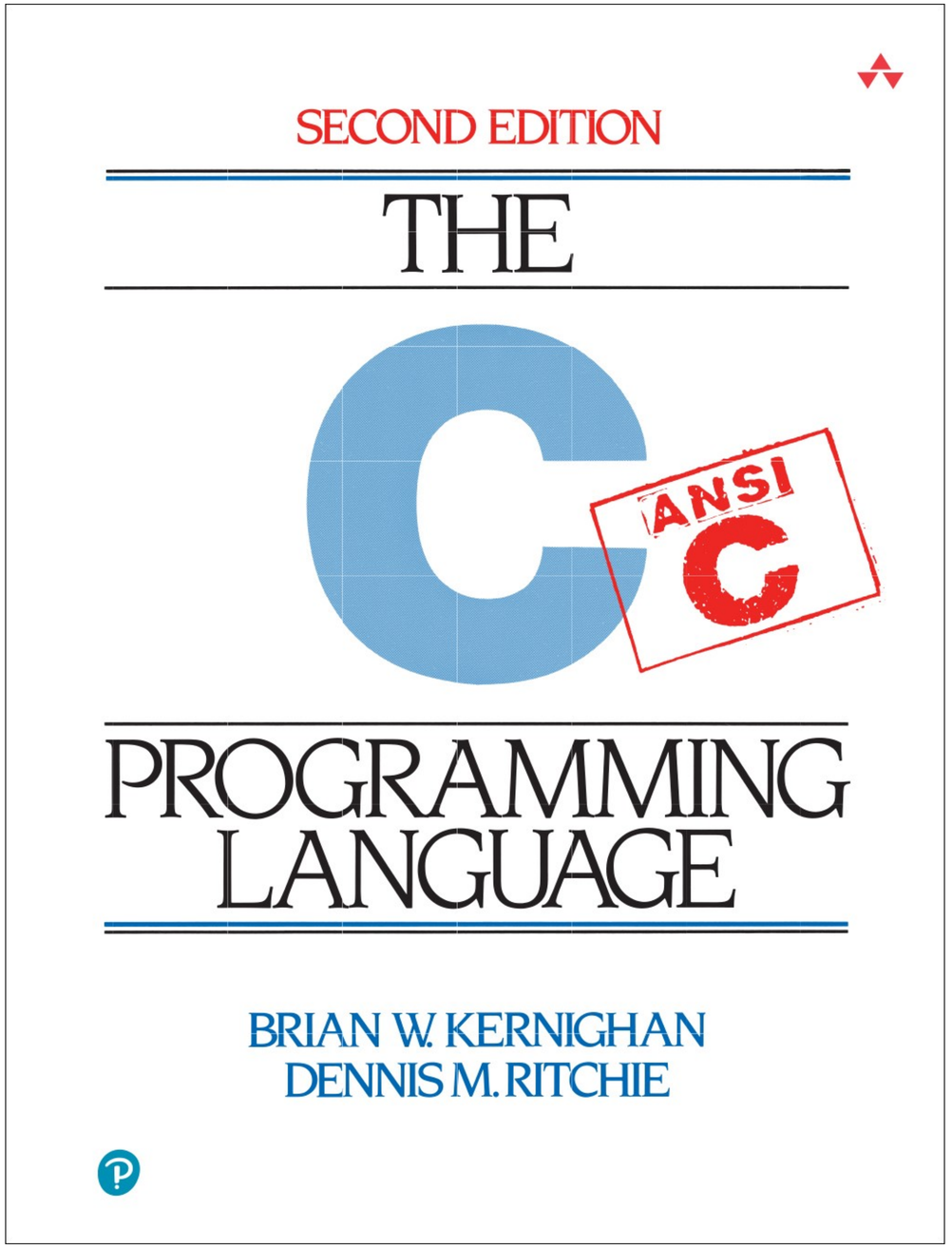


Virtual Memory



Virtual Memory

- Makes each program “believe” it as the *entire* memory it itself!
- Combination of OS + hardware
- Programmers need **not** worry about other programs.
- Easier for OS to manage all programs.
- In this course—and in most of your career as a systems programmer—you will mainly deal with virtual memory.


SECOND EDITION
THE
C
ANSI
C
PROGRAMMING
LANGUAGE
BRIAN W. KERNIGHAN
DENNIS M. RITCHIE

The C Programming Language

- Invented in 1972 by Dennis Ritchie
- Building blocks for our modern digital world.
  - OS, web servers, databases, systems libraries, …

What are the fundamental elements of a programming language?

What Makes Up a Programming Language?

- Data types
  - int, char, boolean, etc.
- Variables
- Operators and expressions
  - arithmetic, assignment, comparison, etc.
- Functions
  - parameters and return
- Control flow
  - conditional/unconditional branch, loop, call/return

You already know C—to a great extent.

C Constructs (Familiar)

Construct	Syntax
conditionals	`if` and `else`
loops	`while {}`, `do {} while`, `for`
basic types	`int`, `float`, `double`, `char`
aggregate	arrays, struct(ure),…
functions	`ret_val fn_name (arg_list) {}`

What is Different From Java?

- No object-oriented programming. C is *procedural*.
- No function overloading
- No classes
- But C has `struct` instead, which is similar but also different.
- Compiled not interpreted
- No public/private
  - By default, everything is public.
- Pointers!!
  - Source of superpower but also root causes for disastrous bugs.

Compound Types

- Consist of basic types of data
- Continuous memory: each data is laid out next to each other.

Type	Usage
`struct`	related variables (like class, but no functions)
`union`	same, but *shared* memory
array	continuous sequence of items of the same

`enum`

- Enumeration, essentially named integer constants
- Much less rich than Java's enum

No boolean

- Mimic it using `int` values
  - `0 -> false`
  - any non-zero value `-> true`

Header Files (.h)

- Declares and define elements shared across C source files.
  - e.g., functions, data types, constants, etc.
- Included in C source files and other header files
- Libraries usually only expose header files.
  - both standard C lib and 3rd-party libs

Including Header Files

- Tells the current src what it can use defined somewhere else
- Similar to `import` in Java
  - but must *explicitly* include everything needed

Method	What is included
`#include <stdio.h>`	Common libraries
`#include “my_header.h”`	User header files

Including Header Files

- Tells the current src what it can use defined somewhere else
- Similar to `import` in Java
  - but must *explicitly* include everything needed

Method	Location of Header Files
`#include <…>`	Installed in the system, e.g., `/usr/include/*` in Linux; can also be anywhere and specified during compilation, e.g., “`-I/my_home/libs/lib_crypto/include`”
`#include “…”`	path in the current project

- We can ask the compiler to list the default search directories.
  - `gcc -E -v`

Some Common C Libraries

Library	Function
`stdio.h`	standard input/output, e.g. `printf()`
`stdlib.h`	common utilities, e.g. memory allocations
`string.h`	string manipulation, `strcpy()`
`math.h`	math utility functions, `sqrt()`
`unistd.h`	POSIX system interfaces, e.g. read/write

Unix Manual (man) Pages

- Compilation of Unix (and C) knowledge
- In terminal, type “man <topic>”, e.g., “man printf”
- Organized into sections

#	Contents
1	genera commands, e.g., `ls`
2	system calls, e.g., `read/write`
3	library functions, e.g., `printf`
4	special files, e.g., `/dev/null`
5	file formats, e.g., `passwd`
6	games & screensavers
7	miscellaneous, e.g., `socket`
8	system administration, e.g., `useradd`

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Example

man 3 printf

```
PRINTF(3)                                                  Linux Programmer's Manual

NAME
       printf, fprintf, dprintf, sprintf, snprintf, vprintf, vfprintf, vdprintf, vsprintf, vsnprintf - formatted output conversion

SYNOPSIS
       #include <stdio.h>

       int printf(const char *format, ...);
       int fprintf(FILE *stream, const char *format, ...);
       int dprintf(int fd, const char *format, ...);
       int sprintf(char *str, const char *format, ...);
       int snprintf(char *str, size_t size, const char *format, ...);

       #include <stdarg.h>

       int vprintf(const char *format, va_list ap);
       int vfprintf(FILE *stream, const char *format, va_list ap);
       int vdprintf(int fd, const char *format, va_list ap);
       int vsprintf(char *str, const char *format, va_list ap);
       int vsnprintf(char *str, size_t size, const char *format, va_list ap);

   Feature Test Macro Requirements for glibc (see feature_test_macros(7)):

       snprintf(), vsnprintf():
           _XOPEN_SOURCE >= 500 || _ISOC99_SOURCE ||
```

Basic Types

Type	Description/Size in C	Size in Java
`char`	smallest type, typically one byte[1]	one byte
`short int / short`	typically two bytes[2]	two bytes
`int`	typically four bytes[3]	four bytes
`long int / long`	larger int, typically four bytes[4]	eight bytes
`float`	floating point, typically four bytes	four bytes
`double`	double precision, typically eight bytes	eight bytes

1. The C standard requires at least 8 bits.
2. short: at least $-(2^{15} - 1)$—$(2^{15} - 1)$, so at least 16 bits or 2 bytes
3. int: Also $-(2^{15} - 1)$—$(2^{15} - 1)$, must be larger or equal to short; typically 4 bytes
4. Floating point numbers are not defined by the C standard.

Code Samples

```c
#include <stdio.h>

int main()
{
    return 0;
}
```

- Every C program requires a `main()` function, where the execution starts and ends.
- Here `main` takes no arguments, but it can also take arguments.

Code Samples

```c
#include <stdio.h>

int main()
{
    char c = 'a';
    int i;
    float f;
    double d;

    i = 100;
    f = 1.0;
    d = 12398723897.2332;

    printf( "Memory sizes of variables...\n\n \
            size of char: %lu \
            size of int: %lu \
            size of float: %lu \
            size of double: %lu\n",
            sizeof(c), sizeof(int), sizeof(f), sizeof(d) );

    printf( "\n" ); // adding an extra line for nice printing at the end
    return 0;
}
```

Compound Types

- Consist of basic types of data
- Continuous memory: each data is laid out next to each other.

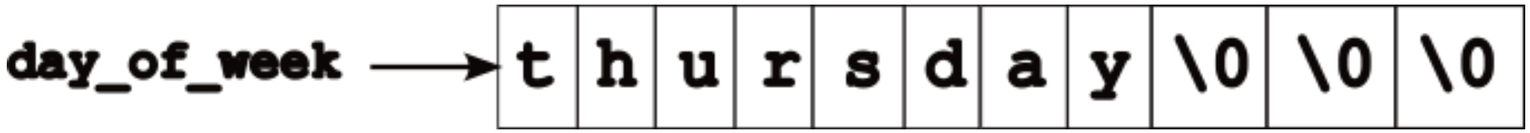
Type	Description	Size
`struct`	collection of different values	sum of all fields + padding
`union`	one of a set of values	size of the largest field
array	continuous sequence of items of the same type	sum of all items

`enum`

- Enumeration, essentially named integer constants
- Much less rich than Java's enum
- Size: typically size of `int`

Strings

- An array of characters that are null terminated, i.e., \0



Type Modifiers

- `unsigned`: variables that cannot be negative
- `signed`: signed variable. char, int, long all default to signed.
- `static`: this variable/function are only accessible inside its source file.
- `const`: an immutable value

Format Strings

- %d: int
- %ld: long int
- %u: unsigned int
- %c: char
- %x: unsigned int printed as hexadecimal
- %s: prints out a string
- %p: prints out a pointer value