Welcome to Systems Programming!

- A *Computer System* is the *hardware* and systems software that work in concert to run an application program.
- In this course, you will learn many practical skills and hopefully obtain a *deep* knowledge of the system that makes you a better programmer.
- The course has two major components of nearly equal weight:

  Lectures/Assignments/Quizzes 56% — C Labs 44%
- You need to work on both to do well in the course. Details in the **Course Outline**.
- There is ample help available: Lab TAs will be on duty (TEAMS) **every** day of the week. Take advantage of it!.

  What happened in a past term:

Lab 4			
Score	Count	% Sub	% All
10	51	42.50%	29.48%
5	29	24.17%	16.76%
0	40	33.33%	23.12%
NoSub	53		30.64%
TotalSub	120		
TotalAll	[illegible]		

Lab 5			
Score	Count	% Sub	% All
10	78	65.00%	45.09%
6	2	1.67%	1.16%
4	16	13.33%	9.25%
0	24	20.00%	13.87%
NoSub	53		30.64%
TotalSub	120		
TotalAll	[illegible]		

Lab 6			
Score	Count	% Sub	% All
10	85	68.00%	49.13%
6	29	23.20%	16.76%
4	1	0.80%	0.58%
3	1	0.80%	0.58%
0	9	7.20%	5.20%
NoSub	48		27.75%
TotalSub	125		
TotalAll	[illegible]		

Administrivia

- The course text: **Computer Systems:** *A Programmer's Perspective* 3^{rd} *Ed.* is the best text I know of, on the subject. I expect you will read the sections we cover **carefully**!
- The lectures will follow the text closely. We will cover Chapters 1 - 3, 6, 7 & 8 (selected parts).
- There is a public channel for asking lecture & assignment related questions. Please ask questions in that channel, unless the content of your question is private. Treat the channel as a discussion forum - i.e. if you know how to answer a fellow student, please do so.
- Assignment submission should be *(i)* properly organized *(ii)* legibly written. If a marker cannot read your submission or they need a *scavenger hunt* to put your answer together, the problem will be awarded a zero. After solutions is posted, **a resubmission will not be accepted**. *(iii)* A Method for re-assessment of a]ssignments will be posted. Please follow that

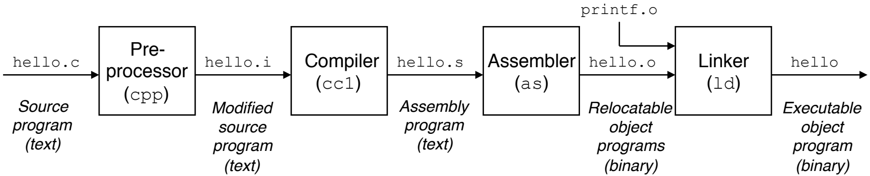
Administrivia *continued*

- Please work on the assignment solutions on your own. Avoid looking for solutions on the web/from friends who have taken the course in past terms *etc etc* .
- Assignment submission is via Crowdmark
- **Academic Integrity:**
  Past experience shows that there is a great temptation to copy code for the labs and answers for the quizes. Please understand that we are looking for this. Your submissions will be put through a plagiarism detector. In a past term, 52 students were reported to the AIO, for cheating. 49 of them were found to be **in violation of academic integrity rules**. L:ast term, in 1120, 43 people were reported to the AIO office.
- *The Safety Rule:* Discuss the problems with your friends/classmates. **However** the work you turn in **must** be your own. Also remember: Both sides of the copying couplet are considered **equally** guilty.
- Besides, you will be glad you worked on the course when you get to OS (CS3120)!
- Now, ENOUGH OF THIS! Lets get started

The C compilation Chain

```
#include <stdio.h>
 int main(void) {
   printf("Yeah Whatever\n");
   return 0;
}
```

The C compilation chain:



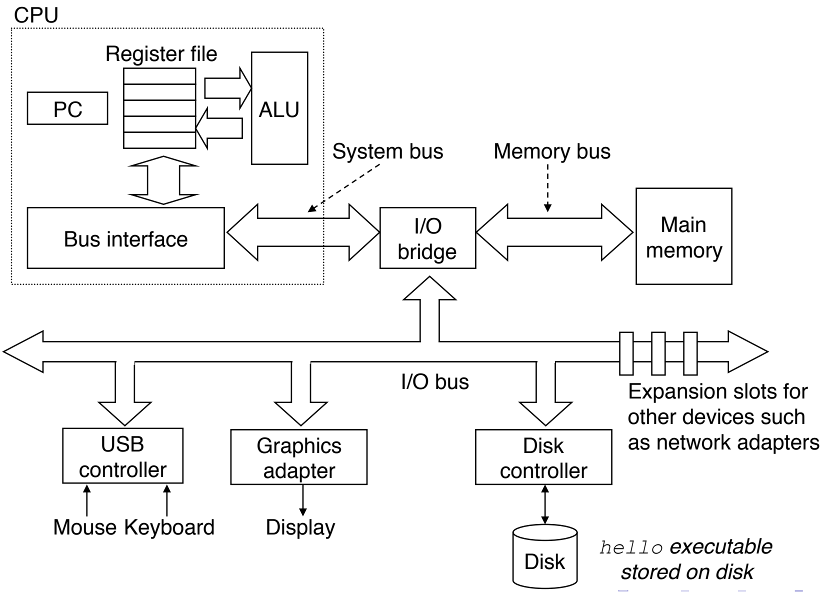
`gcc -Og -S hello.c` *generates* `hello.s`

`gcc -Og -o hello.o hello.c` *generates* `hello.o`

`gcc -Og -c hello.c` *generates* `hello.o`

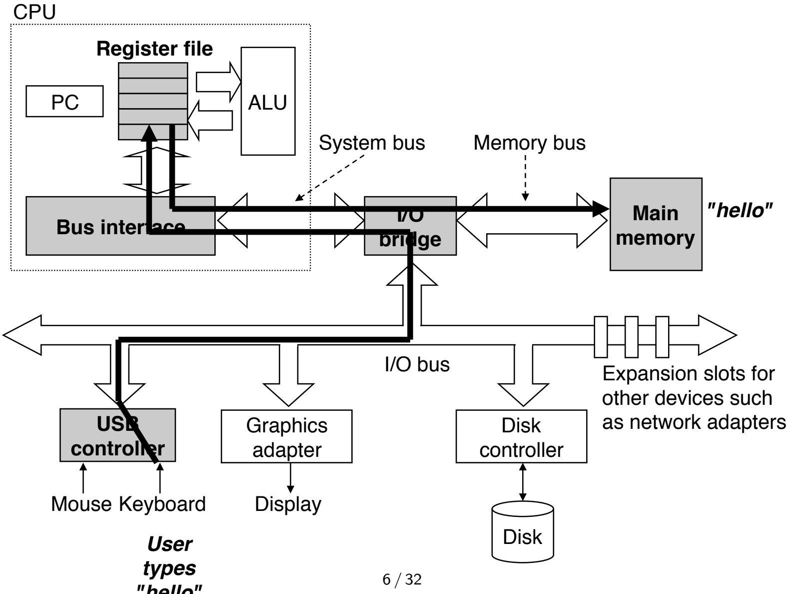
To run the code ./hello

Basic Hardware Organization



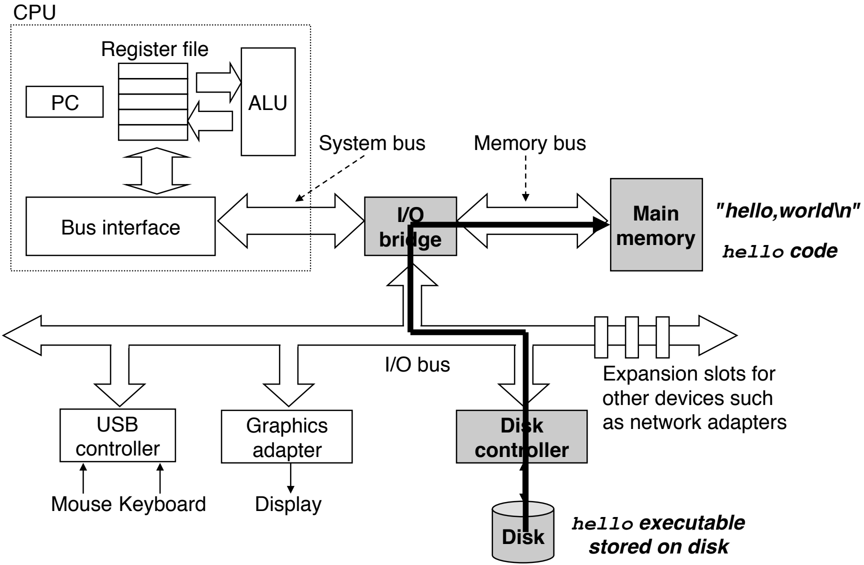
Keyboard read - `hello.c`

Step 1



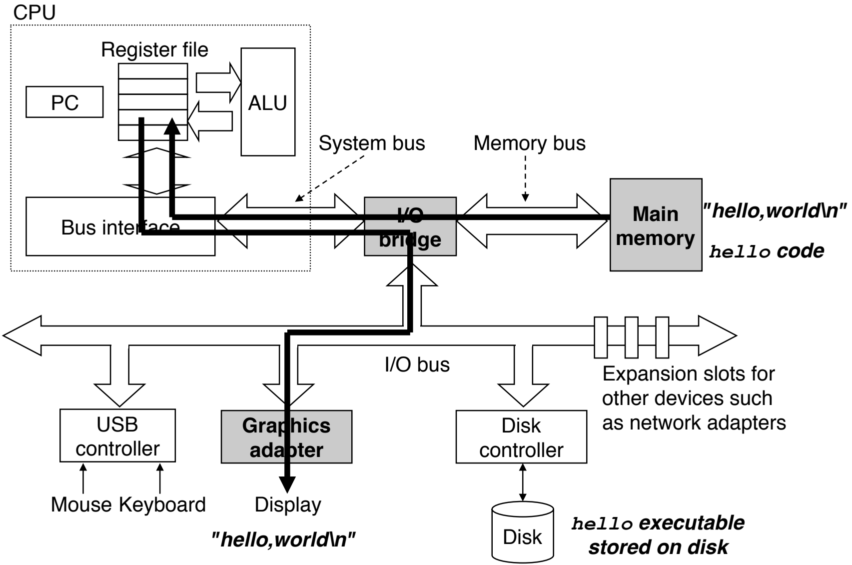
Load - `hello.c`

Step 2



Execute - `hello.c`

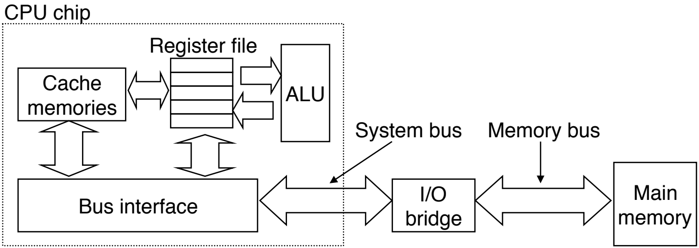
Step 3



running `hello.c`

- The system spends a lot of time moving information around:
- `hello.o` stored on the hard disk
  $\rightarrow$ Loaded into Memory $\rightarrow$ Instructions copied to processor
  Data string `''Yeah....''` copied $\rightarrow$ Mem. $\rightarrow$ display device.
- Moving stuff around is **"overhead"** to running the program
- *(i)* Large storage devices slower than smaller devices
  (ii) Faster storage devices more expensive than slower.
- Typical Hard disk: $\sim 1TB$; RAM: $\sim 1GB$; Reg.File $\sim 0.5KB$
- Processor reads data from Register File ~ 100 times faster than from RAM.
  Processor reads data from RAM $\sim 10^7x$ faster than from Disk.
- To deal with the Processor-Memory gap: Use smaller faster devices: *Cache Memories* between Processor & Memory.

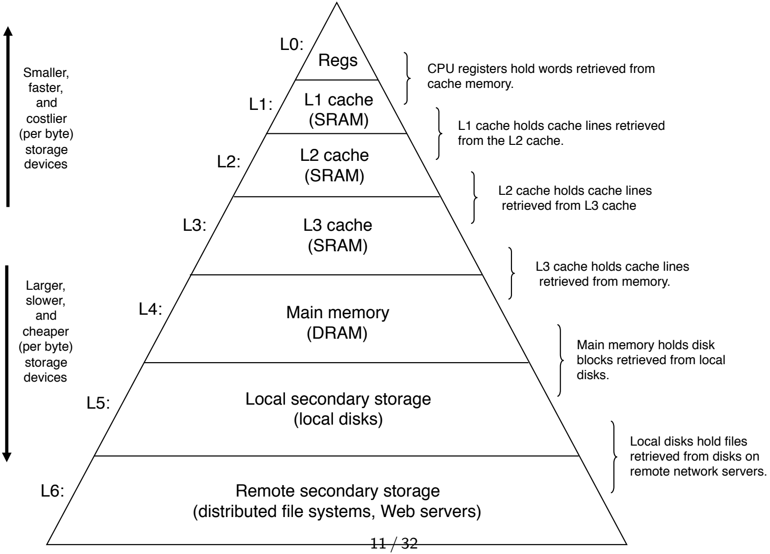
Cache Memories



Instructions that are repeatedly accessed from memory are "cached" closer to the CPU. Think of the instructions in a loop. The speed-up is greater if the code written takes advantage of caches.

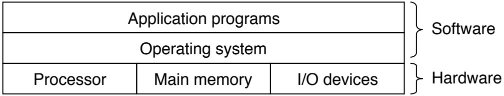
Memories Hierarchy

Inserting smaller, faster storage between Processor and a larger, slower storage is a general idea.

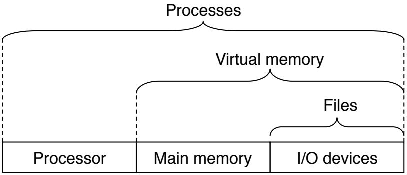


Role of the Operating System in the Execution

The OS manages the hardware. Applications programs do not directly access memory.



OS: *(i)* Protects hardware from runaway applications
(ii) Provides applications a uniform mechanism to access device that wildly differ in speed.

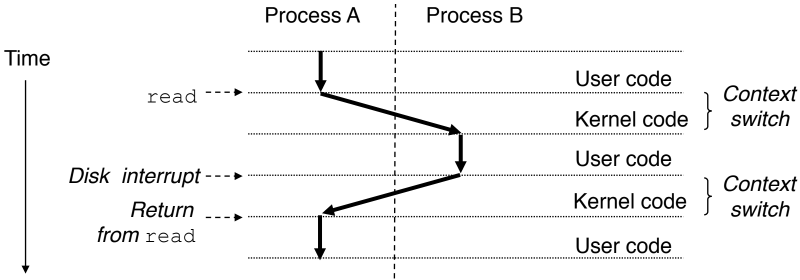


The OS handles this by providing Applications program with abstractions: *Processes; Virtual Memory; & Files*

Fundamental abstractions provided by the OS

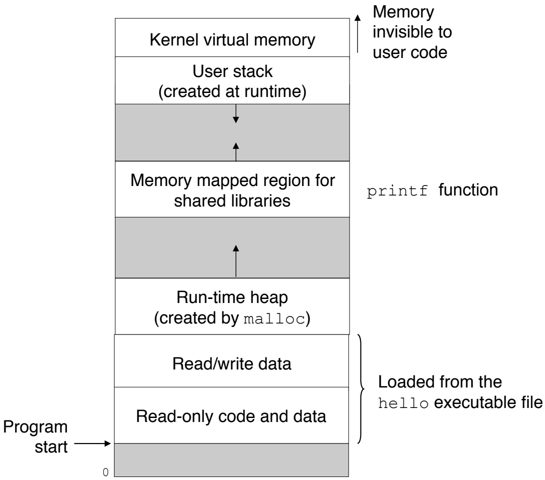
⋆ **Process:** OS's abstraction of a running program.

- Processes can be run concurrently.
- Traditional system sequential & more processes than processors.
- Instructions of P_A interleaved with those of P_B.
- Context Switching



Fundamental abstractions provided by the OS

⋆ **Virtual Memory** Abstraction that allows each process the illusion that it has exclusive use of memory.
The virtual address space seen by each process has several well defined areas with specific purposes:



Fundamental abstractions provided by the OS

⋆ **Files**: A *file* is a sequence of bytes. Every I/O device including displays. keyboards and even the network is modelled as a file. Files provide applications a uniform view across many types of I/O devices.

Quantifying performance of the ‘system’

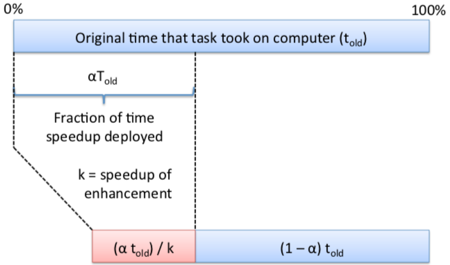
Amdahl’s law

- α is the fraction of time an enhancement can be used
- ‘k’ is the speedup due to the enhancement
- So,
    - αt_{old} is the original time
    - $(\alpha t_{old})/k$ is the new time
- Or

$$t_{new} = (1 - \alpha)t_{old} + (\alpha t_{old})/k$$

- Let ‘speedup’ $(S) = t_{old}/t_{new}$
- So,

$$S = \frac{1}{(1 - \alpha) + \alpha/k}$$



This holds for any ‘system’.

Amdahl's Law Example:

- The design goal for a new release of a 'system' is to provide a 2X performance improvement. Adding additional processors, can only enhance 70% of the system. How much would you need to improve this part for the application to reach the design goal? (Find k)

- If we could speed-up the processing of the 70% of the system, so that the time spent by it is negligible, what will be the overall speed-up?

Bits and Bytes: Review

- A Computer Stores *everything* as numbers.
- The only symbols (modern) computers use are '0' and '1'.
  A single '0' or '1' is called a *bit* (for *b*inary dig*it*).
- A group of 8 contiguous bits, treated as a unit is called a *Byte*.
  A lesser know unit: a group of 4 bits is called a *Nybble*.
- When the bits are grouped, there are different methods for interpreting them.
- Each method of interpretation is called a *bit model*.
  The bit model used to represent strictly non-negative integers is *unsigned binary*.
- A study of the bit-models of the different C data types allows a deeper understanding based on the actual memory the bits occupy.

Placeholder representation

We write numbers in a *positional representation* system: $(357)_{10}$ is

$$3 \times 10^2 + 5 \times 10^1 + 7 \times 10^0$$

A number in base (or *radix*) r: $(d_{n-1}d_{n-2}\ldots d_1 d_0)_r$ is

$$d_{n-1} \times r^{n-1} + d_{n-2} \times r^{n-2} + \ldots + d_1 \times r^1 + d_0 \times r^0$$

In base 2 or binary: the *value* of: $(b_{n-1}b_{n-2}\ldots b_1 b_0)_2$ is:

$$b_{n-1} \times 2^{n-1} + b_{n-2} \times 2^{n-2} + \ldots + b_1 \times 2^1 + b_0 \times 2^0$$

So, in (unsigned) binary 101010_2 is:

$$1 \times 2^5 + 0 \times 2^4 + 1 \times 2^3 + 0 \times 2^2 + 1 \times 2^1 + 0 \times 2^0$$

which is equal to 42_{10}.

Conversion Decimal $\rightarrow$ Binary

A simple algorithm allows is to convert decimal $\rightarrow$ binary:

1. Start with two columns: $value$ and bit, next to each other
2. For the given value, $bit = 0$ if value *even* and $bit = 1$ if *odd*.
3. Update: value $\leftarrow \lfloor number/2 \rfloor$
4. If *value* $=$ *1* stop, else goto 1.
5. The binary representation of the given value is now read bottom(MSB) to top (LSB)in the *bit* column.

.

The process carried out for 123_{10}

$\lfloor v/2 \rfloor$	value (v)	BIT
–	123	1
$\lfloor 123/2 \rfloor$	= 61	1
$\lfloor 61/2 \rfloor$	= 30	0
$\lfloor 30/2 \rfloor$	= 15	1
$\lfloor 15/2 \rfloor$	= 7	1
$\lfloor 7/2 \rfloor$	= 3	1
$\lfloor 3/2 \rfloor$	= 1	1

Reading the bit column bottom→top gives: 1111011_2

Let $\overrightarrow{x} = [x_{w-1}, \ldots, x_0]$ be a vector of w-bits.

Ntn: $B2U_w(\overrightarrow{x}) = \sum_{i=0}^{w-1} x_i 2^i$

Q: Is the algorithm *correct*?

Q: Why does it work?

Q: Can you think of another algorithm to do the same?

Note: Practice: $63_{10}, 127_{10}, 255_{10}, 254_{10}, 511_{10}, 1024_{10}$ **Q.** What gen. can you make about how decimal numbers are related to their bit-patterns in binary? Can you use this knowledge to convert 1033_{10} mentally?

A few Examples:

Hexadecimal Representation:

Modern computers have 32 or 64-bit units words. It is difficult to examine groups of 32 or 64 bits. To overcome this, we use base 16.

Representation in base 16 or HEXADECIMAL (commonly: HEX). Need 16 symbols, identifying "higits" from 0 to 15.

Problem: In decimal, we represent values larger than nine using two or more symbols.

In HEX the symbols 0 - 9 are the same as in decimal.
After that: $10 \rightarrow A;\ 11 \rightarrow B; 12 \rightarrow C; 13 \rightarrow D;\ 14 \rightarrow E; 15 \rightarrow F$.

HEX values are identified with the prefix `0x`. *e.g. 0xF00D*

Q: How many bits does it take to represent all possible values between 0 & 15?

Hex	Binary	Decimal
0	0000	0
1	0001	1
2	0010	2
3	0011	3
4	0100	4
5	0101	5
6	0110	6
7	0111	7
8	1000	8
9	1001	9
A	1010	10
B	1011	11
C	1100	12
D	1101	13
E	1110	14
F	1111	15

Conversion Binary $\longleftrightarrow$ Hex

- To convert *Binary* $\rightarrow$ *Hex*:
  Starting from the LSB (right end), create groups of 4 bits.
  Pad the front with zeros if necessary:
  e.g. $0111 \quad 1111 \quad 1111 \quad 1000$
- Replace each group of 4 with the "higit" from table on the prev. slide: *e.g.* 0x7 $\quad F \quad F \quad 8$
- To go *Hex* $\rightarrow$ *Binary*:
  Replace each "higit" with the group of 4 bits from table:
- *e.g.* 0x$B \quad A \quad D$
  e.g. $1011 \quad 1010 \quad 1101$
- **Q:** How do we go *Decimal* $\longleftrightarrow$ *Hex*? **Q:** Written in hex, what is the range of values of a single byte?

Practice

Practice Problem (pp) 2.2 - text, p. 38

- For $n = 19$ find 2^n in decimal & hex
- For $2^n = 32$, Find n in decimal & 2^n in Hex
  item For $2^n = 0x80$, Find n in decimal & 2^n in Hex
- For $2^n = 0x10000$, Find n in decimal & 2^n in decimal
- For $2^n = 16,384$, Find n in decimal & 2^n in Hex
- **Q**(pp2.4): Without converting, what is: *(i)* $0x503c + 0x8$ *(ii)* $0x503c + 0x40$ *(iii)* $0x50ea - 0x503c$?

Practice

Basic C data types

Every computer has a *word size*. Technically, it is the largest number of contiguous bits that the ALU handles. Practically, it manifests itself as the nominal size of pointer data *i.e.* the the number of bits required for a virtual address.

A 32-bit *word* limits virtual address space to $4GB$ and A 64-bit *word* to $2^{64} = 2^4 \cdot 2^{60} = 16$ Exabytes!

Signed	Unsigned	Bytes
`[signed] char`	`unsigned char`	1
`short`	`unsigned short`	2
`int`	`unsigned`	4
`long`	`unsigned long`	4, 8
`int32_t`	`unit_32`	4
`int64_t`	`unit_64`	8
`char *`		8
`float`		4
`double`		8

- These are typically allocated sizes. Not guaranteed.
- The C standard only guarantees *minimum* sizes. Actual size is implementation dependant.
- To avoid vagaries of "typical" sizes **ISO C99** defines `int32_t`, `int64_t`. These are guaranteed 4 & 8 bytes. In fact `intN_t` for $N = 8, 16, 32, 64$.
- **All** pointers are 8 bytes (4 bytes for 32-bit systems).
- Compilers typically treat `char` as signed. Not guaranteed by C std. Use prefix `signed`.
- C std. only guarantees lower bounds. Not upper bounds (except `intN_t` types).

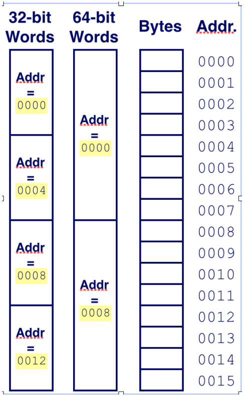
`printf`, `scanf`

`printf( )`: A general purpose output formatting function.
`scanf( )`: Reads data from stdin and stores them according to the format into the location(s) pointed to by additional arguments.

- Not defined in C. These are part of the standard library of functions (`stdio.h`).
- 1^{st} arg: string of chars to be printed, each % indicating where one of the arguments substituted.
  e.g. `printf("%2d\t %4.2f", dayNum, temperature, cost)`
  The *format string* above specifies print:
  `dayNum` is an `int` at least 2 digits wide %2d;
  `temperature` as floating point;
  `cost` print as floating point, at least 4 characters wide, 2 after the decimal point.
- Other format specifiers: `u` unsigned; `x, X` (int) hex; `c` single char `f, g, G` floating point; `p` pointer; `(void *).`
- More on this next class.

Multi-byte Data and Addressing

- Programs refer to data by address: Conceptually, a very large array of bytes (not in reality).
- An address is like an index into that array and, a pointer variable stores an address.
- System provides private address spaces for each process.
- Addresses specify byte locations: Address of first byte in word. Successive word addresses differ by 8 bytes (for 64-bit) and



Multi-byte Data and Addressing

Variable `x` has a 4-byte value: `0x01234567`
Address given by `&x` is `0x100`

Big Endian

		0x100	0x101	0x102	0x103		
		01	23	45	67		

Little Endian

		0x100	0x101	0x102	0x103		
		67	45	23	01		