CS 201
Computer Systems Programming

Prof. Harry Porter

`www.cs.pdx.edu/~harry/cs201`

Agenda for Today

Attendance

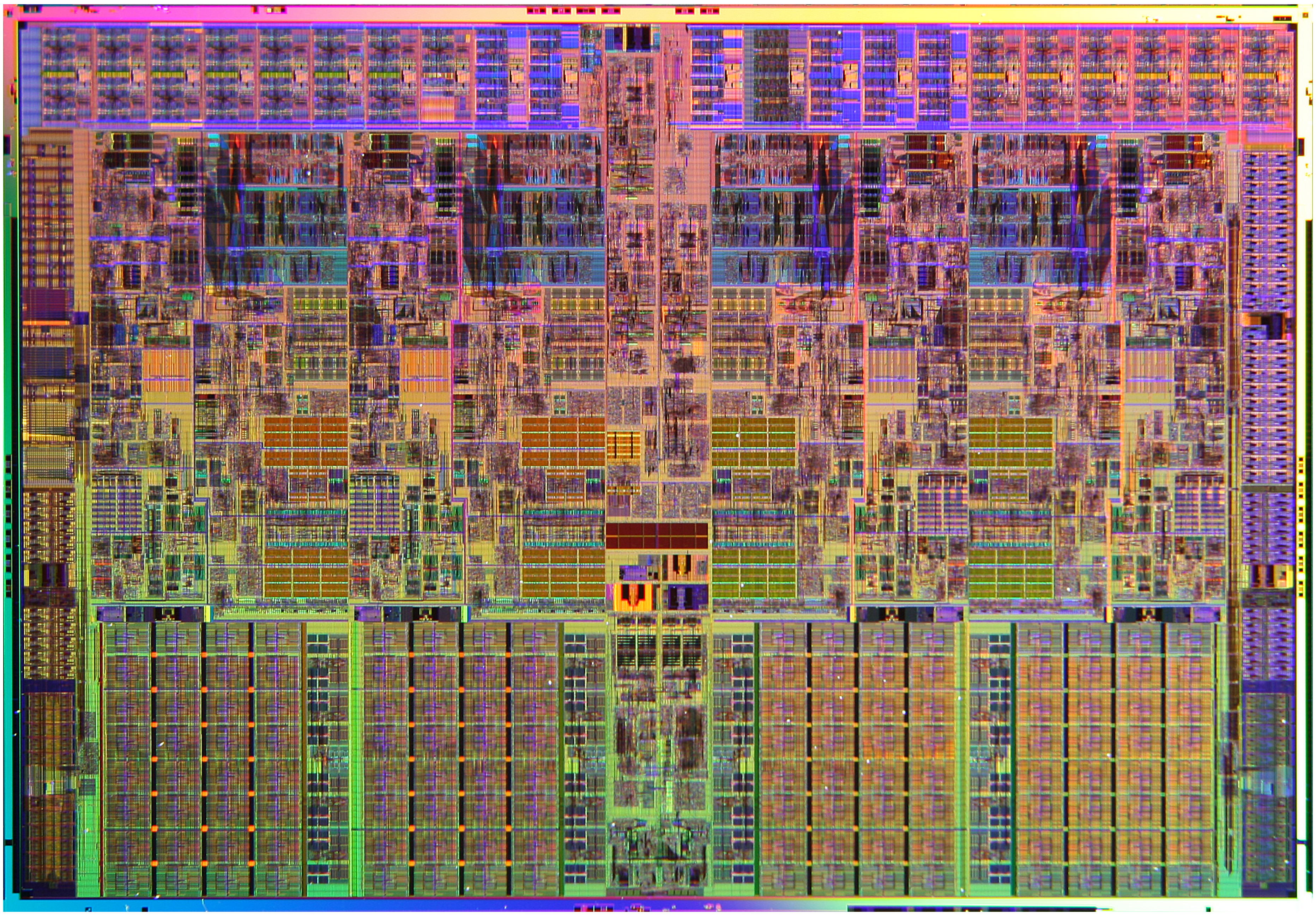
Course objectives

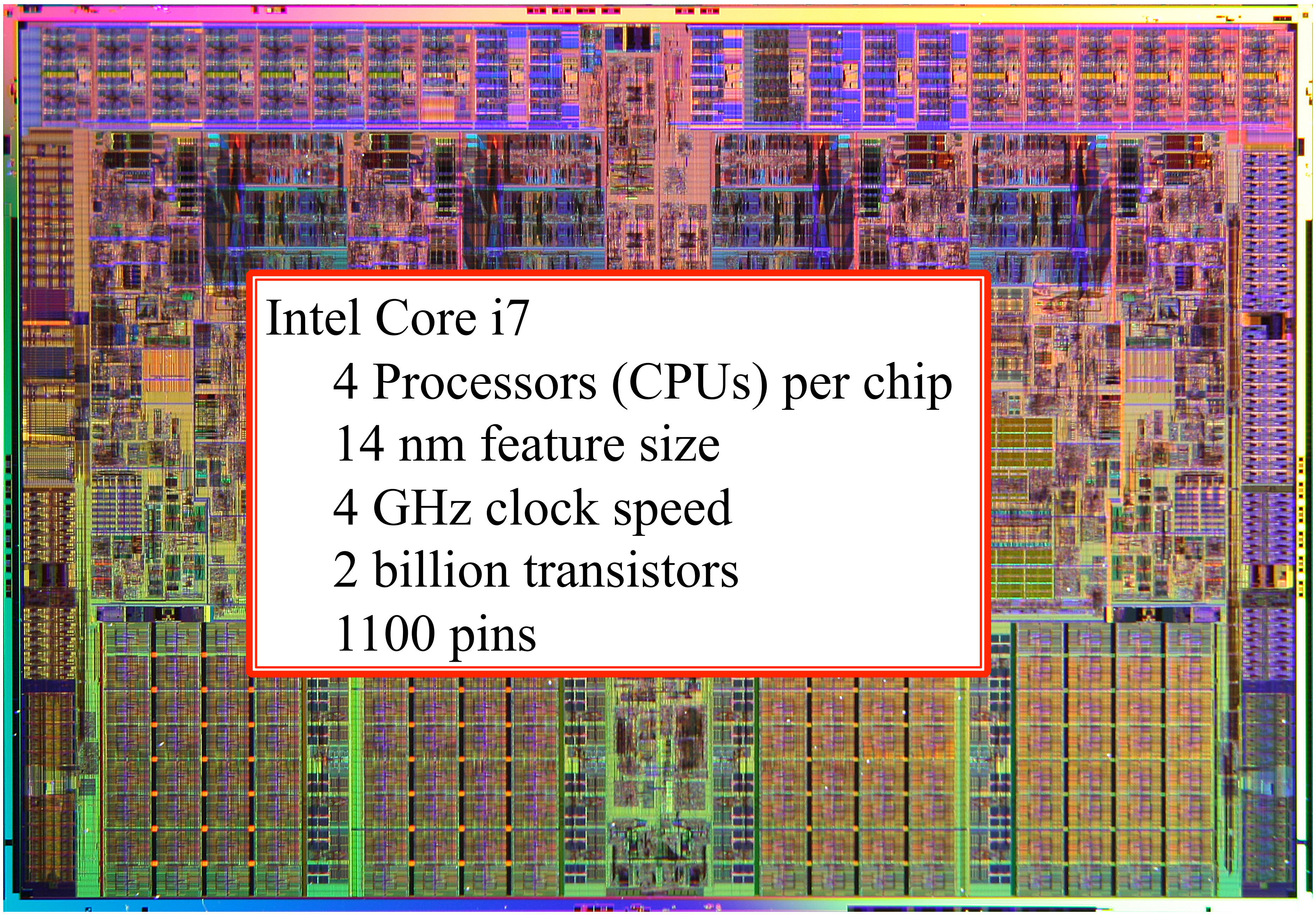
Syllabus

- Textbooks, policies, class mailing list, etc.

Assignment 1

Overview of the “C” programming language





Intel Core i7

- 4 Processors (CPUs) per chip
- 14 nm feature size
- 4 GHz clock speed
- 2 billion transistors
- 1100 pins

The Big Questions

What is “System Software” and how does it work?

- Compiling
- Assembly Language
- OS organization

How is a program actually executed?

- Skills and knowledge of “C” programming

How does the hardware get the job done?

- Computer Architecture

Syllabus

Course home page

cs.pdx.edu/~harry/cs201

Course Schedule
Homeworks
Lecture Slides
Information about instructor, TA, office hours
Email mailing list (mailman):

PorterClassList

Syllabus

Accounts

<u>Instructions on course web page</u>

Activate your account in person at CAT front desk.

linux.cs.pdx.edu

Linux systems in FAB 88-09 and FAB 88-10

(Homework assignments will be tested here.)

<u>Login remotely</u> or in person (Basement of EB)

ssh user@linux.cs.pdx.edu

- **ssh is included in the “putty” package**

  http://www.chiark.greenend.org.uk/~sgtatham/putty

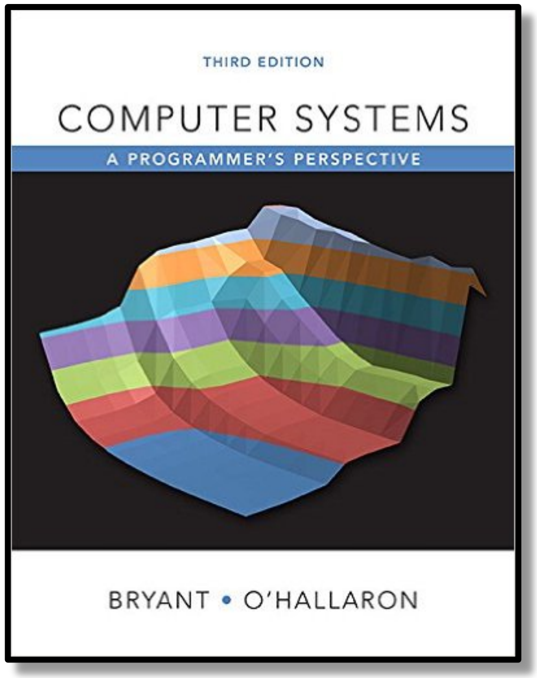
- **ssh is included in “cygwin”**

  http://www.cygwin.com

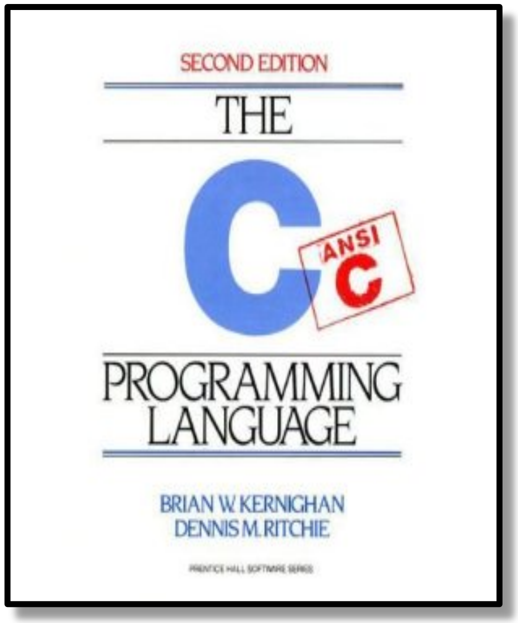
  Alternatively, you can develop your code via cygwin

  Code will be graded on linuxlab so make sure it works on linuxlab systems

Textbooks



Randal E. Bryant and David R. O'Hallaron,
"Computer Systems: A Programmer's Perspective", Third Edition, Prentice Hall 2003.



Brian Kernighan and Dennis Ritchie,
"The C Programming Language, Second Edition", Prentice Hall, 1988.

Syllabus

Getting help

- CS Tutors
- TA and instructor office hours
- On-line resources for gdb, make, etc.

Policies

- You are responsible for everything that takes place in class
- Reading assignments will be posted with each lecture
- Homework assignments due at start of class on due date
  - Follow submission instructions on home page carefully, especially for programming assignments.
  - Late policy: 50% off, if not submitted before class time.

Syllabus

Academic integrity

- Automatic failing grade given
- Departmental guidelines available in CS office

What is not cheating?

- Discussing the design for a program is OK.
- Helping each other orally (not in writing) is OK.
- Using anything out of the textbook or my slides is OK.
- Copying code “snippets”, templates for system calls, or declarations from a reference book or header files are OK

What is cheating?

- Copying code verbatim without attribution
  - Source-code plagiarism tools
- Copying someone’s answer or letting someone copy your answer.
- Mailing code to the class mailing list.

Syllabus

Grading

Reading assignments

Practice problems in the textbook – do them!

Homework:

- Programming assignments in C – email to grader
- Written homework – hand in hardcopy

Two exams

- Midterm exam
- Final comprehensive exam (covering entire term)

Syllabus

Supporting Video Material

- Accessible through website
- To augment lectures

100% Attendance is required

"Binary Numbers"

"Assembly Language and Processor Architecture"

Homework Assignment 1

The specification is on course web site

cs.pdx.edu/~harry/cs201

The Task: Write a small C program

Will use several system calls

rand, gettimeofday, printf, scanf, strlen, etc…

Goal: Learn C

- **Discover an algorithm**
- **Write clean, well-formatted code**
- **Write appropriate comments**

Grader will run and read your program

Due in two weeks

If you are unable to complete this program on time, you should consider dropping the course.

Introduction to C Programming

Why Learn C?

Used prevalently

- Operating systems (e.g. Windows, Linux, OS X)
- Web servers
- Web browsers
- Mail servers
- DNS servers
- Video games
- Graphics card programming

Why?

- Performance
- Portability
- Flexibility / Ability to do things

Why Learn C?

Compared to other high-level languages

- Maps almost directly into hardware instructions
- Code efficiency!!!
  - C Provides a minimal set of abstractions
  - Other *High-Level Languages* make programming simpler at the expense of efficiency

Compared to assembly programming

- Abstracts out hardware (i.e. registers, memory addresses)
  - Possible to write portable code
  - A “portable assembly language”
- Provides variables, functions, arrays, complex arithmetic and boolean expressions

Why Learn Assembly?

Learn how programs map onto underlying hardware

- Allows programmers to write efficient code

Perform platform-specific tasks

- Access and manipulate hardware-specific registers
- Interface with hardware devices
- Utilize latest CPU instructions

Reverse-engineer unknown binary code

- Analyze security problems caused by CPU architecture
- Identify what viruses, spyware, rootkits, and other malware are doing
- Understand how cheating in on-line games work

The C Programming Language

One of many programming languages

Imperative (procedural) programming language

- Computation consisting of statements that change program state
- Language makes explicit references to state (i.e. variables)
- Computation broken into modular components (“procedures” or “functions”) that can be called from any point

Declarative programming languages

- Describes what something is like, rather than how to create it
- Implementation left to other components
- Examples: HTML, SQL

The C Programming Language

Simpler than C++, C#, Java

No support for…
- Objects
- Memory management
- Array bounds checking
- Non-scalar operations

Simple support for…
- Typing
- Structures

Extended Functionality? Just a collection of functions
- Functions are in “libraries” (libc, libpthread, libm)

Low-level, direct access to machine memory specifics

Easier to write bugs, harder to write programs, typically faster

The C Programming Language

Compilation is to machine code

- Same as C++
- Compiled, assembled, linked via gcc

Compared to interpreted languages…

Perl / Python / Ruby …

- Commands interpreted by interpreter software
- Interpreter runs natively

Java

- Compiles to virtual machine “byte codes”
- Byte codes interpreted by virtual machine software
- Virtual machine runs natively (and is written in C)
  (Exception: “Just-In-Time” (JIT) compilation to machine code)

Our environment

All programs must run on the CS Linux Lab machines

```
ssh user@linuxlab.cs.pdx.edu
```

Architecture will be x86-64

- **IA-32 (32 bits)**
  - **i386**
- **x86-64 (64 bits)**
  - **Intel-64, AMD64**
- **IA-64 (64 bits)**
  - **“Itanium”**

Our environment

GNU gcc compiler

```
gcc –m64 –Wall hello.c –o hello
```

–m64 = compile for 64-bit machines

–Wall = print warnings as well as errors

GNU gdb debugger

Must use "-g" flag when compiling and remove –O flags

```
gcc –g hello.c
```

(Will add debug symbols; will not reorder instructions for optimized performance)

- ddd is a graphical front end to gdb
- "gdb -tui" is a graphical curses interface to gdb

Variables

Identifiers use letters, numbers, some special characters

Examples:

`x`   `mySizeVar`   `x_43`   `_init`

Must be declared before use

- **Contrast to typical scripting languages**
  (Perl, Python, PHP, JavaScript)
- **C is statically typed**

Static Typing

Compiler checks for type errors

x = 123 – “hello”;

Dynamic Typing

Less checking; Errors may occur at runtime

Data Types and Sizes

char – single byte integer

- 8-bit characters
- Strings implemented as arrays of char and referenced via a pointer to the first char of the array

short – short integer

- 16-bit (2 bytes), not used much

int – integer, *size varies by architecture*

- Normally 32-bits (4 bytes)
- Qualifiers: ‘unsigned’, ‘short’, ‘long’

float – single precision floating point

- 32-bit (4 bytes)

double – double precision floating point

- 64 bit (8 bytes)

Integer Types

16 bit integers

short int

32 bit integers

int

32 or 64 bits

long int

64 bit integers

long long int

Integer Types - Synonyms

16 bit integers

short int

short

32 bit integers

int

32 or 64 bits

long int

long

64 bit integers

long long int

long long

Integer Types - Synonyms

16 bit integers

short int

short

32 bit integers

int

32 or 64 bits

long int

long

64 bit integers

long long int

long long

Preferred

Constants

Integer literals

```
1234
0xFE    0xab78
```

Character constants

`'a'` is the numeric value of character ‘a’ in the ASCII code (decimal=97, hex=0x61)

```
char letterA = 'a';
int asciiA = 'a';
```

$\Big\}$ What’s the difference?

String Literals

```
"I am a string"
""    // This is the empty string.
```

Constant pointers

Used for static arrays

- Symbol that points to a fixed location in memory

```
char amsg[ ] = "This is a string";
```

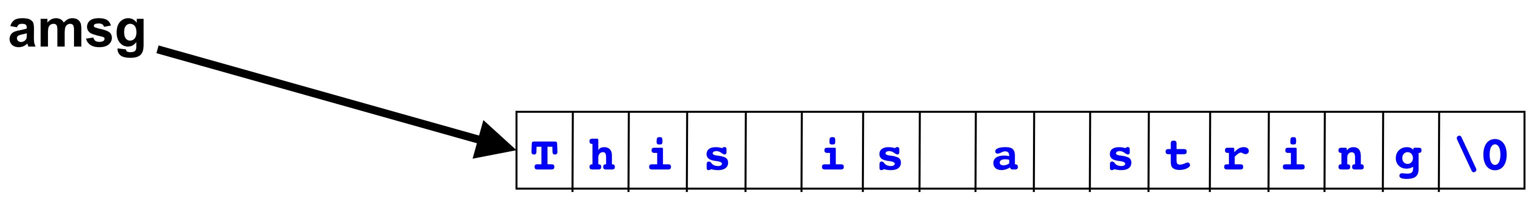
- Can change change characters in string

```
amsg[3] = 'x';
```

- Can not reassign amsg to point elsewhere

```
char p[ ] = "This is a different string";
```

~~amsg = p;~~



Declarations and Operators

Variable declaration

```
int foo;
char *ptr;
float ff;
```

Can include initialization

```
int foo = 34;
char *ptr = "fubar";
float ff = 34.99;
```

Arithmetic operators

- +, - , *, /, %
- Modulus operator (%)
- Arithmetic operators associate left to right

Expressions

In C, oddly, assignment is an expression

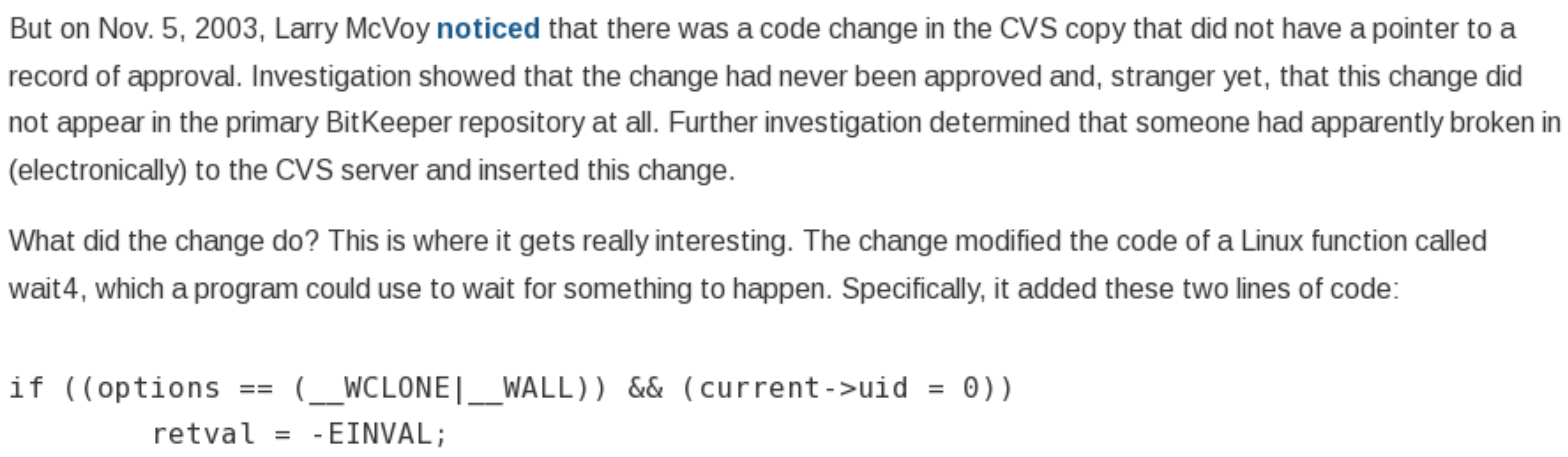
“x = 4” has the value 4

```
if (x == 4)
  y = 3;     /* sets y to 3 if x is 4 */

if (x = 4)
  y = 3;     /* always sets y to 3 */

while ((c=getchar()) != EOF) …
```

Example: Using == in an Exploit



But on Nov. 5, 2003, Larry McVoy **noticed** that there was a code change in the CVS copy that did not have a pointer to a record of approval. Investigation showed that the change had never been approved and, stranger yet, that this change did not appear in the primary BitKeeper repository at all. Further investigation determined that someone had apparently broken in (electronically) to the CVS server and inserted this change.

What did the change do? This is where it gets really interesting. The change modified the code of a Linux function called wait4, which a program could use to wait for something to happen. Specifically, it added these two lines of code:

```
if ((options == (__WCLONE|__WALL)) && (current->uid = 0))
        retval = -EINVAL;
```

https://freedom-to-tinker.com/blog/felten/the-linux-backdoor-attempt-of-2003/

Increment and Decrement

Comes in prefix and postfix flavors

```
i++
++i
i--
--i
```

Makes a difference in evaluating complex statements

- **A major source of bugs**
- **Prefix: increment happens before evaluation**
- **Postfix: increment happens after evaluation**

Important to understand:

When the actual increment/decrement occurs

Is “`i++*2`” the same as “`++i*2`” ?

Comparison to Java

Operators same as Java:

- **Arithmetic**

```
+   -   *   /   %
i = i+1;  i++;  i--;  i *= 2;
```

- **Relational and Logical**

```
<   >   <=   >=   ==   !=
&&   ||   &   |   !
```

Control flow syntax same as in Java:

```
if ( ) { } else { }
while ( ) { }
do { } while ( );
for (i=1; i <= 100; i++) { }
switch ( ) {case 1: … }
continue; break;
```

Simple data types are the same

datatype	size	values
char	**1**	**-128 … 127**
short	**2**	**-32,768 … 32,767**
int	**4**	**-2,147,483,648 … 2,147,483,647**
long long	**8**	**-10^{18} … $+10^{18}$**
float	**4**	**$3.4 \times 10^{\pm 38}$ (7 digits)**
double	**8**	**$1.7 \times 10^{\pm 308}$ (15 digits long)**

Exact details of size are "implementation dependent"!

Java programmer gotchas (1)

You must declare variables ahead of time in C:

```
{
  int i
  for (i = 0; i < 10; i++)
    …
```

This is not okay in C:

```
{
  for (int i = 0; i < 10; i++)
    …
```

Java programmer gotchas (2)

Uninitialized variables in C are allowed!!!

- Best practice: Always use `-Wall` compiler option

```
#include <stdio.h>

int main(int argc, char* argv[])
{
  int i;
  factorial(i);
  return 0;
}
```

Java programmer gotchas (3)

Error handling

There is no “throw/catch” mechanism

Ways to deal with an error:

- Return a special code to indicate an error.
- Set a global variable.
- Install a signal handler.
  (We will learn about “signals” later)

Java programmer gotchas (4)

Dynamic memory

- Managed languages such as Java perform memory management (i.e., garbage collection) for programmers.
- C requires the programmer to *explicitly* allocate and deallocate memory.
- No “new” construct to create objects.

Memory can be allocated dynamically at run-time.

Allocate with `malloc()`

Deallocate with `free()`

You supply the number of bytes you want.

The “Hello, world” Program

```c
#include <stdio.h>
int main(int argc, char* argv[])
{
   /* print a message*/
   printf(”Hello, world!\n");
   return 0;
}
```

```
$ gcc -Wall hello.c -o hello
$ ./hello
Hello, world!
$
```

Breaking down the code

`#include <stdio.h>`

- Include the contents of the file stdio.h
  - Case sensitive – lower case only
- No semicolon at the end of line

`int main(…)`

- The OS calls this function when the program starts running.

`printf(format_string, arg1, …)`

- Calls a function from libc library
- Prints out a string, specified by the format string and the arguments.

Command Line Arguments

main has two arguments from the command line

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

`argc`

Number of arguments (including program name)

`argv`

Pointer to an array of string pointers

- `argv[0]`: = program name
- `argv[1]`: = first argument
- `argv[argc-1]`: last argument

Example: `$ find . -print`

argc = 3
argv[0] = “`find`”
argv[1] = “`.`”
argv[2] = “`-print`”

Command Line Arguments

```
#include <stdio.h>

int main(int argc, char* argv[])
{
  int i;
  printf("%d arguments\n", argc);
  for(i = 0; i < argc; i++)
    printf("  %d: %s\n", i, argv[i]);
  return 0;
}
```

Command Line Arguments

```c
#include <stdio.h>

int main(int argc, char* argv[])
{
  int i;
  printf("%d arguments\n", argc);
  for(i = 0; i < argc; i++)
    printf("  %d: %s\n", i, argv[i]);
  return 0;
}
```

```
$ ./cmdline CS-201 is for SERIOUS programmers
6 arguments
  0: ./cmdline
  1: CS-201
  2: is
  3: for
  4: SERIOUS
  5: programmers
$
```

Arrays

```
char foo[80];
```

An array of 80 characters

```
        sizeof(foo)
            = ???
```

Array elements are stored contiguously in memory.

Arrays

```
char foo[80];
```

An array of 80 characters

`sizeof(foo)`
= 80 × `sizeof(char)`
= 80 × 1
= 80 bytes

Array elements are stored contiguously in memory.

Arrays

```
char foo[80];
```

An array of 80 characters

```
sizeof(foo)
```

= 80 × `sizeof(char)`

= 80 × 1

= 80 bytes

```
int bar[40];
```

An array of 40 integers

```
sizeof(bar)
```

=

=

=

Array elements are stored contiguously in memory.

Arrays

`char foo[80];`

An array of 80 characters

```
sizeof(foo)
```
= 80 × `sizeof(char)`

= 80 × 1

= 80 bytes

`int bar[40];`

An array of 40 integers

```
sizeof(bar)
```
= 40 × `sizeof(int)`

= 40 × 4

= 160 bytes

Array elements are stored contiguously in memory.

Structures

Aggregate data

```
#include <stdio.h>

struct person {
  char* name;
  int   age;
};    /* <== DO NOT FORGET the semicolon */

int main(int argc, char* argv[])
{
  struct person prof;
  prof.name = "Harry Porter";
  prof.age = 59;

  printf("%s is %d years old\n", prof.name, prof.age);
  return 0;
}
```

Pointers

Pointers are variables that hold an address in memory.

The address "points to" another variable.

Very powerful idea!

```
int x;
```

Pointers

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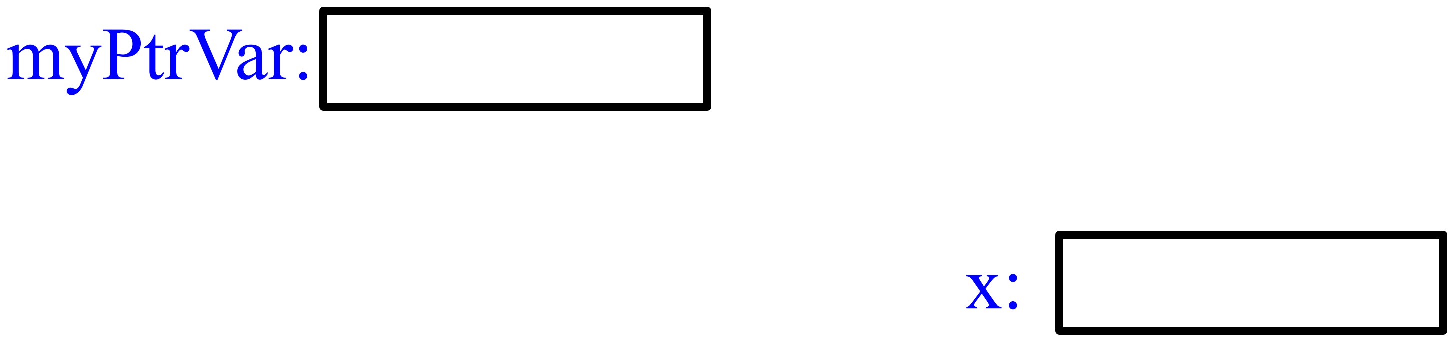
The address "points to" another variable.

Very powerful idea!

```
int x;
int * myPtrVar;
```



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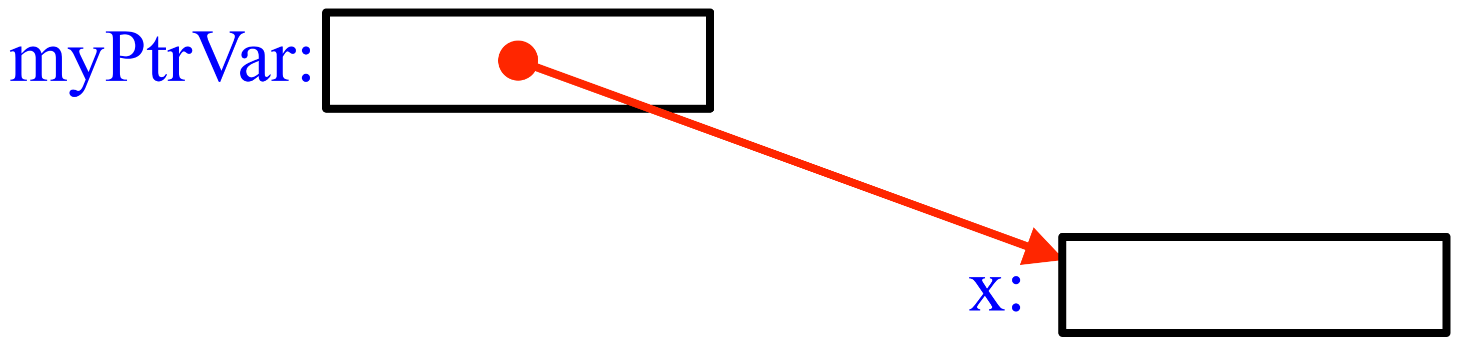
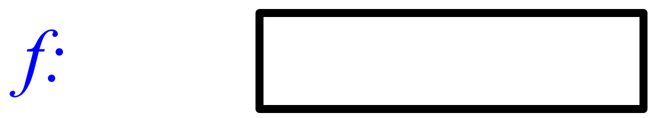
Very powerful idea!

```
int x;
int * myPtrVar;
myPtrVar = &x;
```



Using Pointers

```
float f;                /* data variable */
```



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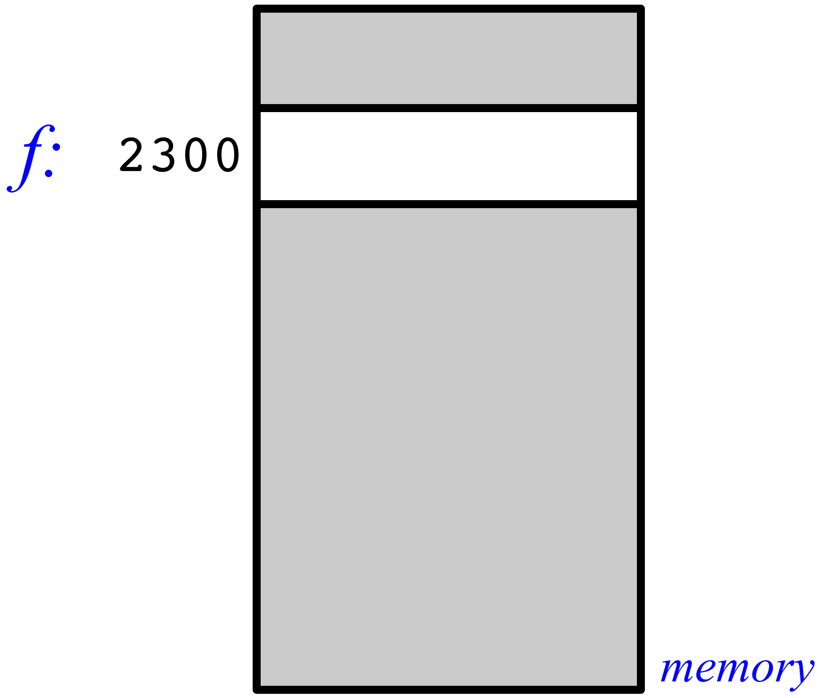
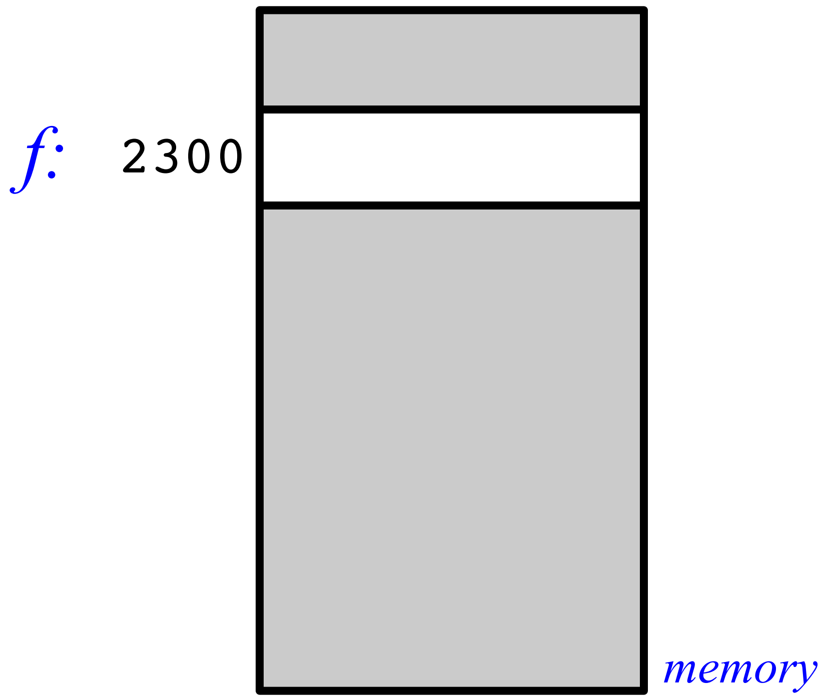


Using Pointers

```
float f;             /* data variable */
float *f_addr;       /* pointer variable */
```



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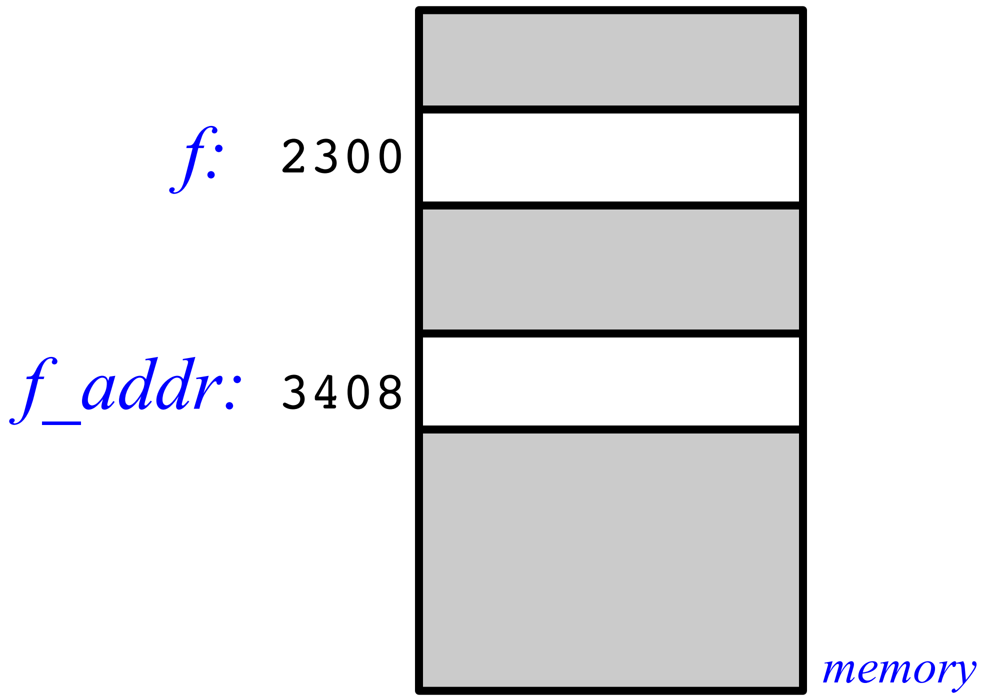
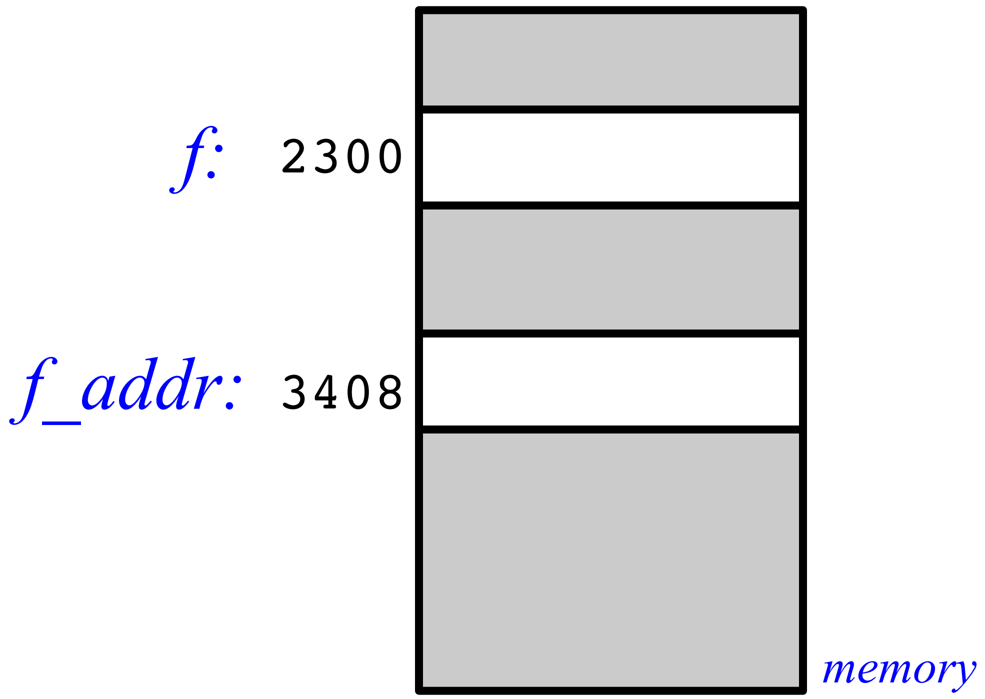


Using Pointers

```
float f;                /* data variable */
float *f_addr;          /* pointer variable */
f_addr = &f;            /* & = address operator */
```



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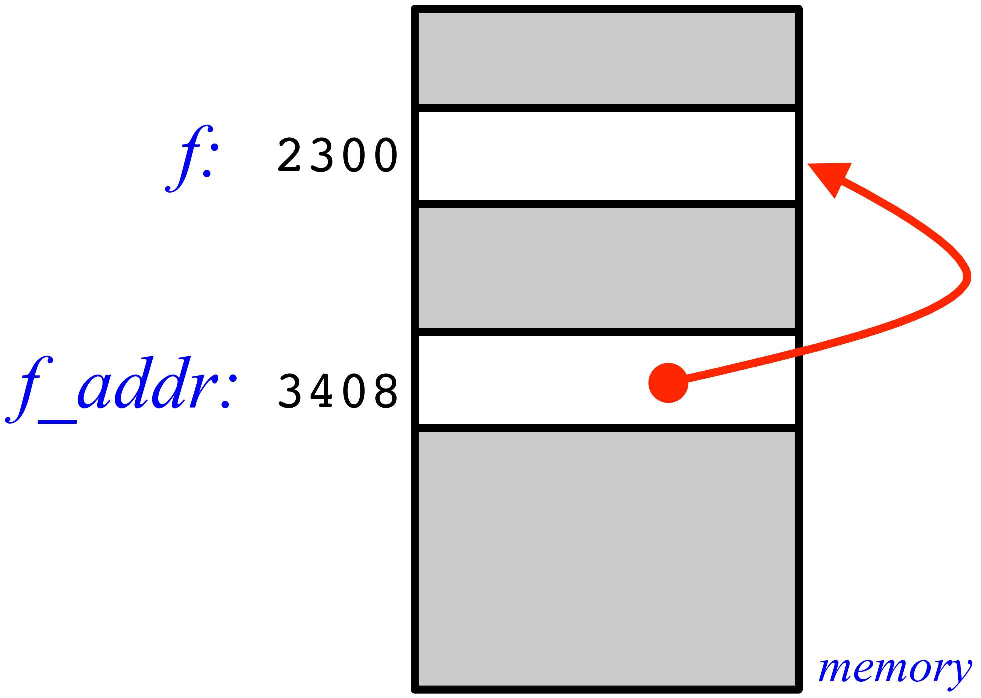

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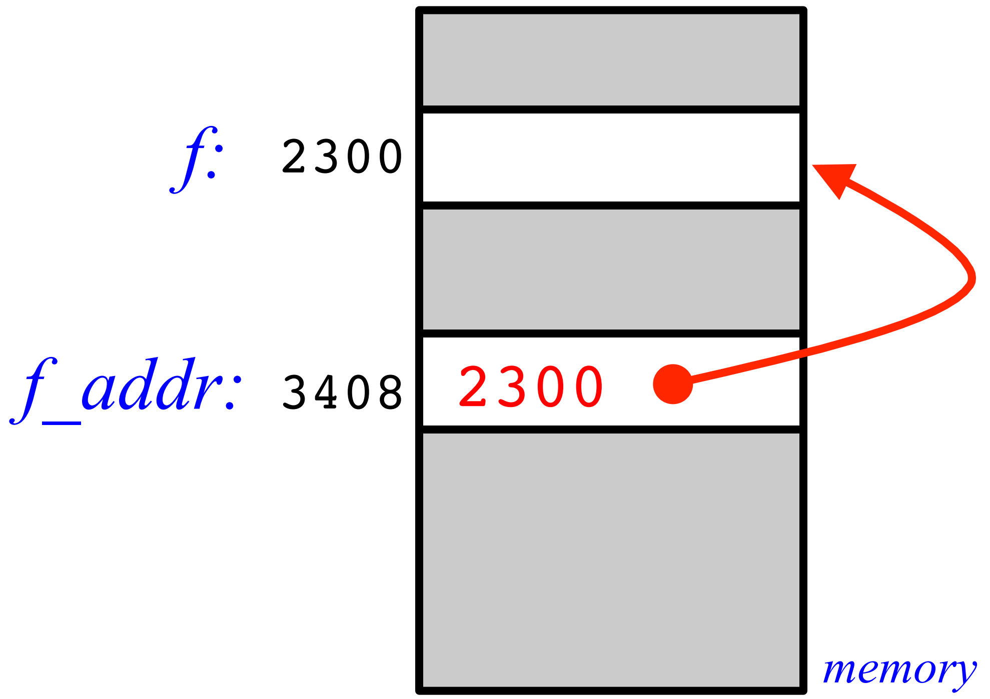
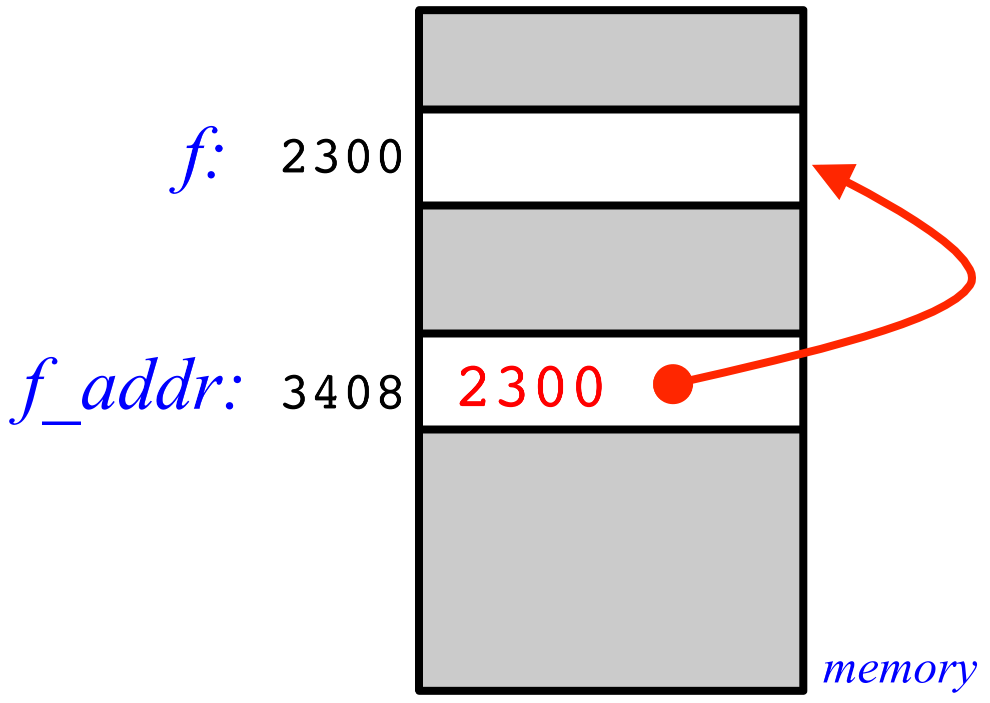


Using Pointers

```
float f;              /* data variable */
float *f_addr;        /* pointer variable */
f_addr = &f;          /* & = address operator */
*f_addr = 3.2;        /* indirection operator */
```



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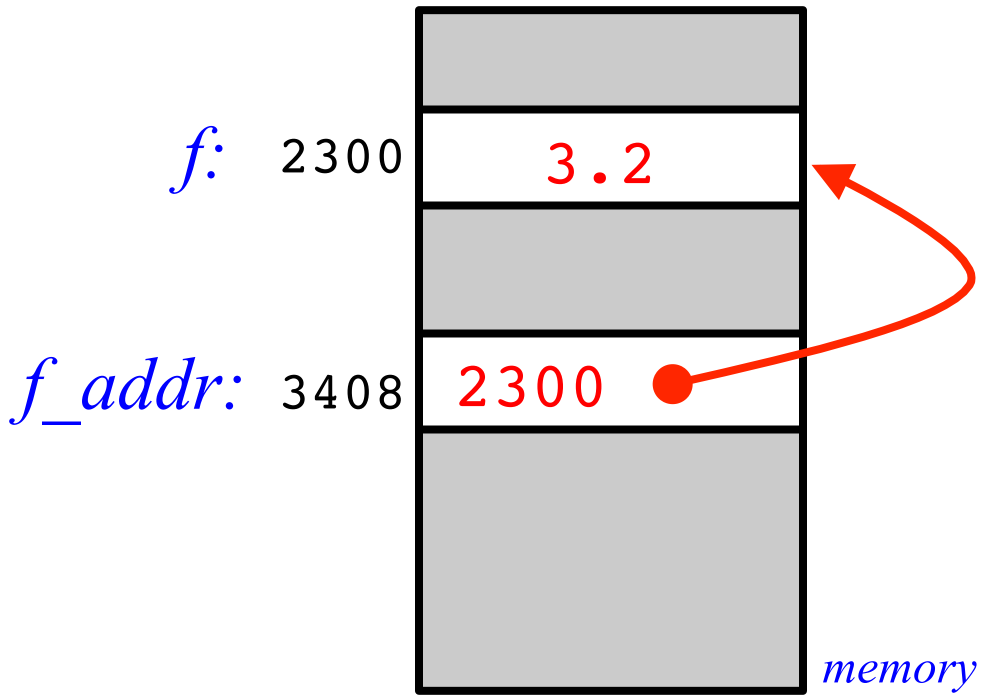
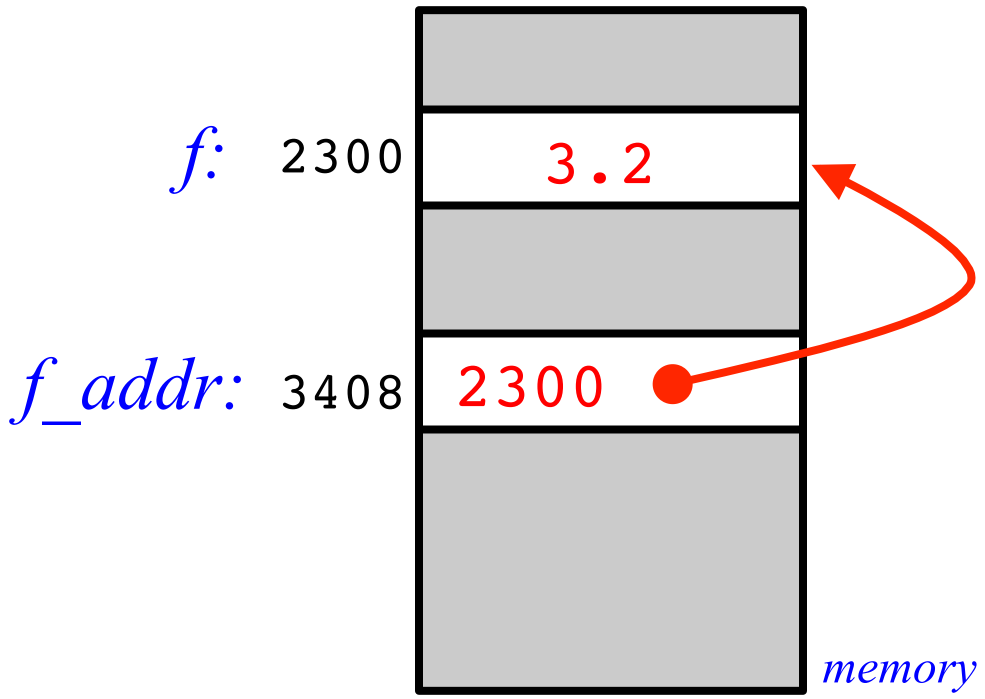


Using Pointers

```
float f;              /* data variable */
float *f_addr;        /* pointer variable */
f_addr = &f;          /* & = address operator */
*f_addr = 3.2;        /* indirection operator */
float g = *f_addr; /* indirection: g is now 3.2 */
```



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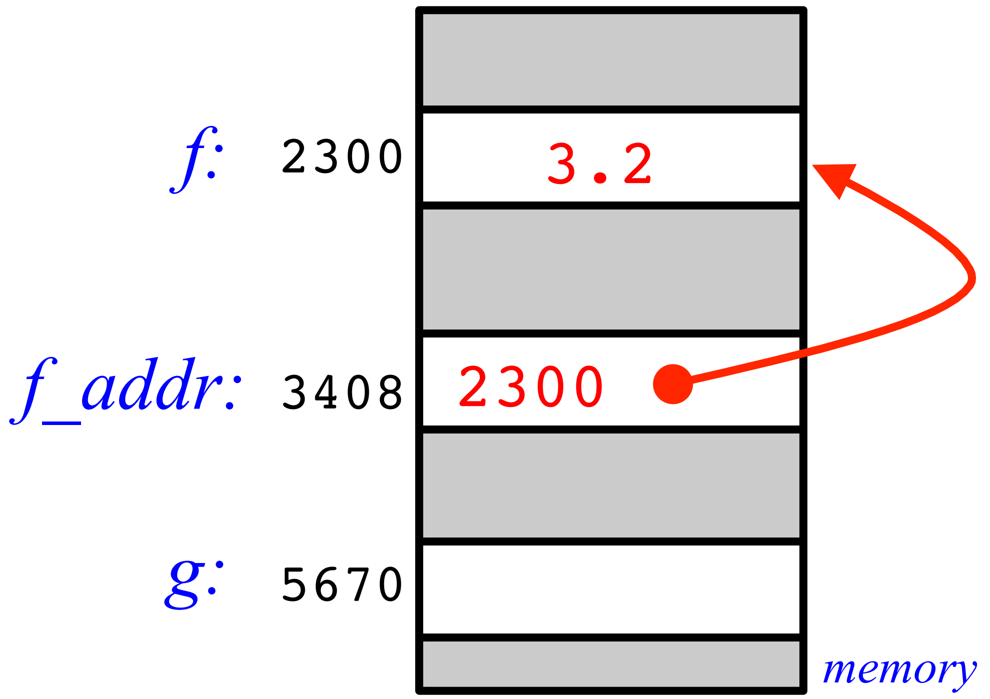

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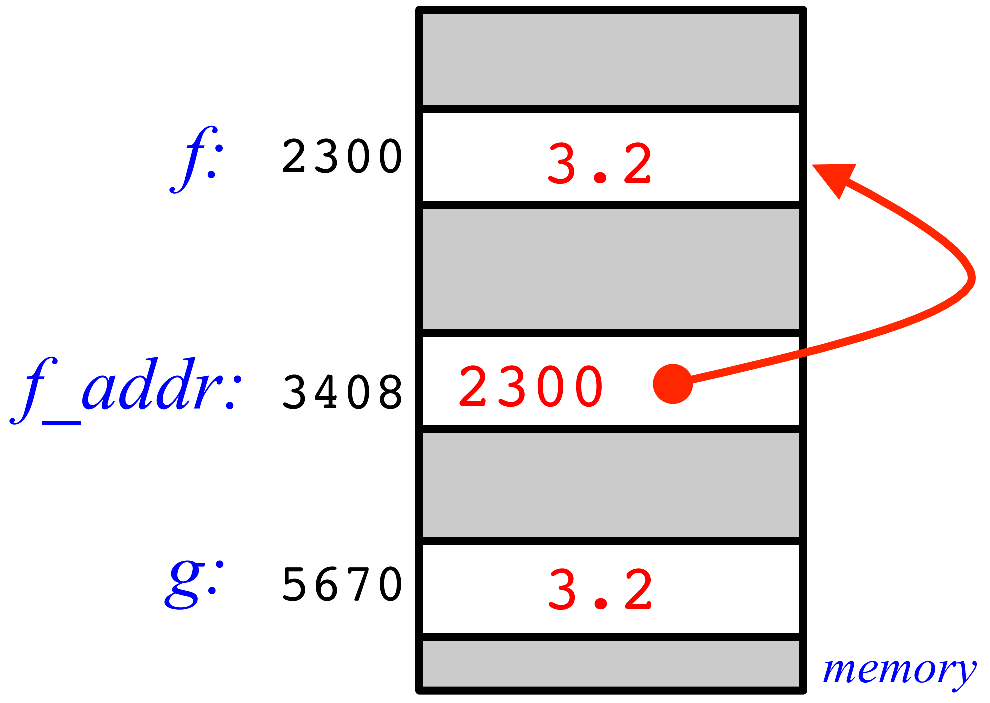

Using Pointers

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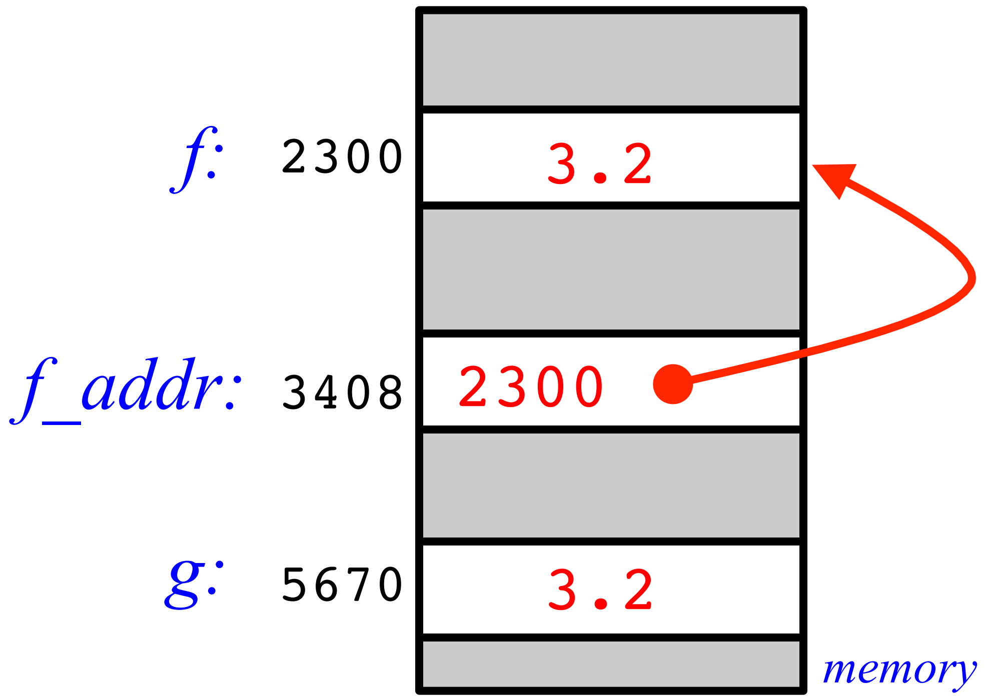
float *f_addr;          /* pointer variable */
f_addr = &f;            /* & = address operator */
*f_addr = 3.2;          /* indirection operator */
float g = *f_addr;  /* indirection: g is now 3.2 */
f = 1.78;               /* but g is still 3.2 */
```



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f_addr = &f;            /* & = address operator */
*f_addr = 3.2;          /* indirection operator */
float g = *f_addr;      /* indirection: g is now 3.2 */
f = 1.78;               /* but g is still 3.2 */
```
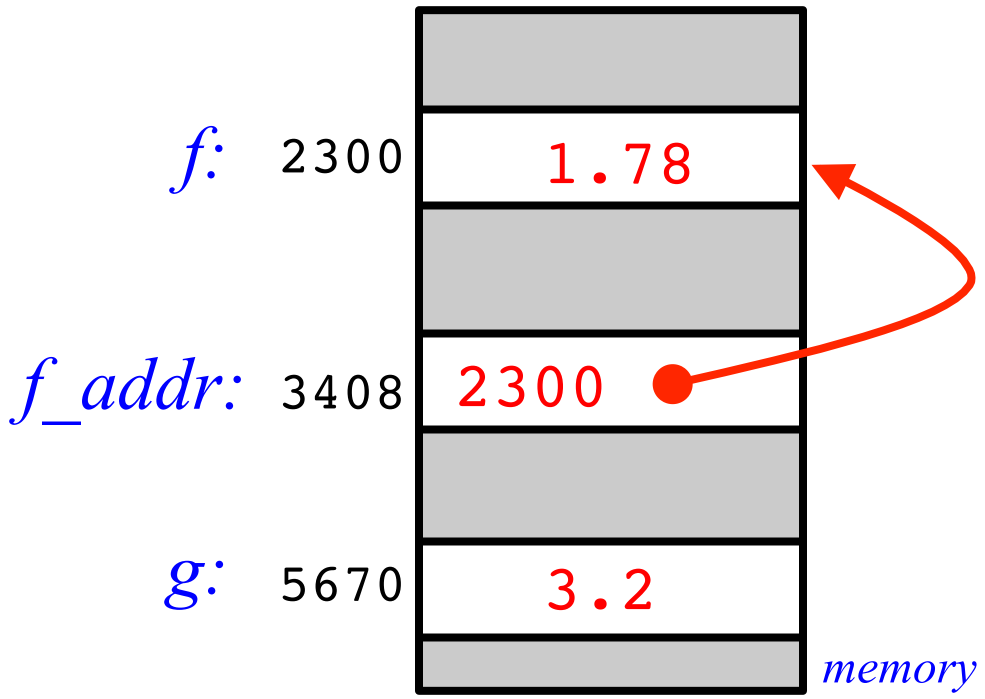
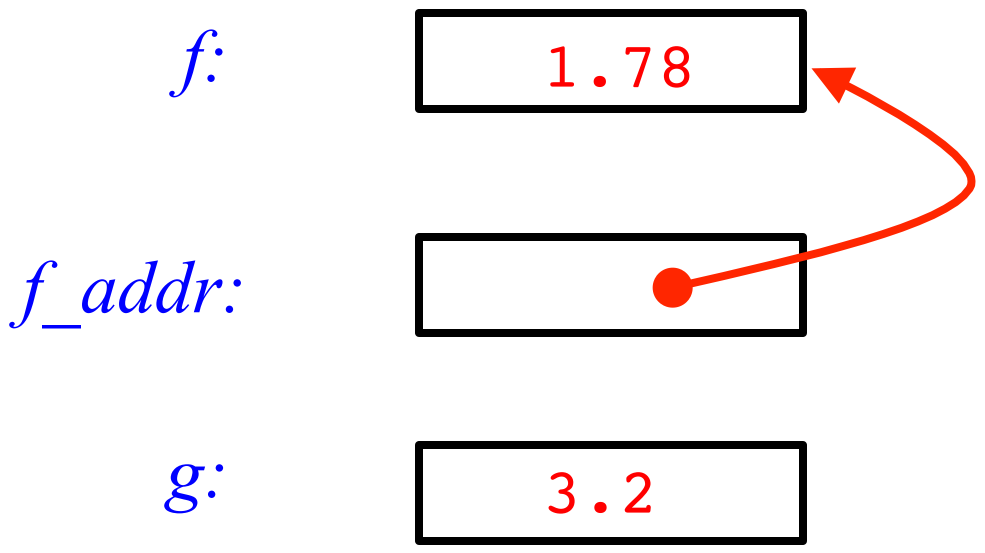



Using Pointers

```
float f;                /* data variable */
float *f_addr;          /* pointer variable */
f_addr = &f;            /* & = address operator */
*f_addr = 3.2;          /* indirection operator */
float g = *f_addr; /* indirection: g is now 3.2 */
f = 1.78;               /* but g is still 3.2 */
```



Arguments vs. Parameters

The caller / calling code

arguments (expressions)

```
x = 123;

w = foo (x*y, z, -1);

printf (…);
```

The callee / called function

parameters (variables)

```
int foo (int a, int b, int c) {

   …

   return (a+b+c);

}
```

Function call parameters

In C, all function arguments are passed “by value”.

“pass by value”

The called function is given a copy of the argument.

The data is copied from “caller” into the function.

Within the function, the parameter is a local variable.

Note:

The function can’t alter variables in the caller function!

Pass by Reference

What if you wish to modify an argument?

"pass by reference"

The called function is given a <u>pointer</u> to the argument.

The data is not copied.

Within the function, the original variable is modified.

Call-by-reference requires language support.

Call-by-reference is NOT SUPPORTED in "C"

… directly.

"C" has a mechanism that you can use:

Pointers!

In C all arguments are passed using "call-by-value."

You can achieve call-by-reference, but you must program it.

Example: Pass by Value

```
void swap1(int a, int b)
{
   int temp;
   temp = a;
   a = b;
   b = temp;
}
```

Before:

x=3 y=4

```
swap1(x,y);
```

After?

x=3 y=4

or

x=4 y=3

Example: Pass by Value

```
void swap1(int a, int b)
{
  int temp;
  temp = a;
  a = b;
  b = temp;
}
```

Before:

x=3 y=4

```
swap1(x,y);
```

After?

x=3 y=4

or

~~x=4 y=3~~

Example: Pass by Reference

```
void swap2(int *a, int *b)
{
   int temp;
   temp = *a;
   *a = *b;
   *b = temp;
}
```

Before:

x=3   y=4

```
swap2(&x,&y);
```

After?

x=3   y=4

or

x=4   y=3

Example: Pass by Reference

```
void swap2(int *a, int *b)
{
   int temp;
   temp = *a;
   *a = *b;
   *b = temp;
}
```

Before:

x=3 y=4

```
swap2(&x,&y);
```

After?

~~x=3 y=4~~

or

x=4 y=3

Pass by value

A copy is made of the argument.

Within the function…

- The parameter is a local variable.
- You can update it, but the orginal will be unchanged.

In C, all arguments are passed “by value”.

Pass by reference

The value is not copied.

A pointer to the argument is passed to the function.

Within the function…

- The original variable is modified.

You can implement “call-by-reference” using pointers.

(The pointers are passed by value.)

Function calls (static)

Calls to functions normally resolved statically

(“Static” means done at compile-time.)

```
void print_ints(int a, int b)  {
  printf(“%d %d\n”,a,b);
}

int main(int argc, char* argv[]) {
   int i=3;
   int j=4;
   print_ints(i,j);
}
```

Function calls (dynamic)

Using function pointers, C can support late-binding of functions where calls are determined at run-time

```c
#include <stdio.h>

void print_even(int i){ printf("Even %d\n",i);}
void print_odd (int i){ printf("Odd %d\n",i); }

int main(int argc, char **argv) {

    void (*fp)(int);

    if !(argc%2)
      fp=print_even;
    else
      fp=print_odd;

    fp(argc);
}
```

```
% ./funcp a
Even 2
% ./funcp a b
Odd 3
```