Integrating R and C/C++

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Introduction

- Background of participants, motivations
- Agenda
  - Day one
    - Linux/emacs basics
    - C hands-on tutorial
  - Day two
    - C wrap-up
    - C++ introduction
    - Calling C/C++ from R
    - Benchmarking, debugging, etc.
    - Rcpp, RcppArmadillo, RcppBUGS, etc.
    - Applications

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Introduction to programming in C: Goals

- To write simple C programs
- To understand and modify existing C code
- To write and use makefiles

C History

- Developed by Dennis Ritchie at Bell Labs in 1969-73
  - Originally designed for system software
  - Impetus was porting of Unix to a DEC PDP-11
    - PDP-11 had 24kB main memory!
- See The C Programming Language by Kernighan & Ritchie (2nd ed.) (aka "K & R")
- Official ANSI standard published in 1989
  - Updated in 1999
- C++ (1983)
  - Author: Bjarne Stroustrup (Bell Labs), 1979, "C with classes"
  - More later…

Compiled vs. Interpreted Languages

- Interpreted languages
  - when you type something, e.g., “x=y+z”, it is immediately parsed, converted to machine language, and executed
  - examples: R, MATLAB, Python
  - advantage
    - interactive, allows fast development
  - disadvantage
    - generally uses more CPU/memory/time for given task

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Compiled (cont'd)

- Compiled languages
  - examples: C, C++, Fortran
  - **source code** must be processed through a **compiler**
    - checks for correct **syntax** and **semantics**
    - translates source code into **assembly**, then assembles (or calls assembler) to produce **machine** code
    - passes machine code to linker, which creates **executable**
      - this is the file that you actually run
      - example: .exe file in Windows
      - default name in Unix/Linux: a.out

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Variables

- Variables are **declared** to have a certain **type**.
- Common types include:
  - int
    - “integer”
      - number with no decimal places: -56,   857436
  - float, double
    - “floating-point”
      - number with decimal: 1.234, 4.0,   7.
    - float: single precision, 32 bits*, ~7 significant digits
    - double: double precision, 64 bits*, ~16 significant digits

*on most computers

Variables (cont'd)

- char
  - "character"
  - enclosed in *single* quotes
  - 'x',   '$'
  - *character string* is string of chars enclosed in *double* quotes
    - "This is a character string."

Syntax

- C is case-sensitive
- Spaces, linefeeds, etc., don't matter except within character strings.
- Source lines end with semicolons (optional in R)
- Comments
  - notes for humans that are ignored by the compiler
  - C: enclosed by /* */
  - C++: // at beginning of comment
    - many C compilers also accept this syntax
  - Official advice: use them liberally (so you can still understand your program next year [or next week, depending on your age])

Functions

- (As in R), source code largely consists of **functions**
  - each one performs some task
  - you write some of them
  - some are supplied, typically in libraries
- every code contains at least one function, called **main**
- functions often, though not always, return a value, e.g.:
  - int, float, char, etc.
  - default return value is int
  - To explicit about returning no value, declare as void

Functions (cont'd)

- functions may, but do not have to, take arguments
  - "arguments" are inputs to the function
    - e.g., y = sin(x)
- code blocks, including entire functions, are enclosed within "curly brackets" { }
- main function is defined in source code as follows:

type declaration function name function arguments (we [currently]have no arguments here but still need parentheses)

```
int main( ) {
   function statements
}
```

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Functions (3)

- Style note: some people like to arrange the brackets like

```
int main( )
{
    function statements
}
```

- Either way is fine
  - Friendly advice: be consistent!
- Emacs advertisement: a good editor can do automatic indentation, help you find matching brackets, etc.

How to say “hello, world”: printf

- printf is a function, part of C’s standard input/output library, that is used to direct output to the screen, e.g.,

  printf(“my string”);

- The above syntax does not include a line feed. We can add one with:

  printf(“my string\n”);

  where \n is a special character representing LF

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printf and stdio.h

- Some program elements, such as library functions like printf, are declared in **header files**, aka “include files.”
- Syntax:

  #include <*stdio.h*> or

  #include “*stdio.h*”
- The contents of the named file are presented to the compiler as if you had placed them directly in your source file. In the case of printf, stdio.h informs the compiler about the arguments it takes, so the compiler can raise a warning or error if printf is called incorrectly. More will be said about this later.

Exercise 1

- Write a “hello, world” program in an editor
- Program should print a character string
- General structure of code, in order:
  - include the file “stdio.h”
  - define main function
  - use printf to print string to screen
- Save it to the file name hello.c
- solution

Compilation

- A compiler is a program that reads source code and converts it to a form usable by the computer/CPU, i.e., machine code
- Code compiled for a given type of processor will not generally run on other types
    - AMD and Intel are compatible
- We'll use gcc, since it's free and readily available

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Compilation (cont'd)

- Compilers have numerous options
  - Try 'man gcc', or see gcc compiler documentation at http://gcc.gnu.org/onlinedocs/
  - gcc refers to the "GNU compiler collection," which includes the C compiler (gcc) and the C++ compiler (g++)
- For now, we will simply use the –o option, which allows you to specify the name of the resulting executable

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Compilation (3)

- In a Unix window:

  gcc –o hello hello.c

  - “hello” is name of executable file (compiler output)
  - “hello.c” is source file name (compiler input)
- Compile your code
- If it simply returns a Unix prompt it worked
- If you get error messages, read them carefully and see if you can fix the source code and re-compile

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Compilation (4)

- Once it compiles correctly, type the name of the executable

```
./hello
```

  at the Unix prompt, and it will run the program
  - should print the string to the screen

Declarations

- different variable types have different internal representations, so CPUs use different machine instructions for int, float, etc.
- must tell compiler the type of every variable by *declaring* them
- example declarations:

```
int  i,  jmax,  k_value;
float  xval,  elapsed_time;
char  aletter, bletter;
```

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Arithmetic

- +, -, *, /
  - No power operator (see next bullet)
- Math functions declared in math.h
  - pow(x,y) raises x to the y power
  - sin, acos, tanh, exp, sqrt, etc.
  - for some compilers, need to add –lm flag (that's a small el) to compile command to link against math library
- Exponential notation indicated by letter "e"

  4.2×10^3 4.2e3

- Good practice to use decimal points with floats, e.g.,

  x = 1.0   rather than   x = 1

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Arithmetic (cont'd)

- Computer math
  - Value of variable on left of equals sign is replaced by value of expression on right
  - Many legal statements are algebraically nonsensical, e.g.,

    i = i + 1;

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Arithmetic (cont'd)

- ++ and -- operators
  - these are equivalent:

```
i = i+1;
i++;
```

  - always increments/decrements by 1
- +=
  - these are equivalent:

```
x = x + 46.3*y;
x += 46.3*y;
```

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Arithmetic (3)

- Pure integer arithmetic *truncates* result!

```
5/2 = 2
2/5 = 0
```

- Can convert types with *cast* operator

```
float xval;
int i, j;
xval = (float) i / (float) j;
```

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A Little More About printf

- To print a value (as opposed to a literal string), must specify a format
- For now we will use %f for a float and %d for an int
- Here’s an example of the syntax:

```
printf(“My integer value is %d and my float value is %f \n”, ival, fval);
```

- The values listed at the end of the printf statement will be embedded at the locations of their respective formats.

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Exercise 2

- Write program to convert Celcius temperature to Fahrenheit and print the result.
  - Hard-wire the Celcius value to 100.0
    - We'll make it an input value in a subsequent exercise
  - Don't forget to declare all variables
  - Here's the equation:

$$F = (9/5)C + 32$$

- solution

Address-of Operator

- Every variable has an address in which it is stored in memory
- In C, we sometimes need to access the address of a variable rather than its value
  - Will go into more details when we discuss pointers
- Address-of operator & returns address of specified variable
  - &ival returns the address of the variable ival
  - rarely need to know actual value of address, just need to use it

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scanf

- reads from keyboard
- 2 arguments
  - character string describing format
  - address of variable
- must include stdio.h
- example

```
int ival;
scanf("%d", &ival);
```

Exercise 3

- Modify Celcius program to read value from keyboard
  - Prompt for Celcius value using printf
  - Read value using scanf
  - Rest can remain the same as last exercise
- solution

Arrays

- Declare arrays using [ ]

  ```
  float  x[100];
  char  a[25];
  ```

- Array indices start at 0 (not 1, as in R)
  - Declaration of x above creates locations for x[0] through x[99]
- Multiple-dimensional arrays are declared as follows:

  ```
  int  a[10][20];
  ```

  - Note: In C, the last axis varies fastest; we say that C stores arrays in "row-major" order. R, on the other hand, stores arrays in "column-major" order.

For Loop

- for loop repeats calculation over range of indices

```
for(i=0;  i<n;  i++) {
        a[i] = sqrt( pow(b[i],2)  +  pow(c[i],2)  );
}
```

- for statement has 3 parts:
    - initialization
    - completion condition (i.e., if true, keep looping)
    - what to do *after* each iteration

Exercise 4

- Write program to:
  - declare two float vectors of length 3
  - prompt for first vector and read values
  - prompt for second vector and read values
  - calculate dot product
  - print the result

$$c = \sum_{i=1}^{3} a_i \times b_i$$

- Solution
- Possible to use “redirection of standard input” to avoid retyping each time:
  - % echo 1 2 3 4 5 6 | dotprod

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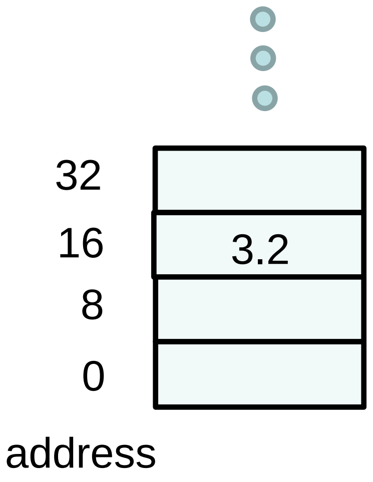
Pointers

- When you declare a variable, a location of appropriate size is reserved in memory
- When you do an assignment, the value is placed in that memory location

```
double  x;
x = 3.2;
```



Pointers (cont.)

- A pointer is a variable containing a memory *address*
- Declared using *

```
double *p;
```

- Often used in conjunction with address-of operator &

```
double x, *p;
p = &x;
```

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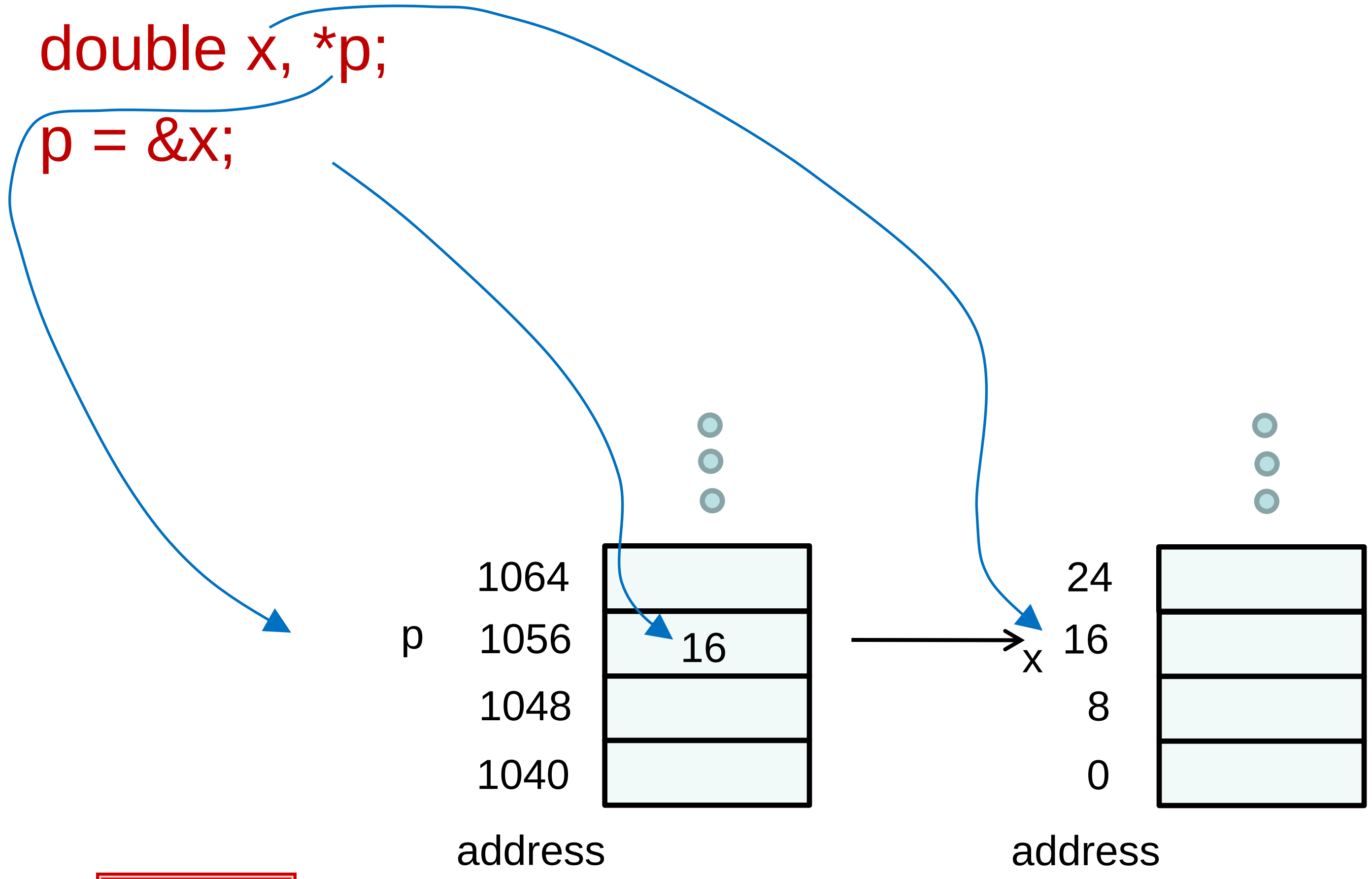
Pointers (3)

```
double x, *p;
p = &x;
```



Pointers (4)

- Depending on context, * can also be the *dereferencing operator*
  - Value stored in memory location pointed to by specified pointer

```
*p = 3.2;
```

- Common error

```
double *p;
*p = 3.2;
```

Wrong! – p doesn’t have value yet

```
double x, *p;
p = &x;
*p = 3.2;
```

correct

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Pointers (5)

- The name of an array is actually a pointer to the memory location of the first element
  - a[100]
  - “a” is a pointer to the first element of the array (a[0])
- These are equivalent:

```
x[0] = 4.53;
*x = 4.53;
```

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Pointers (6)

- If p is a pointer and n is an integer, the syntax p+n means to advance the pointer by n *locations**
- These are therefore equivalent:

```
x[4] = 4.53;
*(x+4) = 4.53;
```

*i.e., for most machines, 4*n bytes for an int, and 8*n bytes for a double

Pointers (7)

- In multi-dimensional arrays, values are stored in memory with *last* index varying most rapidly
  (a[0][0], a[0][1], a[0][2], …)
  - Opposite of R, MATLAB, et al.
- The two statements in each box are equivalent for an array declared as int a[5][5]:

```
a[0][3] = 7;
*(a+3) = 7;
```

```
a[1][0] = 7;
 *(a+5) = 7;
```

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sizeof

- Some functions require size of something in bytes
- A useful function – sizeof(*arg*)
  - The argument *arg* can be a variable, an array name, a type
  - Returns no. bytes in arg

```
double x, y[5];
sizeof(x)                ( 8)
sizeof(y)                (40)
sizeof(double)           ( 8)
```

Dynamic Allocation

- Suppose you need an array, but you don’t know how big it needs to be until run time.
- Tried and true method - use malloc function:

  malloc(*n*)

  - n is no. *bytes* to be allocated
  - returns pointer to allocated space
  - declared in stdlib.h
- Many C compilers now accept “float f[n]”, where ‘n’ is determined at runtime.

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Dynamic Allocation (cont'd)

- Declare pointer of required type

  float *myarray;
- Suppose we need 101 elements in array:
  - myarray = malloc(101*sizeof(float));
- free releases space when it's no longer needed:

  free(myarray);

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Exercise 5

- Modify dot-product program to handle vectors of any length
  - Prompt for length of vectors (printf)
  - Read length of vectors from screen (scanf)
  - Dynamically allocate vectors (malloc)
  - Prompt for and read vectors (printf, scanf)
    - use for loop
  - Don’t forget to include stdlib.h so you have access to the malloc function declaration
- solution

if/else

- Conditional execution of block of source code
- Based on relational operators

<	less than
>	greater than
==	equal
<=	less than or equal
>=	greater than or equal
!=	not equal
&&	and
||	or

if/else (cont'd)

- Condition is enclosed in parentheses
- Code block is enclosed in curly brackets

```
if( x > 0.0  && y > 0.0 ) {
    printf("x and y are both positive\n");
    z = x + y;
}
```

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if/else (3)

- Can have multiple conditions by using else if

```
if( x > 0.0  && y > 0.0 ) {
    z = 1.0/(x+y);
} else if( x < 0.0  &&  y < 0.0 ) {
    z = -1.0/(x+y);
} else {
    printf(“Error condition\n”);
}
```

Exercise 6

- In dot product code, check if the magnitude of the dot product is less than 10^{-6} using the absolute value function fabsf. If it is, print a warning message.
  - With some compilers you need to include math.h for the fabsf function. You should include it to be safe.
  - With some compilers you would need to link to the math library by adding the flag –lm to the end of your compile/link command.
- solution

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Functions

- C functions return a single value
- Return type should be declared (default is int)
- Argument types must be declared
- Sample function *definition*:

```
float sumsqr(float x, float y) {
    float z;
    z = x*x + y*y;
    return z;
}
```

Functions (cont'd)

- Use of sumsqr function:

  ```
  a = sumsqr(b,c);
  ```
- Call by *value*
  - when function is called, copies are made of the arguments
  - scope of copies is scope of function
    - after return from function, copies no longer exist

Functions (3)

```
b = 2.0;  c = 3.0;
a = sumsqr(b, c);
printf("%f", b);        ←——  will print 2.0

float sumsqr(float x, float y) {
    float z;
    z = x*x + y*y;
    x = 1938.6;         ←——  this line has no effect on b
    return z;
}
```

Functions (4)

- If you want to change argument values, pass pointers

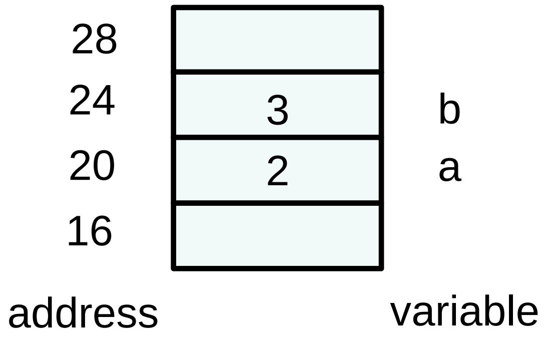
```
int swap(int *i,  int *j) {
    int k;
    k = *i;
    *i = *j;
    *j = k;
    return 0;
}
```

Functions (5)

- Let's examine the following code fragment:

```
int a, b;
a = 2;  b = 3;
swap(&a, &b);
```

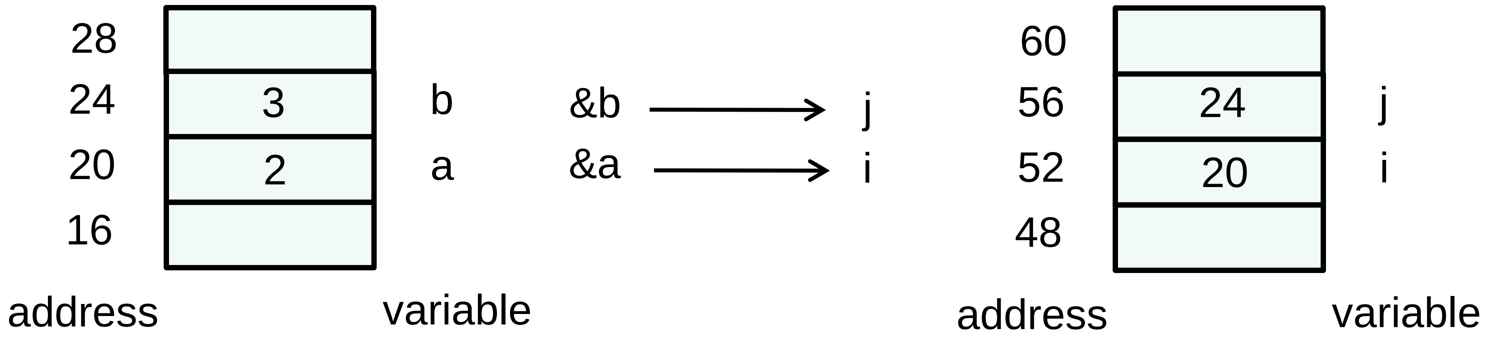
- Memory after setting values of a and b



Functions (6)

- When function is called, copies of arguments are created in memory

swap(&a, &b); ⟶ int swap(int *i, int *j){ ... }



- i, j are pointers to ints with values &a and &b

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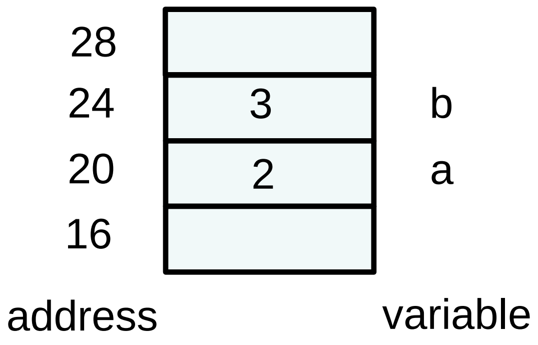
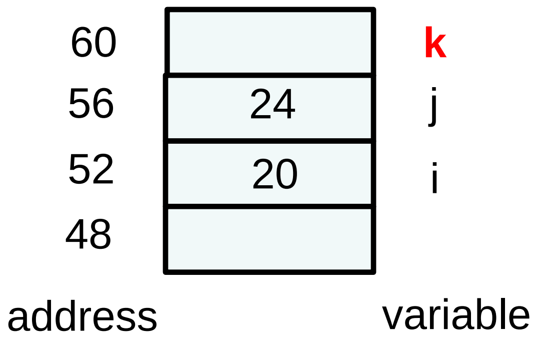
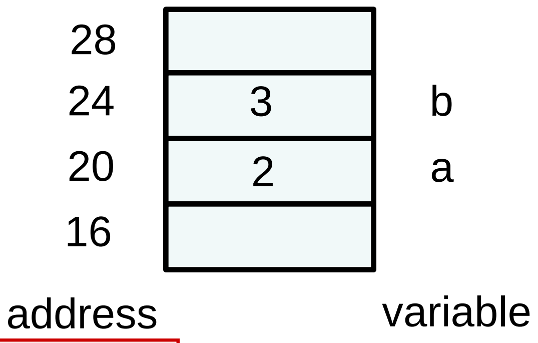
Functions (7)

- What happens to memory for each line in the function?

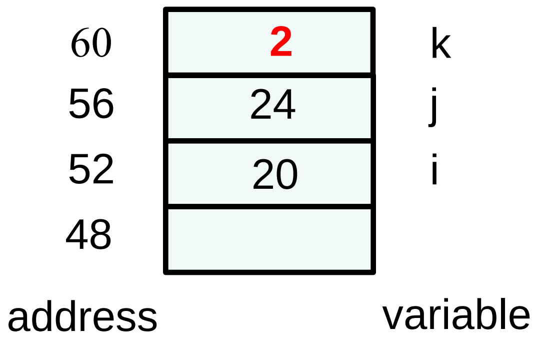


int k;





k = *i;



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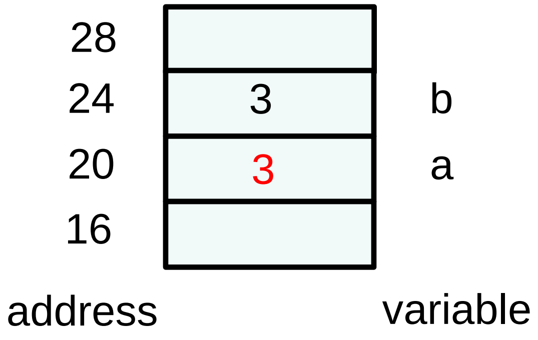
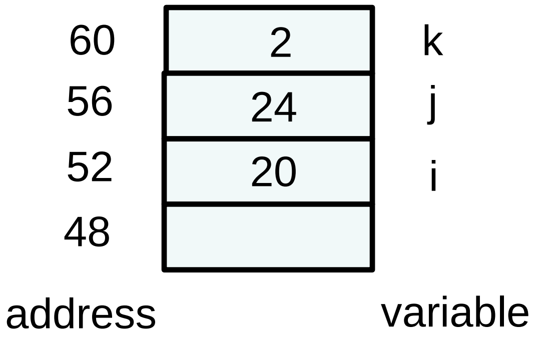
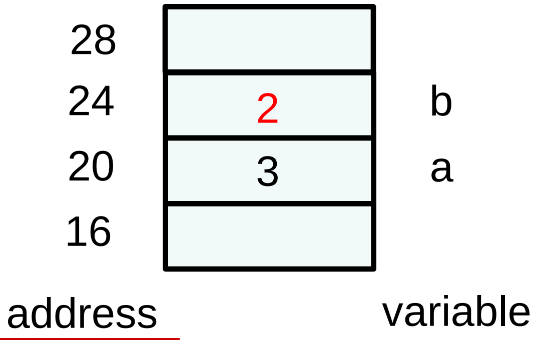
Functions (8)

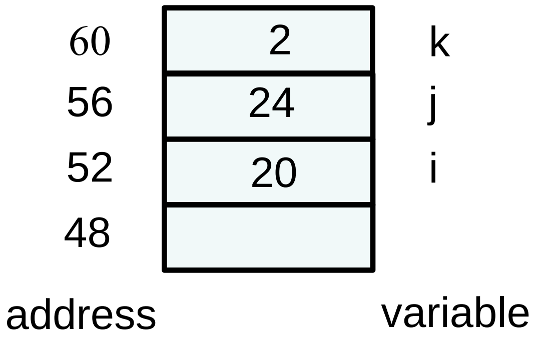


*i = *j;

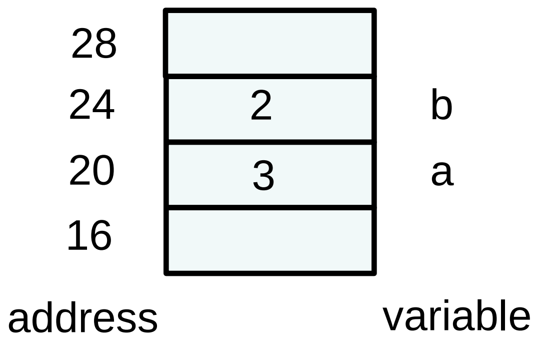




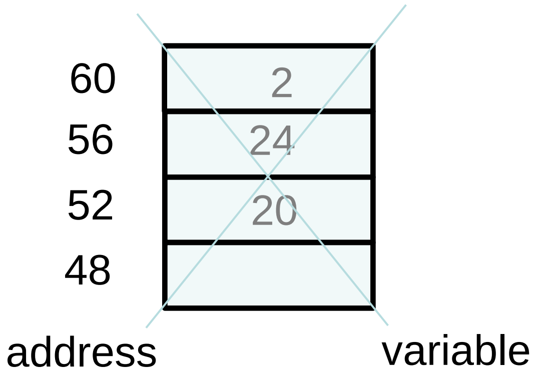
*j = k;



Functions (9)



return 0;



Exercise 7

- Modify dot-product program to use a function to compute the dot product
  - The function definition should go after the includes but *before* the main program in the source file
  - Arguments can be an integer containing the length of the vectors and a pointer to each vector
  - Function should only do dot product, no i/o
  - Do not give function same name as executable
    - I called my executable “dotprod” and the function “dp”
- solution

Function Prototypes

- C compiler checks arguments in function definition and calls
  - number
  - type
- If definition and call are in different *files*, compiler needs more information to perform checks
  - this is done through *function prototypes*

Function Prototypes (cont'd)

- Prototype looks like 1st line of function definition
  - type
  - name
  - argument types

```
float dp(int n,  float *x,  float *y);
```

- Argument names are optional:

```
float dp(int,  float*,  float*);
```

Function Prototypes (3)

- Prototypes are often contained in include files

```
/* mycode.h contains prototype for myfunc */
#include "mycode.h"
int main(){
…
myfunc(x);
…
}
```

Basics of Code Management

- Large codes usually consist of multiple files
- Some programmers create a separate file for each function
  - Easier to edit
  - Can recompile one function at a time
- Files can be compiled, but not linked, using –c option; then object files can be linked later

```
gcc –c mycode.c
gcc –c myfunc.c
gcc –o mycode mycode.o myfunc.o
```

Exercise 8

- Put dot-product function and main program in separate files
- Create header file
  - function prototype
  - .h suffix
  - include at top of file containing main
- Compile, link, and run
- solution

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Makefiles

- make is a Unix utility to help manage codes
- When you make changes to files, it will
  - automatically deduce which files have been modified and compile them
  - link latest object files
- *Makefile* is a file that tells the *make* utility what to do
- Default name of file is “makefile” or “Makefile”
  - Can use other names if you’d like

Makefiles (cont'd)

- Makefile contains different sections with different functions
  - The sections are *not* executed in order!
- Comment character is #
  - As with source code, use comments freely

Makefiles (3)

- Simple sample makefile

```
### suffix rule
.SUFFIXES:
.SUFFIXES: .c .o
.c.o:
        gcc  -c   $*.c

### compile and link
myexe:  mymain.o   fun1.o   fun2.o   fun3.o
        gcc   –o    myexe   mymain.o   fun1.o   fun2.o   fun3.o
```

Makefiles (4)

- Have to define all file suffixes that may be encountered

```
.SUFFIXES:  .c  .o
```

- Just to be safe, delete any default suffixes first with a null .SUFFIXES: command

```
.SUFFIXES:
.SUFFIXES:  .c  .o
```

Makefiles (5)

- Have to tell how to create one file suffix from another with a *suffix rule*

```
.c.o:
	gcc  -c  $*.c
```

- The first line indicates that the rule tells how to create a .o file from a .c file
- The second line tells *how* to create the .o file
- *$ is automatically the root of the file name
- The big space before gcc is a tab, and you must use it!

Makefiles (6)

- Finally, everything falls together with the definition of a *rule*

```
target:  prerequisites
                recipe
```

- The target is any name you choose
  - Often use name of executable
- Prerequisites are files that are required by other files
  - e.g., executable requires object files
- Recipe tells what you want the makefile to do
- May have multiple targets in a makefile

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Makefiles (7)

- Revisit sample makefile

```
### suffix rule
.SUFFIXES:
.SUFFIXES: .c .o
.c.o:
        gcc -c $*.c

### compile and link
myexe: mymain.o fun1.o fun2.o fun3.o
        gcc –o myexe mymain.o fun1.o fun2.o fun3.o
```

automatic variable for file root

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Makefiles (8)

- When you type “make,” it will look for a file called “makefile” or “Makefile”
- searches for the first target in the file
- In our example (and the usual case) the object files are prerequisites
- checks suffix rule to see how to create an object file
- In our case, it sees that .o files depend on .c files
- checks time stamps on the associated .o and .c files to see if the .c is newer
- If the .c file is newer it performs the suffix rule
  - In our case, compiles the routine

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Makefiles (9)

- Once all the prerequisites are updated as required, it performs the recipe
- In our case it links the object files and creates our executable
- Many makefiles have an additional target, “clean,” that removes .o and other files

```
clean:
        rm  –f  *.o
```

- When there are multiple targets, specify desired target as argument to make command

```
make clean
```

Makefiles (10)

- Also may want to set up dependencies for header files
  - When header file is changed, files that include it will automatically recompile
- example:

```
myfunction.o:  myincludefile.h
```

  - if time stamp on .h file is newer than .o file and .o file is required in another dependency, will recompile myfunction.c
  - no recipe is required

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Exercise 9a

- Create a makefile for your dot product code
- Include 2 targets
  - create executable
  - clean
- Include header dependency (see previous slide)
- Delete old object files and executable manually
  - **rm *.o dotprod**
- Build your code using the makefile
- solution

Exercise 9b

- Type **make** again
  - should get message that it's already up to date
- Clean files by typing **make clean**
  - Type **ls** to make sure files are gone
- Type **make** again
  - will rebuild code
- Update time stamp on header file
  - **touch dp.h**
- Type **make** again
  - should recompile main program, but not dot product function

C Preprocessor

- Initial processing phase before compilation
- Directives start with #
- We’ve seen one directive already, #include
  - simply includes specified file in place of directive
- Another common directive is #define

  #define *NAME text*
  - *NAME* is any name you want to use
  - *text* is the text that replaces *NAME* wherever it appears in source code

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C Preprocessor (cont’d)

- #define often used to define global constants

```
#define NX   51
#define NY 201
…
float x[NX][NY];
```

- Also handy to specify precision

```
#define REAL double
…
REAL x, y;
```

C Preprocessor (3)

- Can also check values using the #if directive
- In the current exercise code, the function fabsf is used, but that is for floats. For doubles, the function is fabs. We can add this to dp.h file:

```
#if REAL == double
#define ABS fabs
#else
#define ABS fabsf
#endif
```

C Preprocessor (4)

- scanf format
  - “%f” for 4-byte floats
  - “%lf” (long float) for 8-byte floats
- Can also use a directive for this:

```
#if REAL == double
#define SCANFORMAT “%lf”
#else
#define SCANFORMAT “%f”
#endif
```

C Preprocessor (5)

- #define can also be used to define a macro with substitutable arguments

  ```
  #define  ind(m,n)   (n + NY*m)
  k = 5*ind(i,j);  ⟶  k = 5*(i + NY*j);
  ```

- Be careful to use ( ) when required!
  - without ( ) above example would come out wrong

  ```
                   ⟶  k = 5*i + NY*j
  ```

  } wrong!

Exercise 10

- Modify dot-product code to use preprocessor directives to declare double-precision floats
  - Add directives to header file to define REAL as shown in “C Preprocessor (cont’d.)”
  - Add directives to header file to choose ABS as shown in “C Preprocessor (3)”
  - Add directives to header file to choose SCANFORMAT as shown in “C Preprocessor (4)”
  - Change **all** occurrences of float to REAL in dotprod.c, dp.c, and dp.h
  - Change fabsf to ABS in main routine
  - Change “%f” (including quotes) to SCANFORMAT in main
  - Include math.h in main program if you have not already done so
  - Include dp.h in function dp.c (for definition of REAL)
- solution

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Structures

- Can package a number of variables under one name

```
struct grid{
   int nvals;
   float x[100][100], y[100][100], jacobian[100][100];
};
```

- Note semicolon at end of definition

Structures (cont'd)

- To declare a variable as a struct

```
struct  grid  mygrid1;
```

- Components are accessed using **.**

```
mygrid1.nvals = 20;
mygrid1.x[0][0] = 0.0;
```

- Handy way to transfer lots of data to a function

```
int  calc_jacobian(struct  grid  mygrid1){…
```

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Exercise 11

- Define struct *rvec* with 2 components in your header file (.h)
  - vector length (int)
  - pointer to REAL vector
- Modify dot-product code to use *rvec* structure
- solution

i/o

- Often need to read/write data from/to files rather than screen
- File is associated with a *file pointer* through a call to the fopen function
- File pointer is of type FILE, which is defined in stdio.h.

i/o (cont'd)

- fopen takes 2 character-string arguments
  - file name
  - mode
    - "r" read
    - "w" write
    - "a" append

```
FILE *fp;
fp = fopen("myfile.d", "w");
```

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i/o (3)

- Write to file using fprintf
  - Need stdio.h
- fprintf has 3 arguments
  1. File pointer
  2. Character string containing what to print, including any formats
     - %f for float or double
     - %d for int
     - %s for character string
  3. Variable list corresponding to formats

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i/o (4)

- Special character \n produces new line (carriage return & line feed)
  - Often used in character strings

  “This is my character string.\n”
- Example:

  fprintf(fp, “x = %f\n”, x);
- Read from file using fscanf
  - arguments same as fprintf
- When finished accessing file, close it

  fclose(fp);

Exercise 12

- Modify dot-product code to write the dot-product result to a file
- If magnitude is small, still write message to screen rather than file
- After result is written to file, write message “Output written to file” to screen.
- solution

Binary i/o

- Binary data require *much* less disk space than ascii (formatted) data
- Use “b” suffix on mode

```
fp = fopen(“myfile.d”, “wb”);
```

- Use fwrite, fread functions

```
float x[100];
fwrite( x,      sizeof(float),     100,       fp )
         ↗            ↑              ↗         ↖
pointer to      no. bytes in      max. no. of    file pointer
1st element     each element      elements
```

  - Note that there is no format specification
    - We’re strictly writing data

Exercise 13

- Modify dot-product program to:
  - Write result to binary file
    - just write value, not character string
  - After file is closed, open it back up and read and print result to make sure that it wrote/read correctly
    - don’t forget to open file with “rb” rather than “wb”
- solution

Command-Line Arguments

- It’s often convenient to type some inputs on the command line along with the executable name, e.g.,

  mycode   41.3 “myfile.d”

- Define *main* with two arguments:

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

  1. argc is the number of items on the command line, *including name of executable*
     - “argument count”
  2. argv is an array of character strings containing the arguments
     - “argument values”
     - argc[0] is pointer to executable name
     - argc[1] is pointer to 1st argument, argc[2] is pointer to 2nd argument, etc.

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Command-Line Arguments (cont'd)

- Arguments are character strings, often want to convert them to numbers
- Some handy functions:
  - atoi converts string to integer
  - atof converts string to *double*
    - To convert to float, recast result of atof
  - They live in stdlib.h
  - arguments are pointers to strings, so you would use, for example

    ival = atoi(argv[2])

    to convert the 2nd argument to an integer

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Command-Line Arguments (3)

- Often want to check the value of argc to make sure the correct number of command-line arguments were provided
- If wrong number of arguments, can stop execution with exit statement
  - Can exit with status, e.g.:

    ```
    exit(1);
    ```
  - With bash shell, view status by echoing '$?':

    -
      ```
      $ echo $?
      1
      ```

Exercise 14

- Modify dot-product code to enter the vector length as a command-line argument rather than prompting for it
- Use atoi
- Add test on argc to make sure a command-line argument was provided
  - argc should equal 2, since the executable name counts
  - if argc is not equal to 2, print message and return to stop execution
- solution

References

- Lots of books available
  - Kernighan & Ritchie, “The C Programming Language”
- gcc
  http://gcc.gnu.org/onlinedocs/gcc-4.5.1/gcc/
- If you’d like to move on to C++
  - Good C++ book for scientists:
    - Barton and Nackman, “Scientific and Engineering C++”
  - Quick and dirty C++ book:
    - Liberty, “Teach Yourself C++ in 21 Days”

Survey

- Please fill out the course survey at

http://scv.bu.edu/survey/tutorial_evaluation.html