CSC 4304 - Systems Programming
Fall 2008

Lecture - XIV

Makefiles & Libraries

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Splitting C Programs into Multiple Files

- All our programs so far are written in a single file
- But programs can be very big!
  - E.g., Linux-2.6.0 contains **5,929,913 lines of C code**
- Let's split our programs into multiple source files
  - Easier to write and update
  - Especially with multiple programmers
    - Each programmer writes into his/her own file
  - It is easier to recompile
    - If you change a small part of the program, you can recompile just the part that has changed

Modular C Programming

- A C program usually contains:
  - Multiple `.c` files: contain the functions and global variables
  - Multiple `.h` files: contain **declarations** of functions, types and variables
- Unlike in Java, you can put as many functions/variables/types per file as you want
  - It is up to you to organize everything
  - ☞ But there are general rules that will help you...
  - Most important: keep related things in a single file

Definition vs Declaration

- A **definition** actually creates a function/variable and gives it a value
  - *"From now on, variable foo of type `int` will be created"*
  - *"From now on, function `baz()` will have the following prototype and realize the following operations."*

```
int foo;

double baz(double x, double y) {
  return x*x + y*y;
}
```

- A **declaration** simply informs the compiler that something does exist
  - "**Trust me, it will be defined somewhere else**"

```
extern int foo;

double baz(double, double);  /* no function code here! */
```

Calling an External Function

- If you want to call a function in a piece of code, you must first declare the **prototype** of the function
  - You do not need to write the full code of the function
  - A prototype (i.e., interface) is enough
  - Of course, the code of the function must be present in another file of the program!

```
int this_func_is_defined_somewhere_else(char *);

int foo() {
  return this_func_is_defined_somewhere_else("foo");
}
```

- A function must be **defined** only once in a program
  - Otherwise the compiler wouldn't know which one to use
- But it can be **declared** any number of times
  - Provided all declaration are the same...

Using an External Variable

- To use a (global) variable defined in another file you must first **declare** it
  - Attention: you must **define** the variable only **once**

```
/* file1.c */

extern int my_variable;  /* the variable is declared but not defined */

int foo() {
  return my_variable++;
}
```

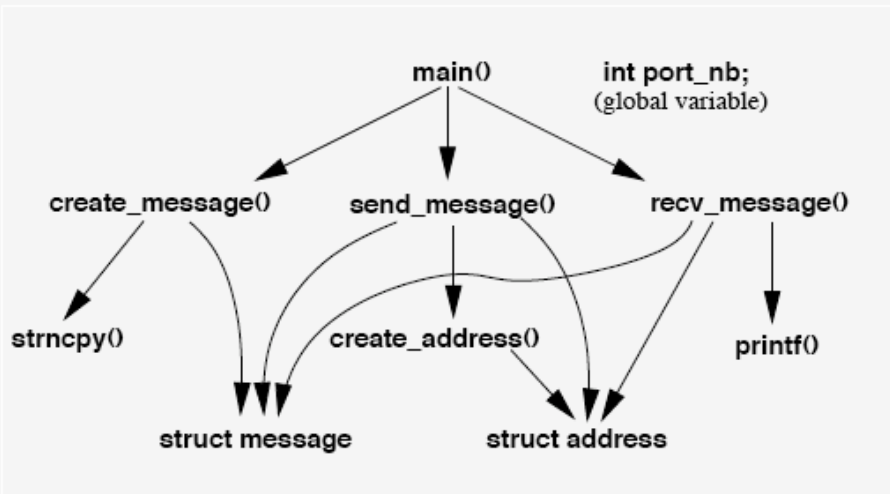
```
/* file2.c */

int my_variable;  /* the variable is declared and defined here */
```

Using Header Files

- Some informations must be present in multiple files
  - Better to write them only once in a "header" file
  - And **include** the header file wherever it is needed
- Header files (`*.h`) should contain:
  - Function prototypes
  - Type declaration
  - Global variable declarations (but not definitions!)
- C files (`*.c`) should contain:
  - `#include <standard_files.h>`
    - Includes files from `/usr/include`, `/usr/local/include` etc.
  - `#include "header_files.h"`
    - Includes files from the working directory
  - Function code (definitions)
  - Global variable (definitions)
- Each C file usually has its corresponding header file...

Example

- A program that exchanges messages across a network



Example

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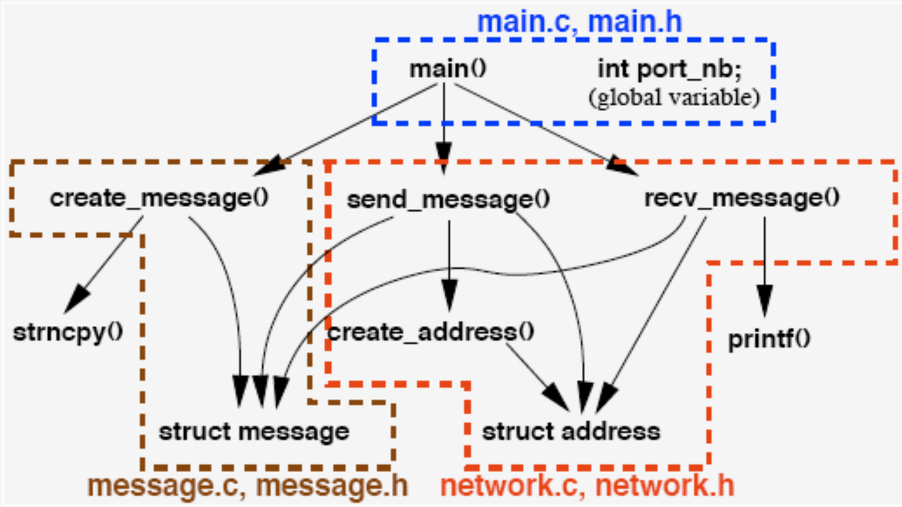

message.h

- message.h contains:
  - The declaration of struct message
  - The declaration of function create_message()

```
#ifndef _MESSAGE_H_
#define _MESSAGE_H_

struct message {
   char buf[1024];
   int  length;
};

struct message *create_message(char *message);

#endif /* _MESSAGE_H_ */
```

message.c

- message.c:
  - Includes standard header files string.h and stdlib.h (they contain the prototypes of strncpy and malloc)
  - Includes header file message.h (it contains the declaration of struct message)
  - Defines function create_message

```
#include <string.h>
#include <stdlib.h>
#include "message.h"

struct message *create_message(char *message) {
   struct message *m = (struct message *) malloc(sizeof(struct message));
   strncpy(m->buf, 1023);
   return m;
}
```


network.h

```
#ifndef _NETWORK_H_
#define _NETWORK_H_

#include "message.h"  /* Why is this required? */

struct address {
   char ip[16];
   int  port;
};

struct address *create_address(char *ip);
int send_message(struct message *m, struct address *dest);
int recv_message(struct message *m, struct address *from);

#endif /* _NETWORK_H_ */
```

network.c

```
#include "network.h"
#include "main.h"

struct address *create_address(char *ip) {
   struct address *a = (struct address*) malloc(sizeof(struct address));
   strncpy(a->ip,ip);
   a->port = port_nb;
   return a;
}

int send_message(struct message *m, struct address *dest) {
  /* ... */
}
int recv_message(struct message *m, struct address *from) {
  /* ... */
}
```

- Can you guess what `main.h` contains?
- Why don't we include `message.h`?
- What would happen if we included it?

main.h

```
#ifndef _MAIN_H_
#define _MAIN_H_

extern int port_nb;     /* Declare the global variable */

/* Do we need to declare the prototype of function main() here? */

#endif /* _MAIN_H_ */
```

main.c

```
#include "main.h"
#include "network.h"

int port_nb;  /* instantiate the global variable */

int main() {
  struct message *m = create_message("Hello, world!");
  struct address *a = create_address("130.37.193.66");
  send_message(m,a);
  recv_message(m,a);
  printf("Received: %s\n",m.buf);
}
```


Compiling it All Together

- Compile each C file separately into an **object** file

```
$ gcc -c -Wall message.c
$ gcc -c -Wall network.c
$ gcc -c -Wall main.c
$
```

☞ This creates files `message.o`, `network.o` and `main.o`.

- Link all object files into an executable

```
$ gcc message.o network.o main.o
$
```

☞ This creates file `a.out`

Compiling it All Together

- One object file must define a `main()` function:

```
$ gcc message.o network.o main.o
/usr/lib/gcc/x86_64-redhat-linux/3.4.2/../../../../lib64/crt1.o(.text+0x21): In
function '_start': undefined reference to 'main'
collect2: ld returned 1 exit status
$
```

- All functions and variables must be defined:

```
$ gcc message.o network.o main.o
main.o(.text+0xa): In function 'main':
: undefined reference to 'create_message'
collect2: ld returned 1 exit status
$
```

- They must be defined only once:

```
$ gcc message.o network.o main.o
network.o(.text+0x0): In function 'create_message':
: multiple definition of 'create_message'
message.o(.text+0x0): first defined here
collect2: ld returned 1 exit status
$
```


Building Complex Programs

- Imagine that you write a program split into 100 C files and 100 header files
  - To compile your program, you must call gcc 101 times (perhaps with long option lines)
- What happens when you update one of these files?
  - You can recompile everything from scratch
    - But it takes a lot of time
  - You can decide to recompile only the parts which have changed
    - Much faster!
  - What happens if the updated file is a header file?
    - You must recompile all C files which include it
    - This is getting quite complex...
- `make` is a standard tool which will do the job for you

Using make

- To use make, you must write a file called Makefile
  - It defines dependencies between files. . .
  - . . . and the command to generate each file from its dependencies

```
# This is a comment

main: message.o network.o main.o
→       gcc -o main main.o message.o network.o

message.o: message.c message.h
→       gcc -c -Wall message.c

network.o: network.c network.h message.h
→       gcc -c -Wall network.c

main.o: main.c main.h network.h message.h
→       gcc -c -Wall main.c
```

  - '→' means "tab": **you cannot use spaces there!**

Using make

- If you type "make main", make will do all that is necessary to generate file main:
  - To generate main, I first need to have files message.o, network.o and main.o
  - These files do not exist, let's try to create them
    - To generate message.o I first need to have files message.c and message.h.
    - OK, I already have them.
    - Let's generate message.o by calling gcc -c message.c
    - To generate network.o I first need to have files network.c, network.h and message.h
    - etc. . .
  - Let's generate file main by calling gcc -o main main.o message.o network.o

Using make to re-compile a program

- If you update a few files, you want to recompile just what is necessary
- `make` will check the **dates** of your files:

```
target: dependency1 dependency2 dependency3
→         command
```

  - If you updated `dependency1` after `target` was generated, then you must re-generate `target`
  - If the target is more recent than all its dependencies, then no re-generation is necessary
- You must not forget dependencies!
  - Otherwise, `make` will not recompile all that is necessary

Generating Dependencies

- `makedepend` will generate dependencies automatically
  - Just create one more rule:

```
depend:
→         makedepend message.c network.c main.c
```

  - If you type "`make depend`", the program `makedepend` will be called
  - It will read files `message.c`, `network.c` and `main.c` and generate dependencies automatically
  - Dependencies will be added at the end of your `Makefile`:

```
# DO NOT DELETE

main.o: /usr/include/stdio.h /usr/include/features.h /usr/include/sys/cdefs.h
main.o: /usr/include/gnu/stubs.h
main.o: /usr/lib/gcc/x86_64-redhat-linux/3.4.2/include/stddef.h
main.o: /usr/include/bits/types.h /usr/include/bits/wordsize.h
main.o: message.h /usr/include/string.h network.h
network.o: network.h message.h /usr/include/string.h /usr/include/features.h
network.o: /usr/include/sys/cdefs.h /usr/include/gnu/stubs.h
network.o: /usr/lib/gcc/x86_64-redhat-linux/3.4.2/include/stddef.h
# etc...
```

Implicit Rules

- Very often, the command to compile a given type of files is the same
  - `gcc -c FOO.c`
  - All `*.o` files depend on the corresponding `*.c` file and are generated using the command `gcc -c XXX.c`

```
%.o: %.c
        gcc -c $< -o $@
```

  - '$<' means "the name of the dependency file" (here: `FOO.c`)
  - '$@' means "the name of the target" (here: `FOO.o`)

Using Variables in Makefiles

- You can create variables in your Makefiles
  - The list of all your `*.c` files, etc.

```
CC     = gcc
CFLAGS = -g -Wall
SRC    = main.c network.c message.c
OBJ    = main.o network.o message.o

main: $(OBJ)
        $(CC) -o $@ $(OBJ)

%.o: %.c
        $(CC) $(CFLAGS) -c $<

depend:
        makedepend $(SRC)

clean:                        # We can write rules which do not create any file
        rm main *.o
```

Libraries

- Libraries are precompiled sets of functions ready to be used in programs
  - For example: you wrote a set of functions to send/receive network messages
  - Let's put them into a library
  - You can use the library in any program which needs networking
  - You can let other programmers use your library
- Libraries always come with one or more header files
  - To **declare** the types/functions/variables present inside the library
- Libraries are named like this:
  - `libsomething.a` (static libraries)
  - `libsomething.so` (dynamic libraries)

Static vs Dynamic Libraries

There are two kinds of libraries:

- **Static libraries:**
  - When compiling a program with the library, the library code will be added to the program
  - If the library is big, this makes a big executable file!
    For example, the standard C library takes around 2.5 MB.
  - All programs must be linked with this library!
  - ☞ This is a waste of storage space
- **Dynamic libraries:**
  - The linked executable does not contain the library
  - It just contains a reference: "**this executable requires library /usr/lib/libc.so**"
  - When you execute the program, the library will be loaded automatically before the program starts

Crating a Static Library

- A static library is made of a number of *.o files

```
$ ar r libnetwork.a message.o network.o
$ ranlib libnetwork.a
$
```

- ar creates the library
  - It can also do other operations on libraries (modifying an existing library, extracting parts from a library, etc.)
  - Read the man page...
- ranlib creates an **index** of all functions in the library
  - And adds the index to the library

Using a Static Library

- Let's write a program main.c which uses our library libnetwork.a
  - Write main.c normally (include header files message.h and network.h that come with the library)
  - Compile main.c normally (gcc -c main.c)
  - Link main.o with the library:

```
$ gcc -o main main.o -lnetwork
$
```

☞ gcc will search for a file called libnetwork.a or libnetwork.so in the standard directories (/usr/lib, /usr/local/lib)

★ If you don't have write access in /usr/lib, then you must specify where libnetwork.a can be found:

```
$ gcc -o main main.o -L. -lnetwork
$
```

Crating a Dynamic Library

- This is slightly different from creating a static library:
  1. Compile each .c file using option -fPIC
  2. Generate the shared library using gcc -shared
  3. You must specify the name of the library (libsomething.so)

```
$ gcc -c -fPIC message.c
$ gcc -c -fPIC network.c
$ gcc -shared -o libnetwork.so message.o network.o
$
```


Using a Dynamic Library

- You can link your program the same way as when linking with a static library:

```
$ gcc -c main.c
$ gcc -o main main.o -L. -lnetwork
$
```

- Remember: dynamic libraries are loaded **at runtime!**
  - The dynamic linker must be able to find the library when you start the program
  - It will search libraries with the right name in paths present in your environment variable $LD_LIBRARY_PATH

```
$ ./main
./main: error while loading shared libraries: libmessage.so: cannot open shared
object file: No such file or directory
$ export LD_LIBRARY_PATH=$LD_LIBRARY_PATH:/home/gpierre/mydirectory
$ ./main
...
$
```

Using a Dynamic Library

- How do you know which libraries an executable requires?

```
$ ldd main
        libmessage.so => not found
        libc.so.6 => /lib64/tls/libc.so.6 (0x0000003206300000)
        /lib64/ld-linux-x86-64.so.2 (0x0000003206100000)
$ LD_LIBRARY_PATH=$LD_LIBRARY_PATH:$PWD
$ ldd main
        libmessage.so => /home/gpierre/foo/libmessage.so (0x0000002a9555
        libc.so.6 => /lib64/tls/libc.so.6 (0x0000003206300000)
        /lib64/ld-linux-x86-64.so.2 (0x0000003206100000)
$
```


Dynamically Loaded Libraries

- Normally, dynamic libraries are loaded automatically when a program starts
- But sometimes you want to load a dynamic library **while a program is running**
  - Example: you start a program which receives a dynamic library through the network and uses it for further communication
- You can explicitely load dynamic libraries:

```
#include <dlfcn.h>
void *dlopen(const char *filename, int flag);
```

```
#include <dlfcn.h>

int main() {
  void *mylibrary;
  /* ... */
  mylibrary = dlopen("/home/gpierre/mydirectory/libnetwork.so",RTLD_NOW);
  /* ... */
}
```

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