CSE 421/521 - Operating Systems
Fall 2014 Recitations

Recitation - IV

Building Complex Programs with Makefiles

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September 23-25, 2014

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++;
}
```

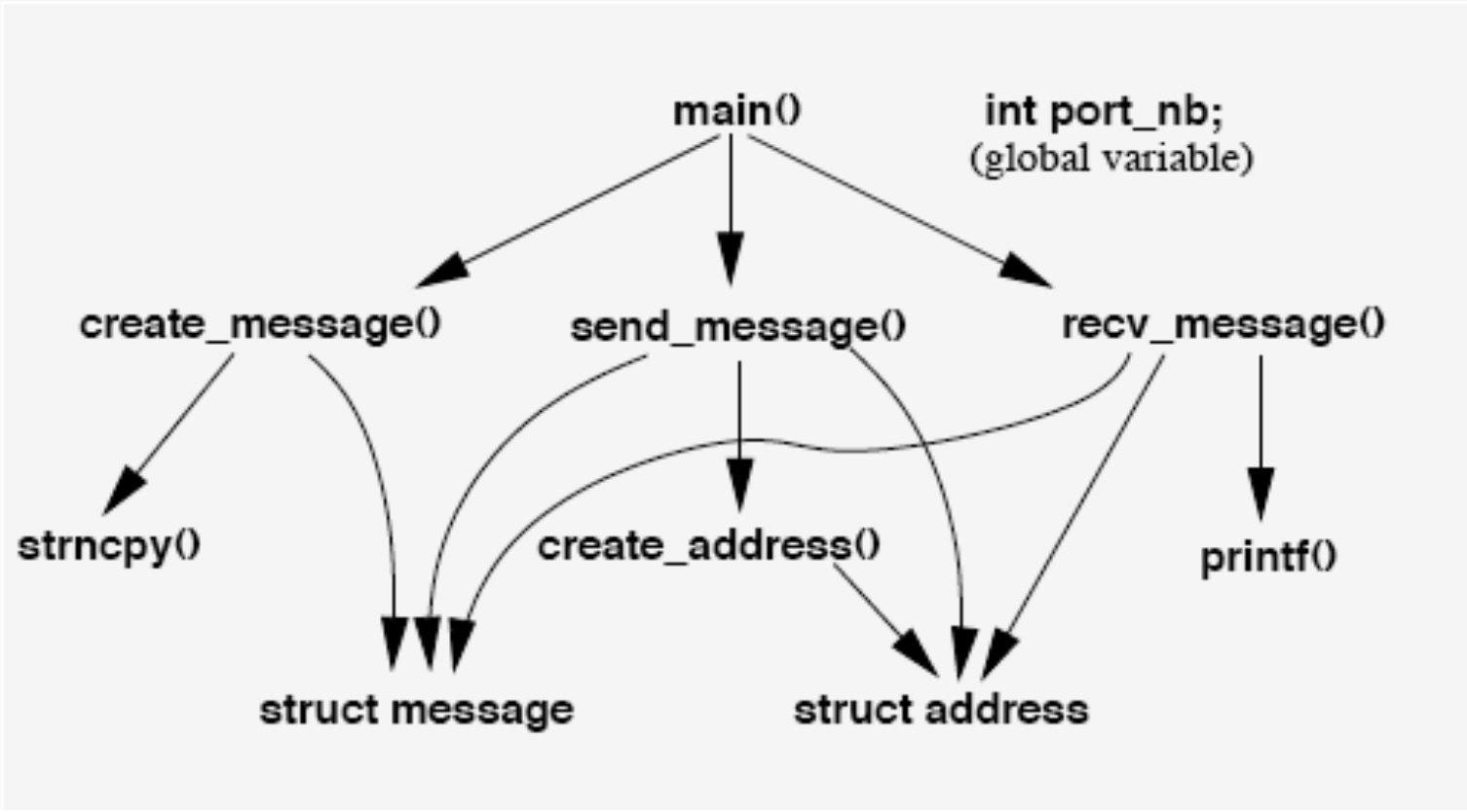
```
/* file2.c */

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...

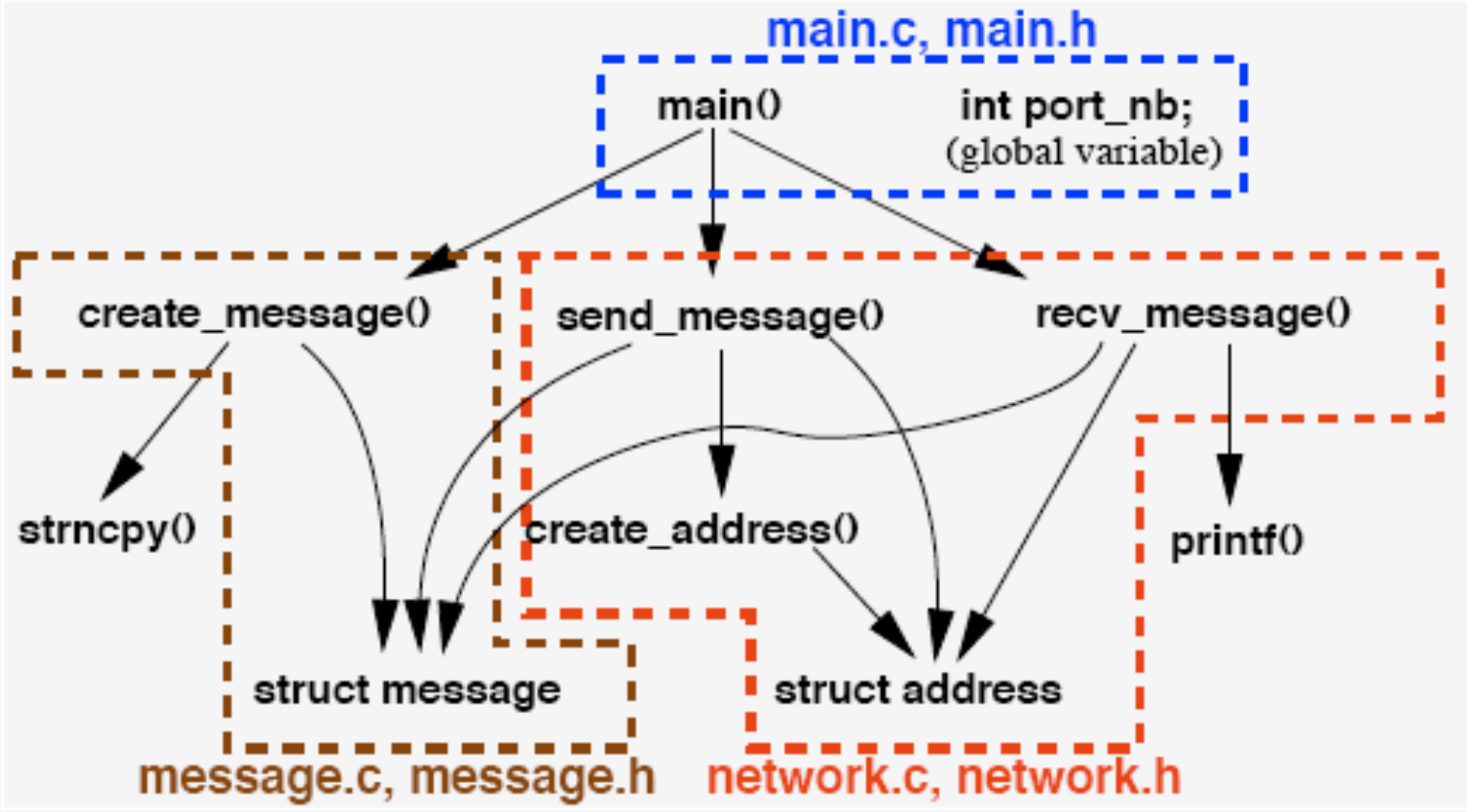
Example

- A program that exchanges messages across a network



Example

- A program that exchanges messages across a network



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
```

Adding new files to Pintos Code

To add a `.c' file, edit the top-level `**Makefile.build'**.
Add the new file to variable `dir_SRC', where dir is the directory where you added the file. A new `.h' file does not require editing the `Makefile's.

Acknowledgments

- Advanced Programming in the Unix Environment by R. Stevens
- The C Programming Language by B. Kernighan and D. Ritchie
- Understanding Unix/Linux Programming by B. Molay
- Lecture notes from B. Molay (Harvard), T. Kuo (UT-Austin), G. Pierre (Vrije), M. Matthews (SC), B. Knicki (WPI), M. Shacklette (UChicago), and J.Kim (KAIST).