Computer Architecture (Lab Class)
Modules and Makefiles

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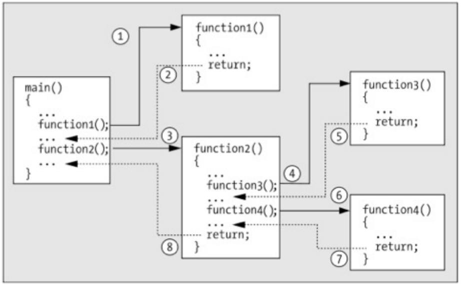
Structure of a C program

- A C program is usually divided into functions
- A function is a block of code that performs a specific task. Functions can call other functions
- Every C program must have a `main` function which is the starting point of the program execution



Three aspects of a C function

- Function declaration (or prototype)
  - Informs the compiler about the function's name, parameters and return value's data type
- Function definition
  - Contains all the statements to be executed
- Function call
  - An expression that passes control and arguments (if any) to a function

Important note

- Functions should either be declared or defined before being called

Function declaration (1/2)

- Function name
  - Defined by the programmer. It can be anything, however it is advised to have a meaningful name
- Return type
  - The data type returned from calling the function (`void` if no return)
- Function parameters
  - The inputs needed for the function to execute. There can be multiple parameters separated by a comma
  - It is only mandatory to specify their types, not their names
- Example:

```
int average(int x, int y);
int average(int, int);
```

Function declaration (2/(2)

Listing 1: main.c

```c
#include <stdio.h>

int average(int, int);

int main(){
  int v[] = { 1, 2 };
  int r = 0;

  r = average(v[0], v[1]);

  printf("average =%d\n", r);
  return 0;
}

int average(int n1, int n2) {
  return (n1+n2)/2;
}
```

- This code does not compile if we omit line 3. Why?

Modules

- It is common practice to have a *header* file (*.h*) to each code file (*.c*) with the prototypes of the functions defined in the program
- We can say that each code file *.c* and its corresponding header file *.h* compose a module of the program. Several times the term "compilation unit" is used
- A program can have several modules

Listing 2: main.c

```c
#include <stdio.h>
#include "average.h"

int main(){
  int v[] = {1,2};
  int r = 0;

  r = average(v[0], v[1]);
  printf("average =%d\n", r);
  return 0;
}
```

Listing 3: average.h

```c
int average(int n1, int n2);
```

Listing 4: average.c

```c
int average(int n1, int n2){
  return (n1+n2)/2;
}
```

Compile a program with several modules

- Modules must be compiled first, followed by the main program
- Command line sequence:

```
$ gcc -g -Wall -Wextra -fanalyzer -c average.c -o average.o

$ gcc -g -Wall -Wextra -fanalyzer -c main.c -o main.o

$ gcc main.o average.o -o prog_avg
```

- Execute the final program:

```
$ ./prog_avg
```

Variable scope

- A scope is a region of the program, and the scope of variables refers to the area of the program where the variables can be accessed after its declaration
- If a variable is declared inside a function it can only be used inside that function. It is called a *local variable*
- If it is declared inside a block ("{ ... }"), it exists only inside that block

```
{
    int a = 0;  /* Declaration of variable "a" */
    /* Refer to "a" here is not an error */
    /* Refer to "b" here is an error! */

    {
        int b = 10; /* Declaration of variable "b" */
        /* One can refer to "a" and "b" here */
    }   /* Variable "b" dies */

    /* Refer to "b" here is an error! */
    /* Refer to "a" here is not an error */
}   /* Variable "a" dies */
```

Scope vs Linkage

- In C, a program that consists of multiple source code files is compiled one at a time
- Until the compilation process, a variable can be described by its scope
- It is only when the linking process starts, that the linkage property comes into play
- Thus, scope is a property handled by the compiler, whereas linkage is a property handled by the linker
- Should a variable be available for another file to use? Should a variable be used only in the file declared? Both questions are decided by the linker

Internal linkage

- A variable or function implementing internal linkage is not accessible outside the compilation unit it is declared in
- It is implemented by the keyword `static`
- The following example gives a linking error. Why?

Listing 5: main1.c

```c
#include <stdio.h>
#include "average1.h"

int main(){
  int v[] = { 1, 2 };
  int r=0;

  r = average(v[0], v[1]);
  printf("average = %d\n", r);
  return 0;
}
```

Listing 6: average1.h

```c
int average(int n1, int n2);
```

Listing 7: average1.c

```c
static int average(int n1, int n2){
  return (n1+n2)/2;
}
```

External linkage

- Externally linked identifiers are shared between translation units and are considered to be located at the outermost level of the program
- In practice, this means that we must define an identifier in a place which is visible to all, such that it has only one visible definition
- It is the default linkage for globally scoped variables and functions
- The keyword *extern* implements external linkage
- When we use the keyword *extern*, we tell the linker to look for the definition elsewhere

External linkage

- In the following example, the header file *average2.h*, that is included in *main2.c*, declares that an `extern` variable with name *result* exits, defined and initialised in *average2.c*

Listing 8: main2.c

```c
#include <stdio.h>
#include "average2.h"

int main(){
  int v[] = { 1, 2 };

  average(v[0], v[1]);
  printf("average = %d\n", result);
  return 0;
}
```

Listing 9: average2.h

```c
void average(int n1, int n2);
extern int result;
```

Listing 10: average2.c

```c
int result = 0;

void average(int n1, int n2) {
  result = (n1+n2)/2;
}
```

Multiple inclusion problem

Listing 11: defs.h

```
typedef struct {
  int x;
  int y;
} point;

typedef struct car{
  int id;
  point start, end;
  int distance;
};
```

Listing 12: main3.c

```
#include "distance.h"
#include "defs.h"

int main(){
  struct point a,b;
  struct car c;
  ...
  fill_car(c);
  return 0;
}
```

Listing 13: distance.h

```
#include "defs.h"

int distance(point a, point b);
void fill_car(car c, point a, point b);
```

Listing 14: distance.c

```
int distance(point a, point b){
...
}

void fill_car(car c, point a, point b){
...
}
```

The problem!

- Note that `defs.h` will be included twice in `main.c`

Solving the multiple inclusion problem

- The header should be wrapped in *header guards* to prevent multiple inclusion
- Header guards are implemented through the use of preprocessor directives: `#ifndef`, `#define` and `#endif`
- If the symbol is defined then this section of code has been seen before and should not be processed again. If the symbol has not been created, then the code it is associated with has not been seen
- The name of the symbol must be unique. A common approach is to use the name of the header file, converting the .h suffix to a _H

Listing 15: defs.h

```c
#ifndef DEFS_H
#define DEFS_H

typedef struct {
  int x;
  int y;
} point;

typedef struct car{
  int id;
  point start, end;
  int distance;
};

#endif
```

Automatically building executable programs

- `make` is a build automation tool that automatically builds executable programs and libraries from source code by reading files called `Makefiles` which specify how to derive the target program
- The `Makefile` specifies **a set of rules to be accomplished and their possible dependencies**
- For each rule, if any of the prerequisites has a more recent modification time than the target, the command lines are run
- This means that `make` only recompiles outdated files, shortening the needed compilation time (particularly noticeable in large projects)

Automatically building executable programs

- The content of the `Makefile` must **follow a specific syntax**:

Listing 16: Structure of a Makefile

```
default_rule: dependency1 dependency2 . . .
        <tab>command1
        <tab>command2
<empty line to break consecutive rules>
dependency1: dependency1_1
        <tab>command1
        ...
<empty line to break consecutive rules>
...
```

- A rule can have zero or more dependencies
- Each command line must start by the <tab> character
- An empty line must be used to set apart the last command of a rule from the declaration of the following rule

A simple Makefile

Listing 17: Makefile

```
prog_avg: average.o main.o
	gcc average.o main.o -o prog_avg

average.o: average.c average.h
	gcc -g -Wall -Wextra -fanalyzer -c average.c -o average.o

main.o: main.c average.h
	gcc -g -Wall -Wextra -fanalyzer -c main.c -o main.o

clean:
	rm -f *.o prog_avg

run: prog_avg
	./prog_avg
```

A simple Makefile

- `prog_avg` is the default rule of this Makefile
- `average.o` and `main.o` are the dependencies to achieve that goal (and also rules by themselves)
- `gcc average.o main.o -o prog_avg` is the command that will be executed in the shell to reach the `program` goal
- If the dependencies `average.o` and `main.o` haven not yet been executed or are out of date, their respective commands will be executed prior to the commands in to build `prog_avg`
- The rules `clean` and `run` are not prerequisites of any other rule. The only purpose of these rules is to simplify the execution of the program and the removal of the executable file and all the object files

How to run `make`

- To execute what is specified in the `Makefile` it is a matter of simply invoking `make`

```
make [-f <makefile>] [<rule>]
```

- If the `-f` parameter is not used to specify which rule file to use, `make` will search in the current directory for a file named "makefile" or "Makefile"
- By default, the goal is the first rule in the Makefile
- However, any rule in the Makefile may be specified as a goal

Note

It is recommended to have a different directory to each practical exercise with the needed modules and the respective Makefile

Cross compiling

- The act of compiling applications to run on a different computer system is referred to as “cross compiling”
- This is oppose to “native compiling” (the previous examples) where what you compile is supposed to run on the same system that you compiled it on
- The classic example for cross compiling is when you compile for a low powered embedded RISC-V device from a powerful x86–64 PC
    - Cross compiling is preferred here because it is orders of magnitude faster to do so than building natively on the embedded device
    - This is a must have if you are iteratively developing an embedded application

QEMU emulation

- Developing solely on real RISC-V boards would require having physical hardware at every iteration
  - Such boards are often scarce or unavailable in our labs
- QEMU's RISC-V target simulates an RV32IM system entirely in software
- With QEMU, you can:
  - Execute your RISC-V ELF directly on an x86_64 virtual machine
  - Connect a debugger (e.g. `gdb`) to single-step through your code
  - Verify correctness before moving to actual hardware
- We'll automate invocation of QEMU via our Makefile to streamline build and run

The Makefile for ARQCP

```
CC=riscv32-linux-gcc
CFLAGS=-Wall -Wextra -fanalyzer -g
ARCHFLAGS=-march=rv32imd -mabi=ilp32d
LIBRV32=${HOME}/bin/bootlin/riscv32-buildroot-linux-gnu/sysroot

program.elf: main.o asm.o
	$(CC) $(CFLAGS) $(ARCHFLAGS) main.o asm.o -o program.elf

main.o: main.c
	$(CC) $(CFLAGS) $(ARCHFLAGS) -c main.c

asm.o: asm.s asm.h
	$(CC) $(CFLAGS) $(ARCHFLAGS) -c asm.s

clean:
	rm -f *.o *.elf

run: program.elf
	qemu-riscv32 -L $(LIBRV32) ./program.elf

debug: program.elf
	@echo "On other terminal window do:"
	@echo "riscv32-linux-gdb -tui ./program.elf"
	qemu-riscv32 -L $(LIBRV32) -g 1234 program.elf -S
```