WORKSHEET, WEEK 04: BUILD AND DEBUG ON LINUX

4.1 Building with Makefile

This is a minimalistic Makefile that builds `myprogram` from a single source file `myprogram.cpp`.

```
CC=g++
CFLAGS=-std=c++17

all: myprogram

myprogram: myprogram.cpp
	$(CC) $(CFLAGS) -o myprogram myprogram.cpp

.PHONY: clean
clean:
	rm -f myprogram
```

Utility *make* was invented in 1976. Analyzes dependencies (which file was updated when), target names are typically same as file names. In the above example

- In a *Makefile* each line should be either non-indented (a variable definition or a target) or be indented by exactly one *TAB* character. Preceding that *TAB* by an (invisible) whitespace would break it.
- *.PHONY clean* declaration says that the target name has nothing to do with any filename. (If we do not use it, then *clean* would not run provided there is a file *clean*.

A more complicated testfile using multiple sources (and even multiple executables – one for software itself, another for unit-tests) is shown in the Catch2 subsection (see below).

Use Makefile to Run Testfiles:

```
# Define variables
PROGRAM = myprogram
INPUT_FILES = $(wildcard test*.txt)
OUTPUT_FILES = $(patsubst test%.txt,output.test%.txt,$(INPUT_FILES))

.PHONY: test
test: $(OUTPUT_FILES)

output.test%.txt: $(PROGRAM) test%.txt
	./$(PROGRAM) < $< > $@ || true

# Clean up target
clean:
	rm -f $(OUTPUT_FILES)
```

The snippet || *true* prevents stopping the `make` task, if some of the program execution returns non-zero return code or crashes.

Note: Currently C++ developers use mostly *CMake* – a "meta-build" tool that creates makefiles or other build artefacts from a description of the project and its dependencies described in the `CMakeLists.txt` file. CMake can participate in other build chains – such as Gradle build tasks, where Android app written in Java or Kotlin needs some native code in C++.

In other cases custom Bash shell, Python or Groovy can be used instead of Makefile or `CMakeLists.txt`. Build tools are often part of larger build infrastructures using `crontab` time-scheduling, Continuous Integration tools such as Jenkins,

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CMakeLists.txt Example:

```
cmake_minimum_required(VERSION 3.10)
project(myprogram)
add_executable(myprogram myprogram.cpp)
```

Here is how to use it:

```
cmake .
make
```

4.2 Unit-tests with Catch2

To run a project with Catch2 tests we need two different build goals in *Makefile*. One of them is builds the executable you can run; another one builds the test harness (executable that can be used to run the unit tests).

The following things are commonly used with Catch2 tests:

- No dependencies on additional libraries; but tests should include header file `catch.hpp` containing various assert definitions and macros.
- Testcases can check normal execution – for example, `REQUIRE(...)` verifies that the expression is true.
- Testcases can check abnormal cases when the expected behaviour is throwing an exception. For example, `REQUIRE_THROWS_AS(...)` means that the expression throws an exception of the specified type.
- It is possible to have common initialization section in a testcase, which is then used by multiple "sections" (each section receives the same initial state, but does something different).
- Using Catch2 means that you produce one more executable (see the next subsection for an example of a Makefile to build two different executables in the same directory).

```
#define CATCH_CONFIG_MAIN

#include "catch.hpp"
#include "Stack.h"

TEST_CASE("Exceptions on empty stack", "[stack]")
{
  Stack stack(3);
  REQUIRE_THROWS_AS(stack.top(), std::out_of_range);
  REQUIRE_THROWS_AS(stack.pop(), std::out_of_range);
  stack.push(17);
```

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```
  stack.pop();
  REQUIRE_THROWS_AS(stack.top(), std::out_of_range);
}

TEST_CASE("Lifo order", "[stack]")
{
  Stack stack(3);
  stack.push(1);
  stack.push(2);
  REQUIRE(stack.top() == 2);
  REQUIRE(stack.pop() == 2);
  REQUIRE(stack.top() == 1);
  REQUIRE(stack.pop() == 1);
  REQUIRE_THROWS_AS(stack.top(), std::out_of_range);
}

TEST_CASE("3-element stack", "[stack]")
{
  // common initialization part
  Stack stack(3);
  stack.push(11);
  stack.push(12);
  stack.push(13);

  SECTION("Stack is full") {
    REQUIRE_THROWS_AS(stack.push(14), std::out_of_range);
  };

  SECTION("Multiple top calls") {
    REQUIRE(stack.top() == 13);
    REQUIRE(stack.top() == 13);
  };
}
```

4.2.1 A Makefile to build Catch2 test executable

In this example we assume that the unit-testing executable is built from these sources:

`TestStack.cpp`: Catch2 testcases; its source is shown above.

`catch.hpp`: Catch2 header file, which you do not need to change.

`Stack.h`: Stack ADT methods.

`Stack.cpp`: Stack implementation.

Meanwhile, there is also the source file `StackMain.cpp` (a program doing something useful and using our stack). In this case the main program can be built with `make all`, but the testcases can be built with `make test`.

The Makefile to compile such project is shown below:

```
CC=g++
CFLAGS=-std=c++17 -g
SRCDIR=.
OBJDIR=.
SRC=$(wildcard $(SCRCDIR)/*.cpp)
OBJ1=$(OBJDIR)/Stack.o $(OBJDIR)/StackMain.o
```

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```
OBJ2=$(OBJDIR)/Stack.o $(OBJDIR)/TestStack.o
EXECMAIN=$(SRCDIR)/stack-main
EXECTEST=$(SRCDIR)/stack-test

all: $(EXECMAIN)
test: $(EXECTEST)

$(EXECMAIN): $(OBJ1)
	$(CC) $(CFLAGS) -o $@ $^

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

$(EXECTEST): $(OBJ2)
	$(CC) $(CFLAGS) -o $@ $^


.PHONY: clean
clean:
	rm -f $(SRCDIR)/*.o $(EXEC1) $(EXEC2)
```

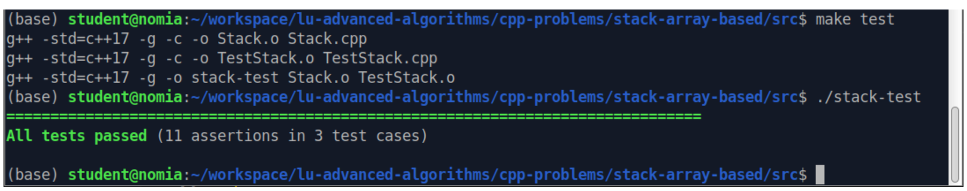


Fig. 1: Sample Output from Catch2 testcases.

4.3 Debugging with gdb

`gdb myprogram`: Start gdb and load the myprogram executable.

`run`: Start the program.

`break <line_number>`: Set a breakpoint at the specified line number.

`info break`: Show all defined breakpoints.

`delete <breakpoint_number>`: Delete the specified breakpoint.

`next`: Step over the current line.

`step`: Step into the function called on the current line.

`finish`: Continue execution until the current function returns.

`backtrace`: Show the current call stack.

`list`: Show the current source code around the current line.

`print <variable_name>`: Print the value of the specified variable.

`display <variable_name>`: Display the value of the specified variable after each step.

`watch <variable_name>`: Set a watchpoint on the specified variable.

`info registers`: Show the current state of all CPU registers.

`x/<length><format><address>`: Examine memory at the specified address, with the specified format and length.

`layout src`: Display the source code and assembly code in separate windows.

`layout regs`: Display the CPU registers and the source code in separate windows.

`layout split`: Display the source code and the program output in separate windows.

`layout next`: Switch to the next layout.

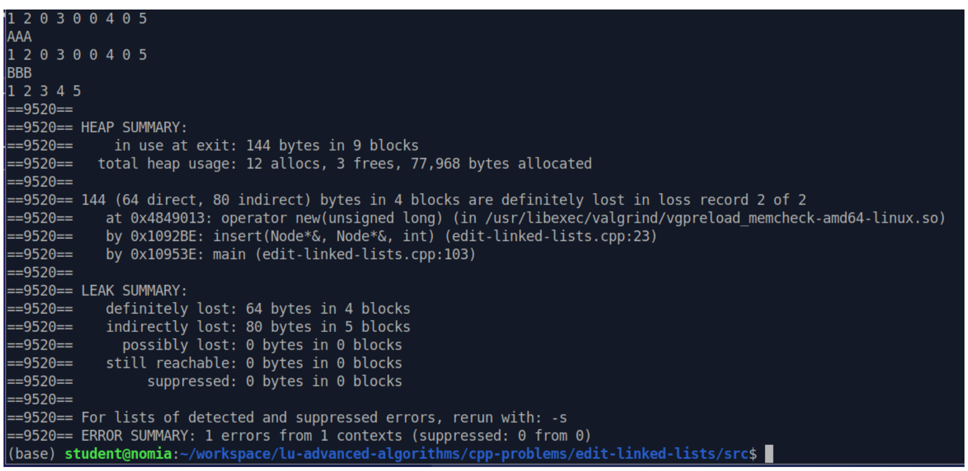
4.4 The Lifecycle of Data Structures

- Constructors for empty data structures and initializer lists.
- Copy constructors during assignments or function calls.
- When are the destructors called.
- When is a proper time to release memory?

4.5 Valgrind

Memory leak detection: Valgrind can detect memory leaks by identifying when memory is allocated but not freed. Use `--leak-check` option.

```
valgrind --leak-check=yes ./myprogram
# (or write directly to a file)
valgrind --leak-check=yes --log-file=leak_report.txt ./myprogram
```



```
1 2 0 3 0 0 4 0 5
AAA
1 2 0 3 0 0 4 0 5
BBB
1 2 3 4 5
==9520==
==9520== HEAP SUMMARY:
==9520==     in use at exit: 144 bytes in 9 blocks
==9520==   total heap usage: 12 allocs, 3 frees, 77,968 bytes allocated
==9520==
==9520== 144 (64 direct, 80 indirect) bytes in 4 blocks are definitely lost in loss record 2 of 2
==9520==    at 0x4849013: operator new(unsigned long) (in /usr/libexec/valgrind/vgpreload_memcheck-amd64-linux.so)
==9520==    by 0x1092BE: insert(Node*&, Node*&, int) (edit-linked-lists.cpp:23)
==9520==    by 0x10953E: main (edit-linked-lists.cpp:103)
==9520==
==9520== LEAK SUMMARY:
==9520==    definitely lost: 64 bytes in 4 blocks
==9520==    indirectly lost: 80 bytes in 5 blocks
==9520==      possibly lost: 0 bytes in 0 blocks
==9520==    still reachable: 0 bytes in 0 blocks
==9520==         suppressed: 0 bytes in 0 blocks
==9520==
==9520== For lists of detected and suppressed errors, rerun with: -s
==9520== ERROR SUMMARY: 1 errors from 1 contexts (suppressed: 0 from 0)
(base) student@nomia:~/workspace/lu-advanced-algorithms/cpp-problems/edit-linked-lists/src$
```

Fig. 2: Sample Output from Valgrind for memory leak check.

Memory error detection: Valgrind can detect memory errors: accessing memory that has already been freed, accessing uninitialized memory, and writing to read-only memory. Use `--tool=memcheck` option.

```
valgrind --tool=memcheck ./myprogram
```

Performance profiling: Valgrind can help identify performance bottlenecks by profiling CPU usage, memory usage, and other metrics. Use `--tool=callgrind` option

```
valgrind --tool=callgrind ./myprogram
```

This generates a file called callgrind.out.<pid>. Can use a tool like `kcachegrind` to visualize the profiling data.

4.6 Problems

Some questions here are open-ended; they are interview-style questions for C++ developers on Linux platforms.

Problem 1: Answer some questions about `Makefile` builds:

(A) What is a dependency in a Makefile, and how is it specified?

(B) How does Makefile determine whether a target needs to be rebuilt or not?

(C) What is the purpose of the `.PHONY` target in a Makefile, and when should it be used?

(D) What is a pattern rule in a Makefile, and how is it used?

(E) What is the meaning of variables `$@` and `$<` in a Makefile ?

(F) How can you specify conditional dependencies in a Makefile, and why would you want to do this? (stuff like `ifeq`, `else`, `endif`)

Problem 2: Answer some questions about `gdb` build.

(A) How would you compile a C++ program (source files `A.cpp`, `B.cpp`, `B.h`). on Linux using the g++ compiler? What flags ensure that it is debuggable?

(B) Which command can be used to set a breakpoint in the program?

(C) Which command can be used to see a value of a variable (or an expression?) in a C++ program while it's running?

(D) How can we use the core file generated by gdb? How would you use it debug a program that has crashed?

(E) What is the purpose of the core file generated by gdb? How to use it to debug a program that has crashed?

(F) Can you explain the difference between a stack overflow error and a segmentation fault error? How would you debug each of these types of errors using gdb?

(G) Which command can examine the contents of memory at a particular address in a C++ program?

(H) Which command can show the call stack of a C++ program during debugging?

(I) Can you explain what the watch command in gdb does? How to use it to monitor a variable in your C++ program?

(J) How would you use `gdb` to examine the assembly code generated by the `g++` compiler?

Problem 3: Consider the following C++ code to store custom objects of type `Pair` in an STL `vector` data structure. Explain which constructors and destructors are invoked – how many and at which locations of the code.

```
#include <vector>
#include <iostream>

using namespace std;

class Pair {
  public:
    int nX,nY;
```

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```
  private:

};

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

  vector<Pair> myVector;
  for(int i=0 ; i<10 ; i++) {
    int x, y;
    cin >> x >> y;
    Pair p;
    p.nX = x; p.nY = y;
    myVector.push_back(p);
  }

  for (auto it = myVector.begin(); it != myVector.end(); ++it) {
    cout << "(" << (*it).nX << "," << (*it).nY << ")" << endl;
  }
  return 0;
}
```