L3: Building, Testing and Debugging Scientific Software

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September 15, 2025

Master Calcul Haute Performance et Simulation - GLHPC | UVSQ

Building, Testing and Debugging Scientific Software

Objectives

- Build systems: Advanced Makefiles, introduction to CMake for managing multi-file and multi-platform projects.
- Debugging: GDB, Valgrind for detecting memory errors and leaks.
- Software testing:
    - Principles: Unit testing, integration testing.
    - Test frameworks in C (e.g., Unity).
    - Importance of testing for regression prevention and validation.
- Code documentation: Doxygen.

Makefiles

- How to determine which files have changed?

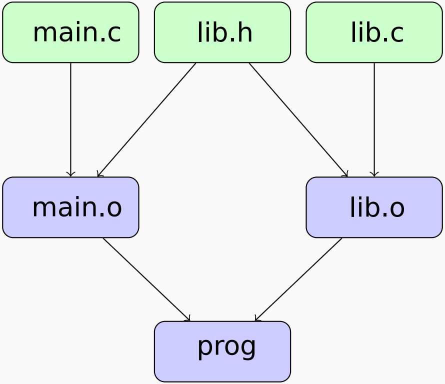


Figure 1: makefile-dependencies

- **dependencies**: `main.o` depends on changes in `lib.h`

Makefile

- A `Makefile` uses a declarative language to describe targets and their dependencies.
- It is executed by the `make` command, which allows building different **targets**.
  - `make` uses timestamps to determine which files have changed.
  - `make` evaluates rules recursively to satisfy dependencies.

Makefile Rule

```
prog: main.c lib.c lib.h
  clang -o prog main.c lib.c -lm

target: dependencies
\t  command to build the target from the dependencies
```

Separate Compilation

```
prog: main.o lib.o
  clang -o prog main.o lib.o -lm

main.o: main.c lib.h
  clang -c -o main.o main.c

lib.o: lib.c lib.h
  clang -c -o lib.o lib.c
```

If `lib.c` is modified, which commands will be executed?

Phony Targets

You can add targets that do not correspond to a produced file. For example, it is useful to add a `clean` target to clean the project.

```
clean:
  rm -f *.o prog
.PHONY: clean
```

`.PHONY` specifies that the `clean` rule should always be executed. Declaring all phony targets ensures they are always called (even if a file with the same name is created).

Default Rule

```
make clean
make prog
make
```

- If `make` is called with a rule, that rule is built.
- If `make` is called without arguments, the first rule is built. It is customary to include a default `all:` rule as the first rule.

```
all: prog

prog: ...
```

```
CC=clang
CFLAGS=-O2
LDFLAGS=-lm

prog: main.o lib.o
  $(CC) -o prog main.o lib.o $(LDFLAGS)

main.o: main.c lib.h
  $(CC) $(CFLAGS) -c -o main.o main.c

lib.o: lib.c lib.h
  $(CC) $(CFLAGS) -c -o lib.o lib.c
```

Variables can be overridden when calling `make`, e.g.,

```
make CC=gcc
```

Special Variables

`$@`	target name
`$^`	all dependencies
`$<`	first dependency

```
prog: main.o lib.o
  $(CC)  -o $@ $^ $(LDFLAGS)

main.o: main.c lib.h
  $(CC) $(CFLAGS) -c -o $@ $<

lib.o: lib.c lib.h
  $(CC) $(CFLAGS) -c -o $@ $<
```

The last two rules are very similar...

Implicit Rules

Before

```
main.o: main.c lib.h
	$(CC) $(CFLAGS) -c -o $@ $<

lib.o: lib.c lib.h
	$(CC) $(CFLAGS) -c -o $@ $<
```

With Implicit Rule

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

main.o: lib.h
lib.o: lib.h
```

Other Build Systems

- **automake / autoconf**: automatic generation of complex makefiles and management of system-specific configurations.
- **cmake, scons**: successors to Makefile, offering more elegant syntax and new features.

CMake

Why CMake?

- **Advantages of Makefiles:**
  - Simplicity and transparency.
  - No additional tools required.
  - Direct control over the build process.
- **Advantages of CMake:**
  - Cross-platform support (Linux, Windows, macOS).
  - Generates build files for multiple build systems (Make, Ninja, etc.).
  - Modular and target-based design.
  - Built-in support for testing, installation, and packaging.

General Design of CMake

- **CMake as a Meta-Build System:**
  - Generates build files for different generators (e.g., Make, Ninja).
  - Abstracts platform-specific details.
- **Workflow:**
  1. Write `CMakeLists.txt` to define the project.
  2. Configure the project:

     ```
     cmake -B build
     ```

  3. Build the project:

     ```
     cmake --build build
     # or when using Make as backend
     make -C build
     ```

  Out-of-source builds are recommended to keep source directories clean.

Basic Structure of `CMakeLists.txt`

```
cmake_minimum_required(VERSION 3.15)
project(MyProject LANGUAGES C)

set(CMAKE_C_STANDARD 11)
```

- `cmake_minimum_required`: Specifies the minimum version of CMake required.
- `project`: Defines the project name and the programming language(s) used.
- `set`: Sets variables, e.g., C standard version.

Adding an Executable

```
add_executable(my_executable src/main.c)
```

- Creates an executable named `my_executable`.

Adding a Shared Library

```
add_library(my_library SHARED src/library.c)
```

- Creates a shared library named `libmy_library.so` (on Linux).

Linking Libraries to Executables

```
add_library(my_library SHARED src/library.c)
add_executable(my_executable src/main.c)
target_link_libraries(my_executable PRIVATE my_library)
```

- `add_library`: Creates a shared library.
- `add_executable`: Creates an executable.
- `target_link_libraries`: Links the library to the executable.

PRIVATE means that `my_executable` uses `my_library`, but `my_library` does not need to be linked when other targets link to `my_executable`.

Library dependency transitivity

```
add_library(libA SHARED src/libA.c)
add_library(libB SHARED src/libB.c)
target_link_libraries(libB PUBLIC libA)
add_executable(my_executable src/main.c)
target_link_libraries(my_executable PRIVATE libB)
```

- `my_executable` is linked to `libB` and also to `libA` because `libB` links to `libA` with `PUBLIC`.
- If `libB` linked to `libA` with `PRIVATE`, `my_executable` would not be linked to `libA`.
- If `libB` linked to `libA` with `INTERFACE`, `my_executable` would be linked to `libA` but not `libB`.
- See this reference for more details.

Global Include Directories

```
include_directories(include)
```

- Adds the `include` directory globally for all targets.
- **Limitation:** Can lead to conflicts in larger projects.

Target-Specific Include Directories

```
target_include_directories(my_library
    PUBLIC include
)
```

- **PUBLIC:** Include directory is needed when building and using the library.
- **PRIVATE:** Include directory is needed only when building the library.
- **INTERFACE:** Include directory is needed only when using the library.

Porting our minimal Makefile example to CMake

```
cmake_minimum_required(VERSION 3.15)
project(MyProject LANGUAGES C)

# Add the executable target
add_executable(prog main.c lib.c)

# Specify include directories for the target
target_include_directories(prog
  PRIVATE ${CMAKE_CURRENT_SOURCE_DIR})

# Add compile options
target_compile_options(prog PRIVATE ${CFLAGS})

# Link libraries if needed
target_link_libraries(prog PRIVATE m)
```

Debug vs Release Builds

- **Debug Build:**
  - Includes debug symbols for debugging.
  - Example flags: `-g`, `-O0`.
- **Release Build:**
  - Optimized for performance.
  - Example flags: `-O3`, `-DNDEBUG`.

Setting Build Types in CMake

```
if(NOT CMAKE_BUILD_TYPE)
  set(CMAKE_BUILD_TYPE RelWithDebInfo CACHE STRING "Build type"
    FORCE)
endif()
```

- Build types: `Debug`, `Release`, `RelWithDebInfo`, `MinSizeRel`.
- CACHE: Makes the variable persistent across CMake runs. In out-of-source builds `CMakeLists.txt` is not re-evaluated on subsequent runs.
- FORCE: Overrides any previous value.
- STRING: "Build type" provides a description in CMake GUI.

Adding Compiler Flags

```
target_compile_options(my_library PRIVATE
    $<$<CONFIG:Debug>:-g -Wall>
    $<$<CONFIG:Release>:-O3 -DNDEBUG>
)
```

- **Generator Expressions:** `$<CONFIG:Debug>` applies flags only for Debug builds.

Installing Targets

```
install(TARGETS my_library
    LIBRARY DESTINATION lib
    PUBLIC_HEADER DESTINATION include
)
```

- Installs the shared library to the `lib` directory.
- Installs public headers to the `include` directory.

Using GNUInstallDirs

```
include(GNUInstallDirs)

install(TARGETS my_library
    LIBRARY DESTINATION ${CMAKE_INSTALL_LIBDIR}
    PUBLIC_HEADER DESTINATION ${CMAKE_INSTALL_INCLUDEDIR}
)
```

- Defines standard GNU library and include directories paths.

Generating and Building the Project

1. **Configure the Project:**

```
cmake -B build
```

   - Generates build files in the `build` directory.

2. **Build the Project:**

```
cmake --build build
# or when using Make as backend
make -C build
```

3. **Run the Program:**

```
./build/my_executable
```

Best Practices for CMake

- **Use Target-Based Commands:**
    - Prefer `target_include_directories` over `include_directories`.
    - Prefer `target_link_libraries` over global linking.
- **Organize `CMakeLists.txt`:**
    - Group related targets together.
    - Use comments to explain sections.
- **Avoid Global Commands:**
    - Avoid `include_directories` and `link_libraries` globally.
- **Use Modern CMake Features:**
    - Generator expressions for conditional configurations.
    - `FetchContent` for managing external dependencies.

Debugging Tools

Buggy program example

```
/* Linked list of n = 5 nodes
         .---------.    .---------.          .--------------.
         | val = 4 |    | val = 3 |          | val = 0      |
 head -> | next  --|--> | next  --|--> ... -> | next =  NULL |
         '---------'    '---------'          '--------------'
 */

#include <stdlib.h>
#include <assert.h>

struct Node
{
  int val;
  struct Node *next;
};

int main()
{
  int n = 5;

  struct Node *head = init_list(n);
  // ... do something with the list ...
  delete(head);

  return 0;
}
```

```c
struct Node *init_list(int n)
{
  struct Node *head = NULL;
  for (int i = 0; i < n; ++i)
  {
    struct Node *p = malloc(sizeof *p);
    assert(p != NULL);
    p->val = i;
    p->next = head;
    head = p;
  }
  return head;
}

void delete(struct Node *head)
{
  while (head)
  {
    struct Node *next = head->next;
    free(head);
    head = head->next;
  }
}
```

Running the program...

```
$ gcc -g -O0 -o buggy buggy.c
$ ./buggy
Segmentation fault (core dumped)
```

- Inspect the state of a program at the moment it crashes.
- Step through the code line by line.
- Inspect variables and memory.
- Set breakpoints to pause execution at specific lines.

(Live demonstration)

```
$ gdb ./buggy
Program received signal SIGSEGV, Segmentation fault.
0x000055555555522b in delete (head=0xa45d97b66d0683e8) at buggy.c
    :28
28          struct Node *next = head->next;
(gdb) x head
0xa45d97b66d0683e8:     Cannot access memory at address 0
    xa45d97b66d0683e8
```

Valgrind: memory debugging and leak detection

- Detects memory leaks, invalid memory access, and uninitialized memory usage.
- Runs the code in a virtual sandbox that monitors every memory operation.

(Live demonstration)

```
$ valgrind --leak-check=full ./buggy
==537945== Invalid read of size 8
==537945==    at 0x109243: delete (buggy.c:30)
==537945==    by 0x109282: main (buggy.c:40)
==537945==  Address 0x4a94188 is 8 bytes inside a block of size
    16 free'd
==537945==    at 0x484988F: free (in /usr/libexec/valgrind/
    vgpreload_memcheck-amd64-linux.so)
==537945==    by 0x10923E: delete (buggy.c:29)
==537945==    by 0x109282: main (buggy.c:40)
==537945==  Block was alloc'd at
==537945==    at 0x4846828: malloc (in /usr/libexec/valgrind/
    vgpreload_memcheck-amd64-linux.so)
==537945==    by 0x1091B2: init_list (buggy.c:15)
==537945==    by 0x109272: main (buggy.c:38)
```

Other tools: ASAN, UBSAN

- **AddressSanitizer (ASAN):** Detects memory errors such as buffer overflows and use-after-free.
- **UndefinedBehaviorSanitizer (UBSAN):** Detects undefined behavior in C/C++ programs.
- Works on threaded programs and has lower overhead than Valgrind.

(live demonstration)

```
$ gcc -fsanitize=address -g -O0 -o buggy_asan buggy.c
$ ./buggy_asan
=================================================================
==538335==ERROR: AddressSanitizer: heap-use-after-free on address
     0x502000000098 at pc 0x5bec7c7343e9 bp 0x7ffdf3015150 sp 0
    x7ffdf3015140
READ of size 8 at 0x502000000098 thread T0
    #0 0x5bec7c7343e8 in delete /home/poliveira/test-gdb/buggy.c
    :30
    #1 0x5bec7c73442c in main /home/poliveira/test-gdb/buggy.c:40
```

Software Testing

- 1996: Ariane-5 self-destructed due to an unhandled floating-point exception, resulting in a $500M loss.
- 1998: Mars Climate Orbiter lost due to navigation data expressed in imperial units, resulting in a $327.6M loss.
- 1988-1994: FAA Advanced Automation System project abandoned due to management issues and overly ambitious specifications, resulting in a $2.6B loss.
- 1985-1987: Therac-25 medical accelerator malfunctioned due to a thread concurrency issue, causing five deaths and numerous injuries.

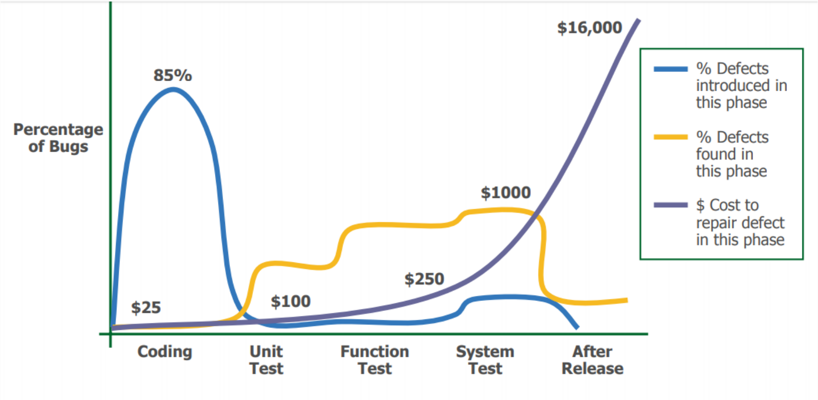


Figure 2: Software Costs (Applied Soft. Measurement, Capers Jones)

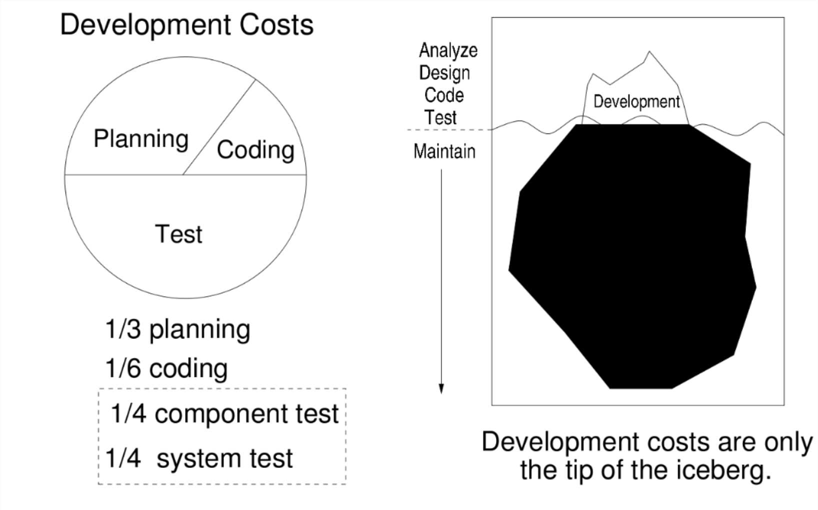


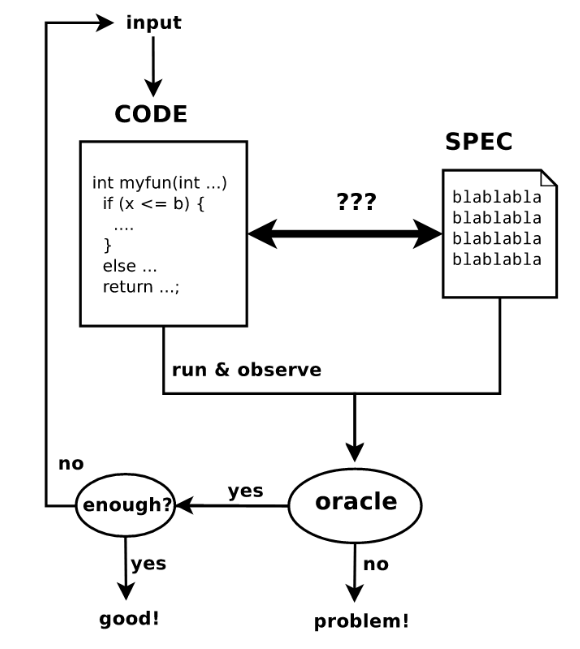
Figure 3: Software Costs (Nancy Leveson)

Verification and Validation (V&V)

- **Validation**: Does the software meet the client's needs?
  - "Are we building the right product?"
- **Verification**: Does the software work correctly?
  - "Are we building the product right?"

Approaches to Verification

- Formal methods
- Modeling and simulations
- Code reviews
- **Testing**


input
CODE
int myfun(int ...)
if (x <= b) {
....
}
else ...
return ...;
SPEC
blablabla
blablabla
blablabla
blablabla
???
run & observe
no
enough?
yes
oracle
yes
no
good!
problem!

V Cycle Model

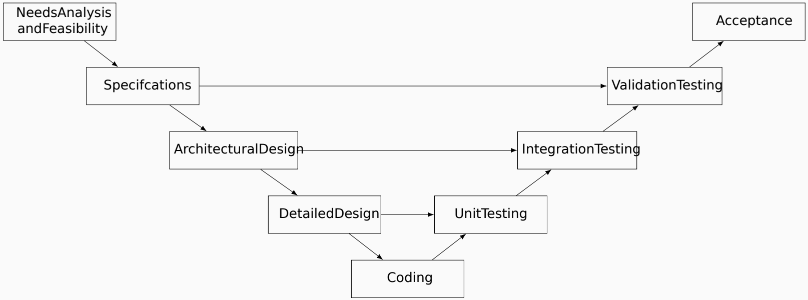


Figure 5: V-Model: Validation followed by Verification

Different Types of Tests

- **Unit Tests:**
  - Test individual functions in isolation.
  - Test-driven development (TDD): Focus on writing maintainable, simple, and decoupled code.
- **Integration Tests:**
  - Test the correct behavior when combining modules.
  - Validate only functional correctness.
- **Validation Tests:**
  - Test compliance with specifications.
  - Test other characteristics: performance, security, etc.
- **Acceptance Tests:**
  - Validate requirements with the client.
- **Regression Tests:**
  - Ensure that fixed bugs do not reappear.

Black-Box and White-Box Testing

Black-Box Testing (Functional)

- Tests are generated from specifications.
- Uses assumptions different from the programmer's.
- Tests are independent of implementation.
- Difficult to find programming defects.

White-Box Testing (Structural)

- Tests are generated from source code.
- Maximizes coverage by testing all code branches.
- Difficult to find omission or specification errors.

Both approaches are complementary.

What to Test?

- Running the program on all possible inputs is too costly.
- Choose a subset of inputs:
  - Partition inputs into equivalence classes to maximize coverage.
  - Test all code branches.
  - Test edge cases.
  - Test invalid cases.
  - Test combinations (experimental design).

Example of Partitioning (1/3)

Specification

```
/* compare returns:
 *   0 if a is equal to b
 *   1 if a is strictly greater than b
 *  -1 if a is strictly less than b
 */
int compare (int a, int b);
```

What inputs should be tested?

Equivalence Classes (2/3)

Variable	Possible Values
a	{positive, negative, zero}
b	{positive, negative, zero}
result	{0, 1, -1}

Example Test Cases

a	b	result
10	10	0
20	5	1
3	7	-1
-30	-30	0
-5	-10	1
...	...	...

It is possible to select a subset of classes!

Boundary Tests (3/3)

a	b	result
-2147483648	-1	-1

Discussion

- Automatic test generation.
- Test coverage calculation.
- Mutation testing.
- Fuzzing.
- Importance of using automated testing tools.
- Importance of using continuous integration tools.

Unity Test Framework

Figure 6: Unity Logo

Unity Test Framework

- Lightweight and simple unit testing framework for C.
- Designed for embedded systems but can be used in any C project.
- Provides a set of macros and functions to define and run tests.

Setting Up Unity

- Separate Unity tests into a separate directory, e.g., `tests/`.
- Include the Unity header in your test files:

```c
#include "unity.h"
```

- Requires linking against the Unity library
- We will link against a static library `libunity.a`, since Unity uses CMake, we will use FetchContent to add it to our projects.

Writing Tests

- test_functions use `TEST` macros provided by Unity to assert conditions.

```
void test_function_name(void) {
    ...
    TEST_ASSERT_EQUAL_INT(expected, actual);
    TEST_ASSERT_NOT_NULL(pointer);
    TEST_ASSERT_TRUE(condition);
    ...
}
```

- Reference for all assertions: Unity Assertions

Example: testing our linked list

```c
#include "unity.h"
#include "buggy.h"
void test_delete_single_node(void) {
    struct Node *head = init_list(1);
    TEST_ASSERT_NOT_NULL(head); // head should not be NULL
    TEST_ASSERT_EQUAL_INT(0, head->val); // head should be 0
    delete(head); // should not crash
    TEST_ASSERT_NULL(head); // head should be NULL after deletion
}
void test_delete_multiple_nodes(void) {
    struct Node *head = init_list(5);
    TEST_ASSERT_EQUAL_INT(4, head->val); // head should be 4
    TEST_ASSERT_EQUAL_INT(3, head->next->val);
    delete(head); // should not crash
    TEST_ASSERT_NULL(head); // head should be NULL after deletion
}
```

Running Tests

- Create a test runner function to execute all tests:

```
int main(void) ## Boundary Tests{
    UNITY_BEGIN();
    RUN_TEST(test_function_name);
    ...
    return UNITY_END();
}
```

SetUp and TearDown

- SetUp and TearDown functions can be defined to run before and after each test.

```c
void setUp(void) {
    // Code to run before each test
}

void tearDown(void) {
    // Code to run after each test
}
```

Code Coverage with unit tests

- Use `gcov` or `llvm-cov` to measure code coverage of your tests.
- Compile your code with coverage flags:

```
gcc --coverage -g -O0 -o test_runner test_runner.c my_code.c -
    lunity
```

- gcov instruments the basic blocks of code to record what is executed during tests.
- gcovr generate HTML reports showing which parts of the code were covered by tests.

Documentation with Doxygen

- Doxygen is a documentation generator for C, C++, and other languages.
- It extracts comments from the source code and generates documentation in various formats (HTML, LaTex, etc.).
- Use special comment blocks to document functions, parameters, return values, and more.
- Example of a documented function:

```c
/**
 * @brief Initializes a linked list with n nodes.
 * @param n Number of nodes to create.
 * @return Pointer to the head of the linked list
 * @return NULL if memory allocation fails.
 */
struct Node *init_list(int n);
```

- Generate documentation using the `doxygen` command with a configuration file (`Doxyfile`).

Credits and Bibliography

- Course “Automated Software Testing,” Sébastien Bardin.
- CMake Tutorial
- CMake Best Practices
- Unity Test Framework
- Valgrind
- GDB
- ASAN/UBSAN
- Doxygen