[Software Development]

Compiling Programs & Libraries

Davide Balzarotti

Eurecom – Sophia Antipolis, France

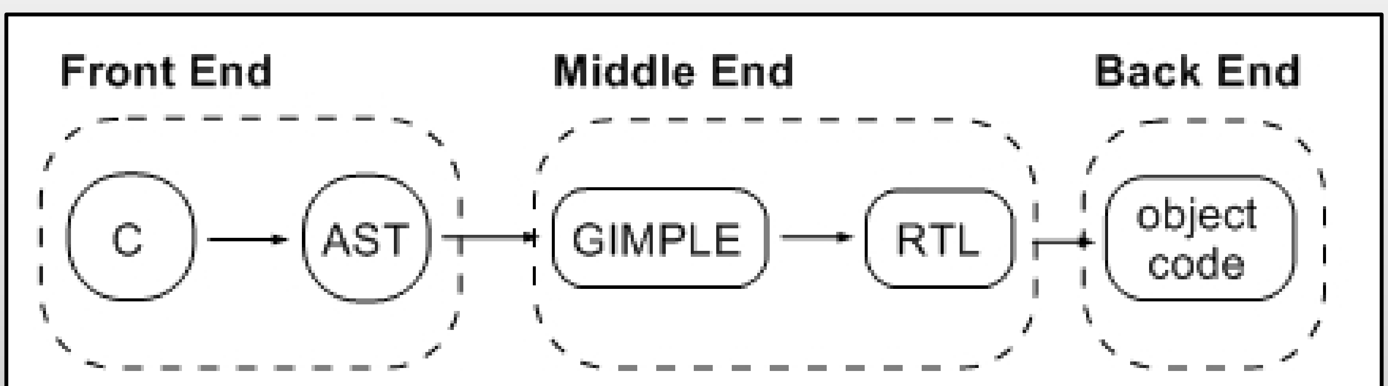
Software Development Tools

1. Configuring and Building a program
   - GCC
   - Makefiles
   - Autotools
2. Writing and managing code
3. Packaging and Distributing the application
4. Debugging and Profiling

The GNU Compiler Collection

GCC is an integrated distribution of compilers for several major programming languages

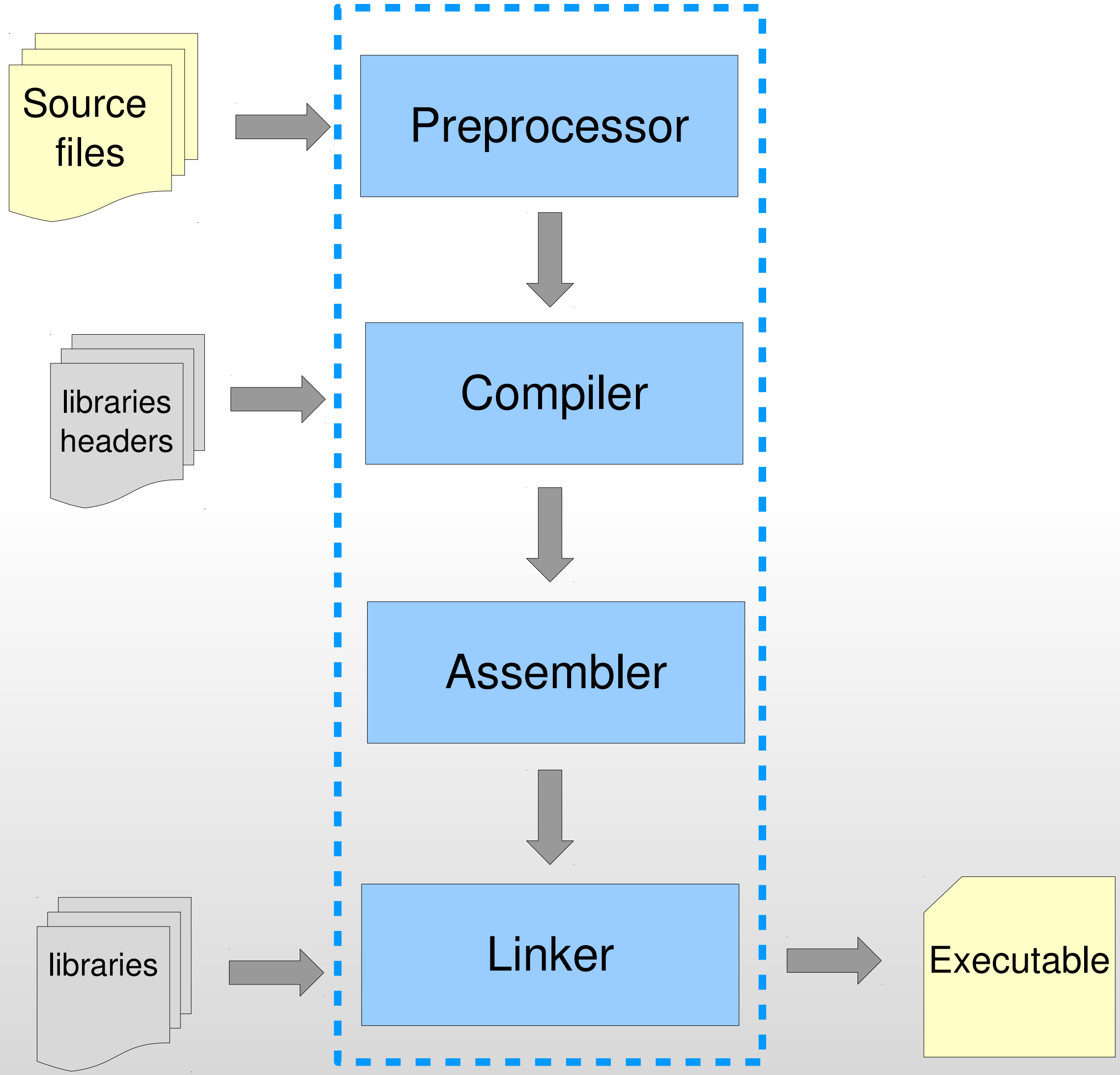
- Historically an acronym for "GNU C Compiler"
  (it used to support only the C language)
- Frontends for C, C++, Objective-C, Fortran, Java, and Ada
  - Plus several other languages that are maintained separately
    (e.g, for Pascal, Mercury, and COBOL)
- Backends can generate code for over 30 different computer architectures



GCC

- GCC is portable: it runs on most platforms and operating systems available today
- GCC is a cross-compiler: it can produce executable files for a different system from the one used to run GCC itself
  - This allows software to be compiled for embedded systems which are not capable of running a compiler
- `gcc` is the program responsible to find and invoke, in the right sequence, the proper compiler, assembler and linker

A 4 Stage Process



*Use: gcc -save-temps to save all the intermediate files

Stage 1 - Pre-Processing

- Performed by a program called the preprocessor (`cpp`)
- Prepare the file for compilation (in memory)
  1. Strips comments from the code
  2. Places all the definitions from the included files into the .c source files
  3. Translates all macros into inline C code
- Syntax error are *not* detected at this stage!
- By default, this step does not change the source file or produce any additional files.
  - `gcc -E` : execute the pre-processing phase and print the result
  - Already pre-processed file have extension "`.i`"

Stage 2 - Compiling

- Performed by a program called compiler
- Translates the preprocessor-modified source code into assembler code
- Checks for syntax errors and warnings
  - In case of errors, it stops and don't produce the result
  - In case of warnings, the output file is created anyway
- Requires the header files for all the library used by the program
- `gcc -S` : compile (and run the preprocessor if required)
  - Saves the assembler code in a "`.s`" file

Compiler Options (warnings)

- Options:
  - `-w` – suppress all warning messages
  - `-Werror` – transform warnings in errors
  - `-ansi` – turns off features that are incompatible with C90 or standard C++
  - `-Wall` – enables all warning for questionable code construct (implicit declarations, newlines in comments, unused functions or variables, questionable lack of parentheses, uninitialized variable usage,...)
  - `-pedantic` – check code for strict ISO conformance and generates warnings otherwise
- You can also enable/disable single warning messages

  `-Wlogical-op, -Wconversion, ...`

Compiler Options (Optimizations)

- It is possible to enable optimizations in the assembler code by using the `-O<level>` option
- Turning on optimizations makes the compiler attempt to improve the performance and/or the code size at the expense of a longer compilation time (and possibly the ability to debug the program)
  - `-O0` straightforward compilation, no optimizations are performed
  - `-O1` use common forms of optimization that do not require too much compilation time or speed-space tradeoffs
  - `-O2` turns on almost all the optimizations, include instruction scheduling (still no optimizations requiring speed-space tradeoffs are used)
  - `-O3` turns on more expensive optimizations such as function inlining (can increase the size of the final executable)
  - `-Os` tries to generate the smaller possible executable

Compiler Options (Others)

- Several fine-grained assembly options can be specified with the -f flag

  `-fstack-protector  -funroll-loops, …`

- By default, gcc searches the following directories for header files:
  - `/usr/local/include/`
  - `/usr/include/`

- The compiler needs to locate the header files
  - `-I path` – specify additional paths for included header files

- `-g` : tells the compiler to include debugging symbols (different format can be specified)

- `-std=c99` : tell compiler to use the c99 (or other) standard

Address Sanitizer

- GCC 4.8 includes AddressSanitizer, a code instrumentation to to detect out-of-bounds and use-after-free vulnerabilities

  ```
  -fsanitize=address
  ```

- It also includes a memory instrumentation to detect data race conditions

  ```
  -fsanitize=thread
  ```

Stage 3 - Assembling

- Performed by a program called assembler (`as`)
  - `gcc -c` : execute all phases (if required) but do not invoke the linkers
  - Saves the result in a "`.o`" file
- The purpose of the assembler is to convert assembly language into machine code and generate an object file
  - The assembler leaves the addresses of the external functions undefined (they will be fixed later by the linker)
- The object files contains:
  - Machine code and program data
  - Relocation information to help the linker to fix the object code
  - A Symbol Table - information about symbols defined in the file and symbols to be imported from other modules
  - Debugging Information (optional)
- The format of the object file depends on the Operating System

ELF

- Executable and Linking Format (ELF) is a flexible and extensible file format for object files (executables, libraries..)
  - Currently used by Linux, *bsd, IRIX, Solaris, OpenVMS, OpenVMS, BeOS, Playstation, Wii...
  - Windows use a different format called Portable Executable (PE)

- ELF has an associated debugging format called DWARF
- ELF files contain different sections:

  `.text` contains the executable instructions of a program

  `.data` contains initialized data

  `.bss` holds uninitialized data

  `.init` `.fini` contain executable instructions for the process initialization and termination

  ...

File Symbols

- The compiler automatically include symbols name in the object files (e.g., the name of the functions)
  - Additional debug symbols can be added by the `-g` option
- The `nm` tool can be used to print the symbols list

```c
#include <math.h>
#include <stdio.h>

int global_var;
float pi = 3.1415;

int main(){
    int   x = 2;
    float r;
    r = sqrt(x);
    printf("sqrt(%d)=%f\n",x,r);
    return 0;
}
```

```
> gcc -c test.c
> nm test.o
0000004 C global_var
0000000 T main
0000000 D pi
        U printf
        U sqrt
```

File Symbols

- The compiler automatically include symbols name in the object files (e.g., the name of the functions)
  - Additional debug symbols can be added by the `-g` option
- The `nm` tool can be used to print the symbols list

```c
#include <math.h>
#include <stdio.h>

int global_var;
float pi = 3.1415;

int main(){
    int   x = 2;
    float r;
    r = sqrt(x);
    printf("sqrt(%d)=%f\n",x,r);
    return 0;
}
```

```
> gcc -c test.c
> nm test.o
0000004 C global_var
0000000 T main
0000000 D pi
        U printf
        U sqrt
```

Symbol Type:

C	uninitialized data
D	initialized data
T	in the .text segment (code)
U	used but not defined (imported)

File Symbols

- Useful options:
  - `-S` : print symbols size
  - `--demangle` : transform back low level symbol names to user level names (very useful for C++)
- To save disk space it is possible to strip out the symbols from the binary using the `strip` command

```
> gcc -c test.c
> file test.o
test.o: ELF 32-bit LSB relocatable, Intel 80386,
version 1 (SYSV), not stripped

> strip -s test.o
test.o: ELF 32-bit LSB relocatable, Intel 80386,
version 1 (SYSV), stripped

> nm strip
nm: test.o: no symbols
```

Stage 4 - Linking

- Executed by a program called linker (`ld`)
- Combines the program object code with library object code to produce the final executable file
- Saves the executable code to a file
  - By default, `gcc` creates an executable program called `a.out`
  - You can specify another name with: `-o filename`
- The linker needs to find the object code for each library
- By default, it searches the following directories for libraries:
  - `/usr/local/lib/`
  - `/usr/lib/`
- `-L path` : add path to the library paths

Linking two files

func.h

```c
void f(int x, int y, int z);
```

func.c

```c
#include <stdio.h>
#include <func.h>

void f(int x, int y, int z){
    printf("%d\n",x+y+z);
}
```

main.c

```c
#include <func.h>

int main(){
    f(1,2,3);
    return 0;
}
```

```
# compile the func file
> gcc -I. -c func.c

# compile the main file
> gcc -I. -c main.c

# link the two and generate the
# executable
> gcc -L. func.o main.o -o main

# or simply..
> gcc -I. func.c main.c -o main
```

*Note: func.h is included in angle brackets to show how to use linker options

Static and Dynamic Libraries

- External libraries are usually provided in two forms: static libraries (.a) and shared libraries (.so)
- Static library are *archives* of object files that are combined into the executable by the linker
  - No dependency problems: everything the program need is inside the file
- Shared library are not included into the executable by the linker (the library code is loaded at runtime)
  - ✔ Save disk space: the executable is much smaller
  - ✔ Save memory: one copy of the library is shared by all running programs
  - ✔ The library can be modified (e.g., to fix a bug) without having to recompile all the applications that use the library

Linking

- It is necessary to tell the linker which library we want to link to our program
- For example, if we want to link the math library (called `libm`):
  - `gcc calc.c /usr/lib/libm.a  -o calc` → static linking
  - `gcc calc.c /usr/lib/libm.so -o calc` → dynamic linking

Linking

- It is necessary to tell the linker which library we want to link to our program
- For example, if we want to link the math library (called `libm`):
  - `gcc calc.c /usr/lib/libm.a  -o calc` → static linking
  - `gcc calc.c /usr/lib/libm.so -o calc` → dynamic linking
- Specifying the complete path of each library is too verbose
  - `-l xx` : search for a library named libxx.so or libxx.a
  - By default, gcc try to use shared libraries (if available)
    If not, it uses static libraries
  - `--static` : force GCC to use the static libraries
  - The order is important, always put the `-l` options at the end (!!)
- gcc automatically add `-lc` in order to link the standard C library (`libc.so`)

Creating a Static Library

- Static libraries are just ***ar*** archives containing the object files
- To transform the `func.c` and `func.h` files to a static library:
  - Compile the files to object files
  - Create an archive named `libfunc.a` and add the file `func.o` to it

```
> gcc -c func.c
> ar rcs libfunc.a func.o
```

- To import the library:

```
> gcc -I. -L. main.c -lfunc
```

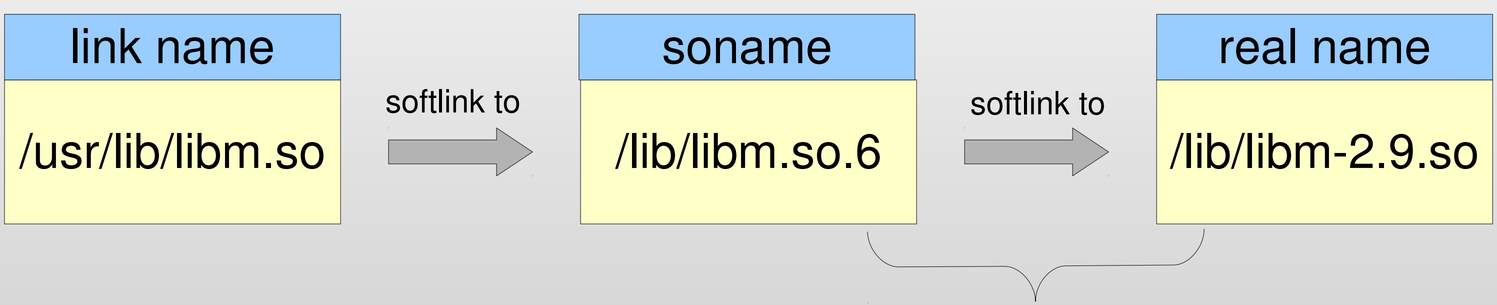
Tell the compiler where to find the func.h file

Tell the linker where to find the libfunc.a library

Tell the linker that we want to link a library called libfunc

Shared Library - Names

- A shared library has two names: the *soname* and the *real name*
  - soname: lib???.so.version (e.g., `libattr.so.1`)
    - Version is the version number that is incremented whenever the library interface changes
  - The real name is the name of the file containing the actual library code (e.g., `libattr.so.1.0.1, or libm-2.12.1.so`)
    - The real name usually includes a minor number and a release number
- In addition, the linker usually look for a library (through the -l option) using yet another name



This link is created automatically by `ldconfig`

Creating a Shared Library

- First, create the object files that will go into the shared library using:
  - `-fPIC` – to generate Position Independent Code required for shared libraries
- Compile the library using:
  - `-shared` – to tell gcc that you want to create a shared library
  - `-Wl,-soname,libname` – to specify the library soname
- Put the result in `/usr/local/lib` and run `ldconfig`
- Create a symbolic link for the linker name (`libname.so`)

Creating a Shared Library

Step 1: Compile the library

```
> gcc -I. -c -fPIC func.c
> gcc -shared -Wl,-soname,libfunc.so.1
    -o libfunc.so.1.0.1 func.o -lc
```

Step 2: Install the library and Fix the names

```
> cp libfunc.so.1.0.1 /usr/local/lib
> ldconfig
> ls -l /usr/local/lib/libfunc*
  … /usr/local/lib/libfunc.so.1.0.1
  … /usr/local/lib/libfunc.so.1 -> libfunc.so.1.0.1
> ln -s /usr/local/lib/libfunc.so.1 /usr/local/lib/libfunc.so
```

Step 3: Compile the application

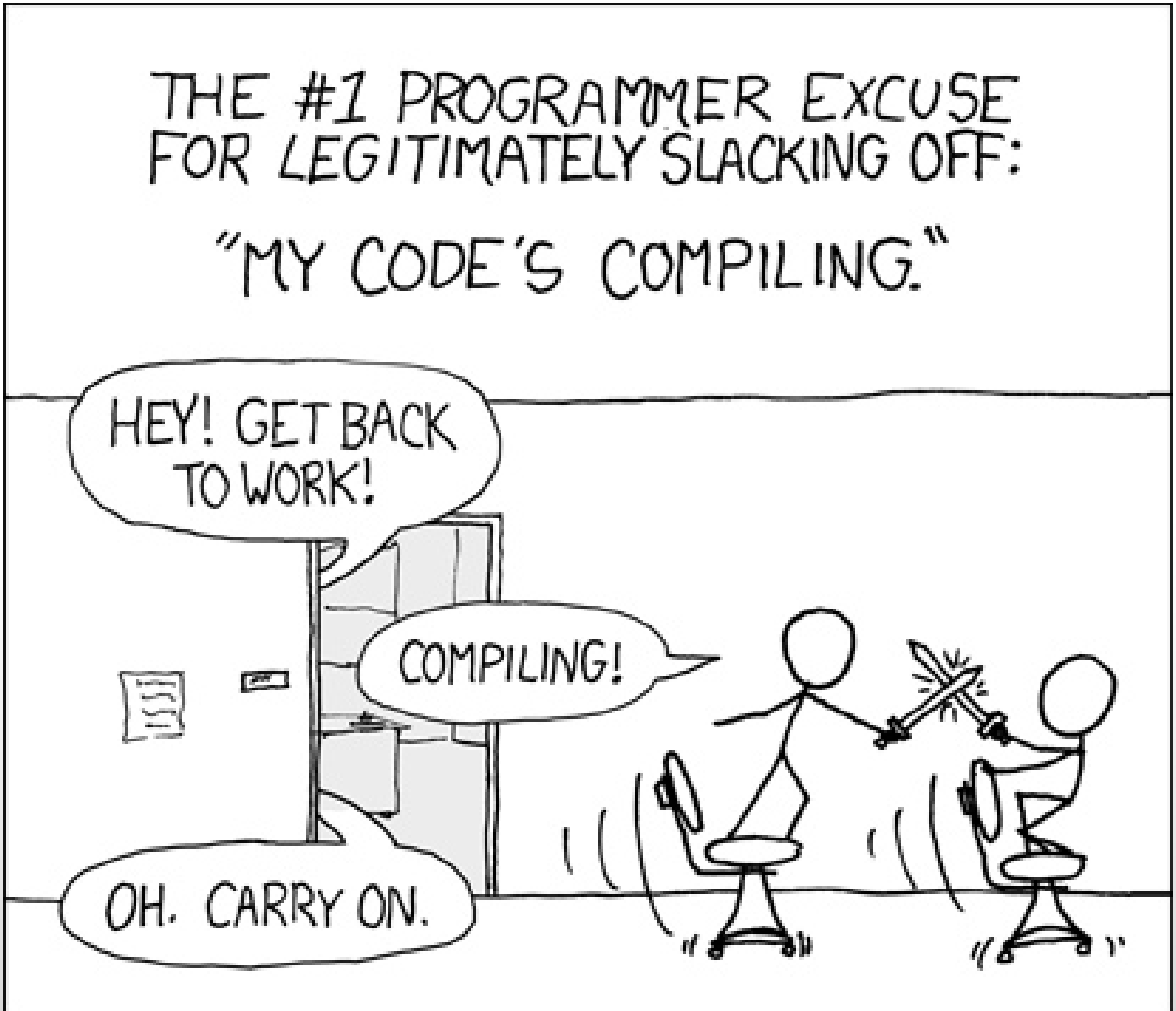
```
> gcc -I. main.c -o main -lfunc
> ldd main
    linux-gate.so.1 =>  (0xb804f000)
    libfunc.so.1 => /usr/local/lib/libfunc.so.1 (0xb8034000)
    libc.so.6 => /lib/tls/i686/cmov/libc.so.6 (0xb7ed1000)
    /lib/ld-linux.so.2 (0xb8050000)
```

Shared Libraries at Runtime

- You can see which shared library is required by a program by using the `ldd` command
- At runtime, when the executable file is started its loader function must find the shared library in order to load it into memory
- If you place the library in a non-standard place:
  - You have to tell the linker with the -L option
  - You have to tell the loader by modifying the `LD_LIBRARY_PATH` environment variable

Clang

- Compiler infrastructure written in C++ by Apple
  - Generates LLVM bytecode that can be interpreted (JIT compilation) or compiled to native code
  - Front ends for C, C++, D, Fortran, Objective-C, GCC
  - Faster than GCC, code quality still a bit lower
- Default compiler on MacOS, and FreeBSD


THE #1 PROGRAMMER EXCUSE
FOR LEGITIMATELY SLACKING OFF:
"MY CODE'S COMPILING."
HEY! GET BACK TO WORK!
COMPILING!
OH. CARRY ON.