# Conduite de Projet
# Cours 5 — The C build process

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2017–2018

# Outline

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# Compiler

## Definition (compiler)

A compiler is a computer program that transforms source code (written in some source language) into another computer language called target language.

- usually, but not always, the source language is a programming language that humans (programmers) are able to understand
  - e.g., C, Java, OCaml, Scala, Python, Ruby, F#, Matlab, ...
- usually, but not always, the target language is object code that can be executed by a hardware platform
  - e.g., x86-32, x86-64, ARM7, powerpc, etc. (native compilers)
  - e.g., JVM bytecode, Python bytecode, etc. (bytecode compilers)

## Intuition

A compiler is a translator from one language to another.

# Interpreter (digression)

**Question**

**What is an *interpreter* then?**

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**What is an *interpreter* then?**

An interpreter is an all-in-one computer program that compiles and execute source code on-the-fly.

Pro/con:

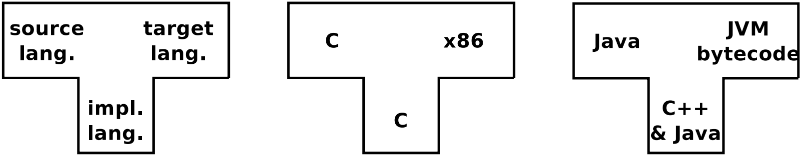
- ✓ higher portability
- ✗ higher startup time
- source-code distribution

# Compiler construction

A compiler is not a magic object. It is a program like others:

- written in some programming language (the implementation language)
- by programmers, like you

At least 3 languages are always involved in compiler construction: source, target, and implementation.




*How do we write a compiler without a compiler?*

This is the compiler bootstraping problem (see modules *introduction à la compilation* L3 and *compilation avancée* M2)

luckily, we've plenty of readily available compilers these days...

# Essential anatomy of a compiler

The architecture of a compiler consists of a few common macro-parts:

1. **front end:** check for program correctness w.r.t. source language semantics and output an intermediate representation (IR) of the input program
   - e.g., lexical checking, syntax checking, type checking, etc.

2. **middle end:** program optimization by rewriting the IR
   - e.g., dead code removal, constant propagation, loop unrolling, etc.

3. **back end:** translate IR to the target language, doing further (platform-specific) optimization
   - e.g., assembly language for the target platform

# Before and after compilation

In spite of being already complex enough, we often need two more steps to get from a source to a target program.

- Before compilation we might have to run the source program through a preprocessor that prepares the program for compilation
  - e.g., the C preprocessor cpp takes care of all `#directives`
  - e.g., the `camlp4` preprocessor can perform arbitrary syntactic transformation on OCaml programs
  - e.g., Lisp preprocessors, Domain Specific Languages (DSL), etc.

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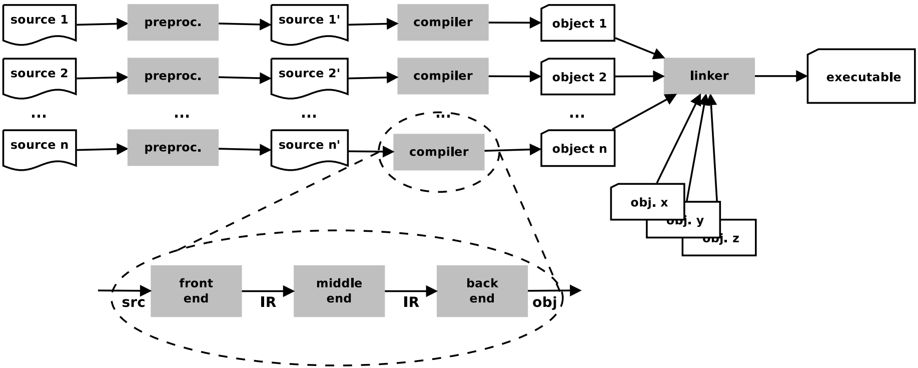
  - e.g., Lisp preprocessors, Domain Specific Languages (DSL), etc.
- After compilation we need to
  1. combine several compiled objects (i.e., the result of compiling different source files) with the needed libraries into a single compiled program
  2. "assemble" assembly language code to the actual sequence of bytes that the operating system will be able to execute

A linker (or *link editor*) is the program that takes care of these steps

# The build process

Putting it all together, the build process looks like this:




- general idea: each step embodies a translation from one language to another
- . . . but the number of phases varies; there might be more!
  - e.g., DSL ⟶ "source" code ⟶ object code ⟶ . . .

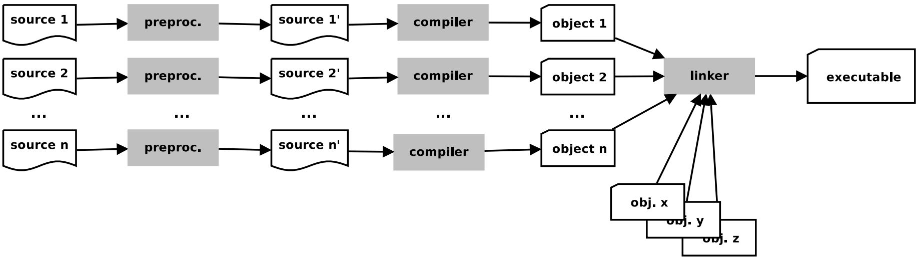
# Terminology and slang — "compilation"

Strictly speaking, "compilation" is only the part of the build process in between preprocessing and linking, *extremes excluded*.

However we (as in "programmers") often use the term "compilation" to refer to the build process as a whole, including preprocessing and linking.

- this slightly imprecise terminology is supported by the practice of using a single tool to drive the entire build process
- the tool is also usually distributed as part of compiler suites
  - `cc` — C "compiler"
  - `ocamlc` — OCaml "compiler"
  - `javac` — Java "compiler"
  - `scalac` — Scala "compiler"
  - etc.

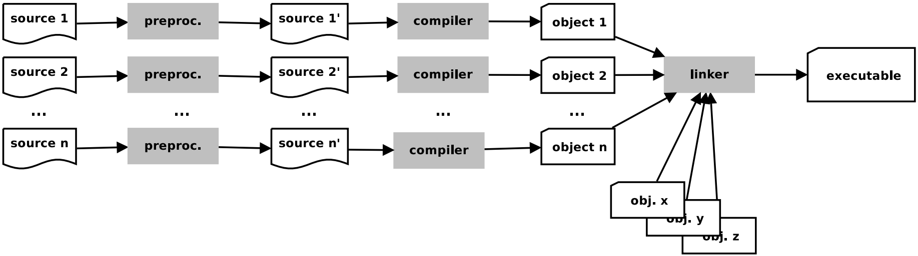
# Build stages




When do the various phases happen?

- usually, preprocessing and compilation happens together, on a file per file basis
- compilation and linking might happen together (in trivial projects) or be separate phases (in medium to complex projects)

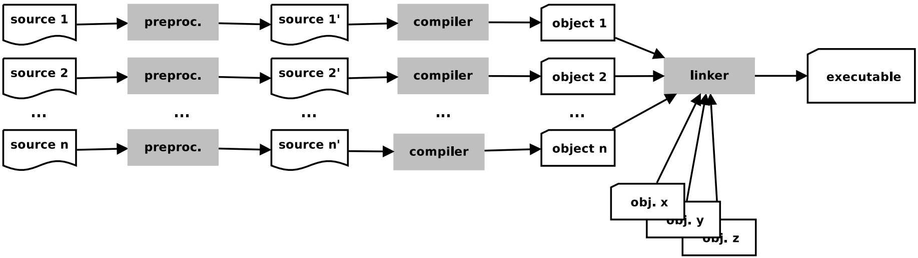
# Build dependencies




- preprocessing might act on several source files at a time
  - e.g., inclusion of a header/interface file in an implementation file
  - e.g., syntactic transformations implemented as compiled programs
- to compile $source_i$ we might need $object_j$, with $i \neq j$

Those are just common examples of build dependencies.

# Build dependencies (cont.)




Typical effects of dependencies on the build process are:

- forcing a (partial) order on compilation steps
  - e.g., the linking step must be performed after the compilation steps of all involved objects
- guiding the (re-)build process to (re-)build only what is needed after only some files get changed
  - e.g., recompiling a C source file is needed only when either itself or its `#include`-s have been changed *after* the last compilation

# The C build process

We are going to focus on the build process for the C language.
Its architecture maps 1-1 to the one we have presented.

- the C preprocessor (sometimes called cpp) transforms C programs with `#directives` to C programs where those directives have been executed (+ line no. annotations)
- the C linker is the ordinary system-level linker, usually provided by the operating system
- the C compiler (traditionally called cc) transforms C programs (w/o `#directives`) to object files supported by the system-level linker
  - can also be used to drive the preprocessing and linking phase
  - we can use the C compiler as driver of the whole C build process

# Outline

# The C preprocessor — generalities

The C language is defined by an international standard, whose most recent incarnation is ISO/IEC 9899:2011 (AKA “C11”)

- the standard supports a number of meta-language directives whose syntax is `#directive`
- the standard does not mandate the preprocessor be *a separate program*; it just defines the 4th phase of the C translation as “macro expansion and directive handling”
  - many C compilers use a separate cpp program to implement that phase
  - as the semantics of directives is language independent, that allows to use the C preprocessor in other contexts

The main C language features implemented as directives are:

1. file inclusion — `#include`
2. macros — `#define`
3. conditional compilation — `#if`, `#ifdef`, `#ifndef`, . . .

# File inclusion

File inclusion is a common feature of many text processing languages:

- an include directive references an external file by name
- the directive gets expanded to the content of the file as if it were included verbatim where, and in place of, the directive is located

The main advantage of file inclusion is factorization:

- we can reuse the *content* of a file in different locations. . .
- . . . while we have to maintain only one copy of it
  - help with adhering to the DRY (“don’t repeat yourself”) principle

# #include

```c
#include <stdio.h>

int main(void) {
	printf("Hello, world!\n");
}
```

# #include

```
#include <stdio.h>

int main(void) {
        printf("Hello, world!\n");
}
```

⇓

```
typedef unsigned char __u_char;
typedef unsigned short int __u_short;
...
extern int printf (__const char *__restrict __format, ...);
...
extern int scanf (__const char *__restrict __format, ...) ;
...

int main(void) {
        printf("Hello, world!\n");
}
```

# #include

Where are referenced files looked for?
It depends on the used #include syntax:

- `#include <file.ext>` ⇒

- `#include "file.ext"` ⇒

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- #include <file.ext> ⇒ file.ext will be looked for in the standard compiler include path
  - i.e., a list of pre-defined directories where to look for header files
  - can be modified using compiler switches
- #include "file.ext" ⇒

# `#include`

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- `#include "file.ext"` ⇒ as above, but the compiler include path will be extended with the current source directory
  - i.e., `file.ext` can be in the same directory of files that want to include it

# #include

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- #include "file.ext" ⇒ as above, but the compiler include path will be extended with the current source directory
  - i.e., file.ext can be in the same directory of files that want to include it

Either way, #include induces a build dependency from the including file to file.ext:

> if file.ext changes, you shall recompile all files that include it

# #include troubles

Consider the following `utils.h`:

```
#include <stdio.h>
void hello(char *msg) {
        printf("Hello %s!\n", msg);
}
```

and `hello.c`: [1]

```
#include "utils.h"
#include "utils.h"
int main(void) {
        hello("world");
}
```

What will happen when you compile `hello.c`?

**?**

1. multiple `#include` only *looks* stupid; they easily (and often) happen due to transitive inclusion

# #include troubles

Consider the following `utils.h`:

```
#include <stdio.h>
void hello(char *msg) {
        printf("Hello %s!\n", msg);
}
```

and `hello.c`:

```
#include "utils.h"
#include "utils.h"
int main(void) {
        hello("world");
}
```

**Error!**

```
In file included from hello.c:2:0:
utils.h:3:6:  error:  redefinition of ‘hello’
utils.h:3:6:  note:  previous definition of ‘hello’ was here
```

# Macros — #define

The general idea of macros is to define identifiers↔content associations (or *bindings*): wherever the identifier is used, it will get replaced by the associated content by the preprocessor.

- object-like macros: act "like constants"
  - take no parameters; replacement content does not depend on the invocation

**Example (object-like macros)**

| | |
|---|---|
| **#define** PI 3.14159 | *definition* |
| circ = 2 * PI * d; | *usage* |
| circ = 2 * 3.14159 * d; | *expansion* |

# Macros — #define (cont.)

- function-like macros: act "like functions"
  - take parameters; replacement content depends on them

**Example (function-like macros)**

| | |
|---|---|
| **#define** RADTODEG(x) ((x) * 57.29578) | *definition* |
| deg = RADTODEG(17 + 1.2); | *usage* |
| deg = ((17 + 1.2) * 57.29578); | *expansion* |

# Macros — #define (cont.)

- function-like macros: act “like functions”
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**Example (function-like macros)**

```
#define RADTODEG(x) ((x) * 57.29578)        definition
deg = RADTODEG(17 + 1.2);                   usage
deg = ((17 + 1.2) * 57.29578);              expansion
```

**Exercise (macros v. functions)**

*What is the difference between the above and the following?*

```
float rad_to_deg(float rad) {
    return (rad * 57.29578);
}
deg = rad_to_deg(17 + 1.2);
```

# Macros — #undef

An existing macro can be undefined using #undef. The macro will not be expanded any longer in the remainder of the file.

```
#define PI 3.1415
circ1 = 2 * PI * d1;
#undef PI
circ2 = 2 * PI * d2;
```

$\Downarrow$

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```

⇓

```
circ1 = 2 * 3.1415 * d1;
circ2 = 2 * PI * d2;
```

# Function-like macros — pitfalls

Function-like macros are powerful, but very tricky to use!

- for a macro definition to be interpreted as function-like, no space should be present before the formal parameter list
  - ✓ **#define**␣RADTODEG(x)␣((x)␣*␣57.29578)
  - ✗ **#define**␣RADTODEG␣(x)␣((x)␣*␣57.29578)
- a function-like macro usage will be expanded only if it's passed actual parameters
  - deg = RADTODEG; will remain unchanged (and hence likely fail)

# Function-like macros — pitfalls (cont.)

- macro expansion is language agnostic
  - pro: can be used with other syntaxes
  - cons: you can cause syntax errors!

```
#define strange(file) fprintf (file, "%s %d",
strange(stderr) p, 35)
```

*expands to:* `fprintf (stderr, "%s %d", p, 35)`

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*expands to:* `fprintf (stderr, "%s %d", p, 35)`

```
#define ceil_div(x, y) (x + y - 1) / y
a = ceil_div (b & c, sizeof (int));
```

*expands to:* `a = (b & c + sizeof (int) - 1) / sizeof (int);`

see http://tigcc.ticalc.org/doc/cpp.html#SEC22 for more

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a = ceil_div (b & c, sizeof (int));
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*expands to:* `a = (b & c + sizeof (int) - 1) / sizeof (int);`

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Best practices:

- always balance parentheses in macro definitions
- always put parentheses around argument usage in macro definitions

# Conditional compilation

Conditional compilation is the ability to selectively compile or avoid to compile parts of the code.

- alternative code paths might exist in the code depending on the target platform (that is selected at build-time); some of them might simply fail to compile on the wrong platform
- optional code paths might exist depending on the desired build-time configuration
  - *development build*: with extensive debugging code, assertions, and logging
  - *production build*: without any of it
- avoiding to compile unneeded optional code paths is beneficial
  - reduce compile time
  - reduce object/executable size → reduce memory usage
  - improve performances (assert-s, if-s, . . . )

# Conditional compilation — #ifdef & co.

Various C preprocessor directives are used to support conditional compilation.

- #ifdef, #ifndef, #if start a conditional block
  - #ifdef and #ifndef evaluates to true, enabling the corresponding conditional block, depending on whether a macro is defined or not
  - #if can be used to test (a very restricted form) of boolean arithmetic expressions based on literal numbers and other macros
- #endif ends a conditional block (mandatory)
- #else, #elif start alternative branches of a conditional block
- #error can be used to fail at preprocessing time
  - useful when no suitable alternative compilation branch exists

# Conditional compilation — examples

```
#ifdef __unix__ /* pre-defined by compilers targeting Unix */
# include <unistd.h>
#elif defined _WIN32 /* pre-def. by compilers targeting Win */
# include <windows.h>
#endif

#ifdef DEBUG
printf("entering magic_fun\n");
# if VERBOSE >= 2
printf("trace message\n");
# endif /* VERBOSE >= 2 */
#endif /* DEBUG */

#if RUBY_VERSION == 190
# error 1.9.0 not supported
#endif
```

# Avoiding multiple inclusion

Best practice to avoid double inclusion issues.
Sample header file `hello.h`:

```
#ifndef __HELLO_H__
#define __HELLO_H__

void hello(char *msg);

#endif /* __HELLO_H__ */
```

What would be the expansion of the following:

```
#include "hello.h"
#include "hello.h"
#include "hello.h"
```

**?**

# The *actual* preprocessor output

```
#include <stdio.h>
int main(void) {
        printf("Hello, world!\n");
}
```

⇓

# The *actual* preprocessor output

```c
#include <stdio.h>
int main(void) {
        printf("Hello, world!\n");
}
```

⇓

```c
# 29 "/usr/include/x86_64-linux-gnu/bits/types.h" 2 3 4
typedef unsigned char __u_char;
typedef unsigned short int __u_short;
...
# 490 "/usr/include/libio.h" 3 4
extern int printf (__const char *__restrict __format, ...);
...
# 414 "/usr/include/stdio.h" 3 4
extern int scanf (__const char *__restrict __format, ...) ;
...

# 2 "hello.c" 2
int main(void) {
        printf("Hello, world!\n");
}
```

# The *actual* preprocessor output (cont.)

The output of the preprocessor is intermixed with line number annotations — of the form `# nnn "file" ...` — that tells the compiler where a specific line of code *really* come from.

Why is this needed?

# The *actual* preprocessor output (cont.)

The output of the preprocessor is intermixed with line number annotations — of the form `# nnn "file" ...` — that tells the compiler where a specific line of code *really* come from.

- the compiler check for errors w.r.t. language semantics
- errors (& warnings) are reported to the user who should fix them
- to be meaningful to the user, error locations should match the files that the user is editing ≠ preprocessor output
  - line and column numbers are affected by macro expansion

# Outline

# GCC

**GNU Compiler Collection — formerly "GNU C Compiler"**

- one of the most popular C compilers
- Free Software, released under the GNU General Public License (GPL), version 3 or above
- actually, a large collection of compilers
  - front-ends: C, C++, Java, Fortran, Objective-C, Ada, Go
  - back-ends: 60+, ever growing list
- support: preprocessing, compilation, linking
- releases: *1987*: 1.0 (by Richard Stallman et al.); *1992*: 2.0; *2001*: 3.0; *2005*: 4.0; *2015*: 5.1.

`man gcc`

# Building with gcc

All in one build:

```
$ gcc main.c
```

- preprocessing
- building
- linking
  - deliver executable `a.out` (default, historical name)

# Preprocessing with gcc

Preprocessing can be executed as a stand-alone phase using cpp:

```
$ cpp main.c

$ # same, asking gcc to stop after preprocessing
$ gcc -E main.c
```

- will dump preprocessor output to standard output

The -o option can be used on all gcc (& friends) invocations to set output destination (overriding default names):

```
$ cpp -o main.i main.c
$ gcc -E -o main.i main.c
```

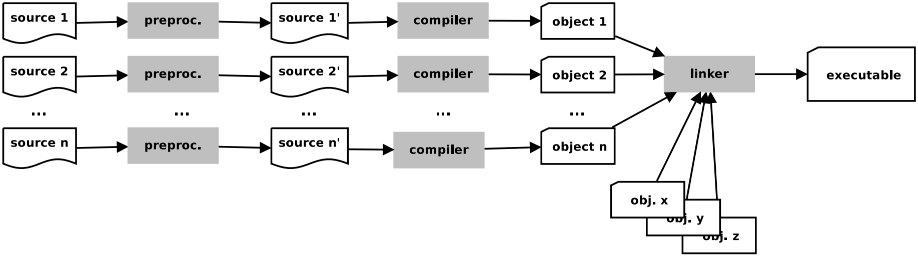
- will save preprocessor output to main.i

# Compiling with gcc

The -c option asks gcc to stop after compilation

- i.e., preprocessing + compilation, but no linking

It is needed in all non trivial build processes, to compile objects separately and postpone linking.



# Compiling with gcc (cont.)

The default destination for the object corresponding to a source file `source.c` is `source.o`. It can be overridden with `-o`, as usual.

It is recommended to always compile with `-Wall` that requires the compiler to enable all warnings about code correctness:

- uninitialized variables
- unused variables
- implicit function declaration
- missing parentheses
- etc.

# Compiling with gcc — examples

```
$ gcc -Wall -c foo.c
$ gcc -Wall -c bar.c
$ gcc -Wall -c main.c
```

- build objects `foo.o`, `bar.o`, and `main.o`, ready to be linked

# Linking with gcc

Once all objects are available, we can use gcc to link them together by simply passing them as arguments—as if they were source files.

```
$ gcc -o my-program foo.o bar.o main.o
```

- will build the executable `my-program` linking together 3 objects
- default linking destination is `a.out` (if `-o` is omitted)

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To link a program that uses external libraries, you will need to reference them using `-l` at link-time.

- passing `-lfoo` will tell the linker to look for the `libfoo` library in the default library search path

```
$ gcc -o my-program foo.o bar.o main.o -lm
```

- link with `libm` (math library)