Modern C++ Programming

18. C++ Ecosystem

CMake, Documentation, and Other Tools

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CMake

CMake Overview

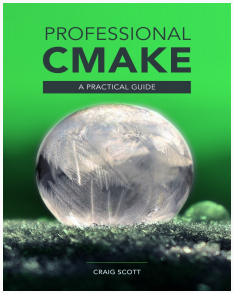
`CMake` is an *open-source*, *cross-platform* family of tools designed to build, test and package software

`CMake` is used to control the software compilation process using simple platform and compiler independent configuration files, and *generate* native `Makefile/Ninja` and workspaces that can be used in the compiler environment of your choice

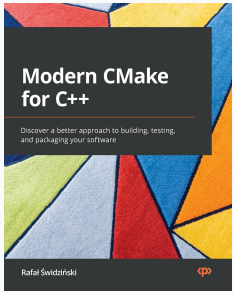
`CMake` features:

- Turing complete language (if/else, loops, functions, etc.)
- Multi-platform (Windows, Linux, etc.)
- Open-Source
- Generate: `makefile, ninja, etc.`
- Supported by many IDEs: `Visual Studio, Clion, Eclipse, etc.`

CMake Books



`Professional CMake: A Practical Guide (21th)`
C. Scott, 2025



Modern CMake for C++ (2nd)
R. Świdziński, 2024

CMake - References

- 19 reasons why CMake is actually awesome
- An Introduction to Modern CMake
- Effective Modern CMake
- Awesome CMake
- Useful Variables

Install CMake

Using PPA repository

```
$ wget -O - https://apt.kitware.com/keys/kitware-archive-latest.asc 2>/dev/null |
  gpg --dearmor - | sudo tee /etc/apt/trusted.gpg.d/kitware.gpg >/dev/null
$ sudo apt-add-repository 'deb https://apt.kitware.com/ubuntu/ focal main' # bionic, xenial
$ sudo apt update
$ sudo apt install cmake cmake-curses-gui
```

Using the installer or the pre-compiled binaries: `cmake.org/download/`

```
# download the last cmake package, e.g. cmake-x.y.z-linux-x86_64.sh
$ sudo sh cmake-x.y.z-linux-x86_64.sh
```

A Minimal Example

CMakeLists.txt:

```
project(my_project)                  # project name

add_executable(program program.cpp) # compile command
```

```
# we are in the project root dir
$ mkdir build     # 'build' dir is needed to isolate temporary files
$ cd build
$ cmake ..        # search for CMakeLists.txt directory
$ cmake --build . # makefile automatically generated, -j to parallelize the build

Scanning dependencies of target program
[100%] Building CXX object CMakeFiles/out_program.dir/program.cpp.o
Linking CXX executable program
[100%] Built target program
```

Parameters and Message

CMakeLists.txt:

```
project(my_project)
add_executable(program program.cpp)

if (VAR)
    message("VAR is set, NUM is ${NUM}") # $ symbol replaces the variable name
else()                                   # with its value
    message(FATAL_ERROR "VAR is not set")
endif()
```

```
$ cmake ..
VAR is not set
$ cmake -DVAR=ON -DNUM=4 ..
VAR is set, NUM is 4
...
[100%] Built target program
```

Language Properties

```
project(my_project
        DESCRIPTION  "Hello World"
        HOMEPAGE_URL "github.com/"
        LANGUAGES     CXX)

cmake_minimum_required(VERSION 3.15)

set(CMAKE_CXX_STANDARD           14) # force C++14
set(CMAKE_CXX_STANDARD_REQUIRED  ON)
set(CMAKE_CXX_EXTENSIONS         OFF) # no compiler extensions

add_executable(program ${PROJECT_SOURCE_DIR}/program.cpp)  #$
# PROJECT_SOURCE_DIR is the root directory of the project
```

Target Commands

```
add_executable(program) # also add_library(program)

target_include_directories(program
                           PUBLIC  include/
                           PRIVATE src/)
# target_include_directories(program SYSTEM ...) for system headers

target_sources(program                      # best way for specifying
               PRIVATE src/program1.cpp     # program sources and headers
               PRIVATE src/program2.cpp
               PUBLIC  include/header.hpp)

target_compile_definitions(program PRIVATE MY_MACRO=ABCEF)

target_compile_options(program PRIVATE -g)

target_link_libraries(program PRIVATE boost_lib)

target_link_options(program PRIVATE -s)
```

Build Types

```
project(my_project)                          # project name
cmake_minimum_required(VERSION 3.15)         # minimum version

add_executable(program program.cpp)

if (CMAKE_BUILD_TYPE STREQUAL "Debug")       # "Debug" mode
                                             # cmake already adds "-g -O0"
    message("DEBUG mode")
    if (CMAKE_COMPILER_IS_GNUCXX)            # if compiler is gcc
        target_compile_options(program "-g3")
    endif()
elseif (CMAKE_BUILD_TYPE STREQUAL "Release") # "Release" mode
    message("RELEASE mode")                   # cmake already adds "-O3 -DNDEBUG"
endif()
```

```
$ cmake -DCMAKE_BUILD_TYPE=Debug ..
```

Custom Targets and File Managing

```
project(my_project)
add_executable(program)

add_custom_target(echo_target            # makefile target name
                  COMMAND echo "Hello"   # real command
                  COMMENT "Echo target")

# find all .cpp file in src/ directory
file(GLOB_RECURSE SRCS ${PROJECT_SOURCE_DIR}/src/*.cpp)
# compile all *.cpp file
target_sources(program PRIVATE ${SRCS}) # prefer the explicit file list instead
```

```
$ cmake ..
$ make echo_target
```

Local and Cached Variables

Cached variables can be reused across multiple runs, while *local variables* are only visible in a single run. Cached `FORCE` variables can be modified only after the initialization

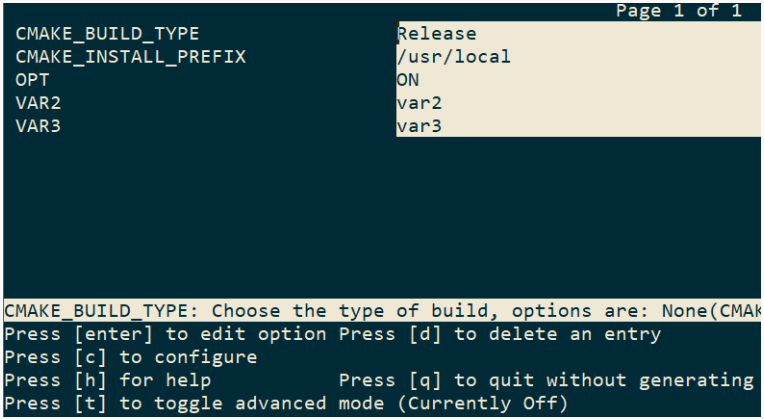
```
project(my_project)

set(VAR1 "var1")                                    # local variable
set(VAR2 "var2" CACHE STRING "Description1")        # cached variable
set(VAR3 "var3" CACHE STRING "Description2" FORCE) # cached variable
option(OPT "This is an option" ON)                  # boolean cached variable
                                                    # same of var2
message(STATUS "${VAR1}, ${VAR2}, ${VAR3}, ${OPT}")
```

```
$ cmake .. # var1, var2, var3, ON
$ cmake -DVAR1=a -DVAR2=b -DVAR3=c -DOPT=d .. # var1, b, var3, d
```

Manage Cached Variables

```
$ ccmake .  # or 'cmake-gui'
```



Find Packages

```
project(my_project)                    # project name
cmake_minimum_required(VERSION 3.15) # minimum version

add_executable(program program.cpp)

find_package(Doxygen REQUIRED)  # compile only if Doxygen is found
find_package(Boost 1.87.0)      # search for a specific version

if (Boost_FOUND)
    target_include_directories("${PROJECT_SOURCE_DIR}/include" PUBLIC ${Boost_INCLUDE_DIRS})
else()
    message(FATAL_ERROR "Boost Lib not found")
endif()
```

Compile Commands

Generate JSON compilation database (`compile_commands.json`)

It contains the exact compiler calls for each file that are used by other tools

```
project(my_project)
cmake_minimum_required(VERSION 3.15)

set(CMAKE_EXPORT_COMPILE_COMMANDS ON)  # <--

add_executable(program program.cpp)
```

Change the C/C++ compiler:

```
CC=clang CXX=clang++ cmake ..
```

CTest is a testing tool (integrated in CMake) that can be used to automate updating, configuring, building, testing, performing memory checking, performing coverage

```
project(my_project)
cmake_minimum_required(VERSION 3.5)
add_executable(program program.cpp)

enable_testing()

add_test(NAME Test1        # check if "program" returns 0
         WORKING_DIRECTORY ${PROJECT_SOURCE_DIR}/build
         COMMAND ./program <args>) # command can be anything

add_test(NAME Test2        # check if "program" print "Correct"
         WORKING_DIRECTORY ${PROJECT_SOURCE_DIR}/build
         COMMAND ./program <args>)

set_tests_properties(Test2
                     PROPERTIES PASS_REGULAR_EXPRESSION "Correct")
```

Basic usage (call ctest):

```
$ make test       # run all tests
```

ctest usage:

```
$ ctest -R Python      # run all tests that contains 'Python' string
$ ctest -E Iron        # run all tests that not contain 'Iron' string
$ ctest -I 3,5         # run tests from 3 to 5
```

Each ctest command can be combined with other tools (e.g. valgrind)

ctest with Different Compile Options

It is possible to combine a custom target with ctest to compile the same code with different compile options

```
add_custom_target(program-compile
                  COMMAND mkdir -p test-release test-ubsan test-asan # create dirs
                  COMMAND cmake .. -B test-release                   # -B change working dir
                  COMMAND cmake .. -B test-ubsan   -DUBSAN=ON
                  COMMAND cmake .. -B test-asan    -DASAN=ON
                  COMMAND make -C test-release -j20 program          # -C run make in a
                  COMMAND make -C test-ubsan   -j20 program          # different dir
                  COMMAND make -C test-asan    -j20 program)

enable_testing()

add_test(NAME Program-Compile
         COMMAND make program-compile)
```

CMake Alternatives - xmake

xmake is a cross-platform build utility based on Lua.

Compared with makefile/CMakeLists.txt, the configuration syntax is more concise and intuitive. It is very friendly to novices and can quickly get started in a short time. Let users focus more on actual project development

Comparison: xmake vs cmake

Code Documentation

Doxygen is the de facto standard tool for generating documentation from annotated C++ sources

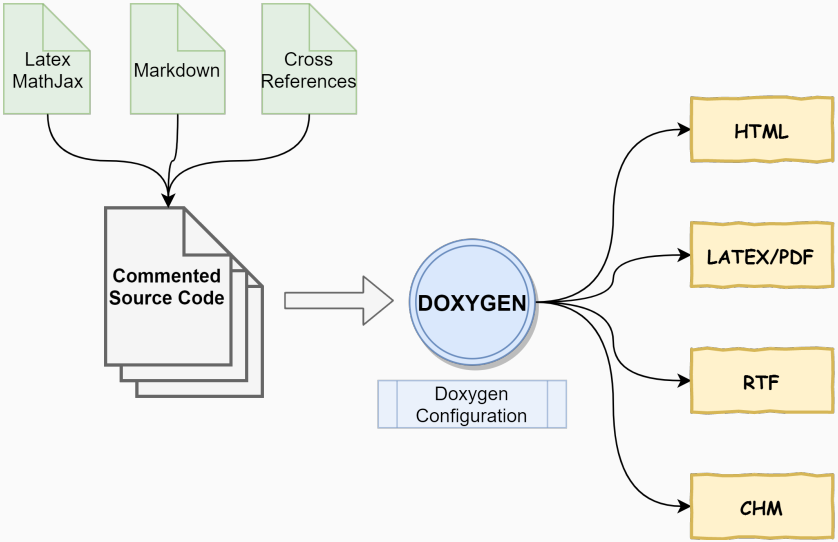
Doxygen usage

- comment the code with `///` or `/** comment */`
- generate doxygen base configuration file

```
$ doxygen -g
```

- modify the configuration file `Doxyfile`, e.g. `PROJECT_NAME`, `OUTPUT_DIRECTORY`, `INPUT`.
- generate the documentation

```
$ doxygen <config_file>
```


Latex
MathJax
Markdown
Cross
References
Commented
Source Code
DOXYGEN
Doxygen
Configuration
HTML
LATEX/PDF
RTF
CHM

Doxygen requires the following tags for generating the documentation:

- `@file` Document a file
- `@brief` Brief description for an entity
- `@param` Run-time parameter description
- `@tparam` Template parameter description
- `@return` Return value description

- *Automatic cross references* between functions, variables, etc.
- *Specific highlight*. Code `` `<code>` ``, input/output parameters `@param[in] <param>`
- *Latex/MathJax* `$<code>$`
- *Markdown* (Markdown Cheatsheet link), Italic text `*<code>*`, bold text `**<code>**`, table, list, etc.
- Call/Hierarchy graph can be useful in large projects (requires `graphviz`)

```
HAVE_DOT = YES
GRAPHICAL_HIERARCHY = YES
CALL_GRAPH = YES
CALLER_GRAPH = YES
```

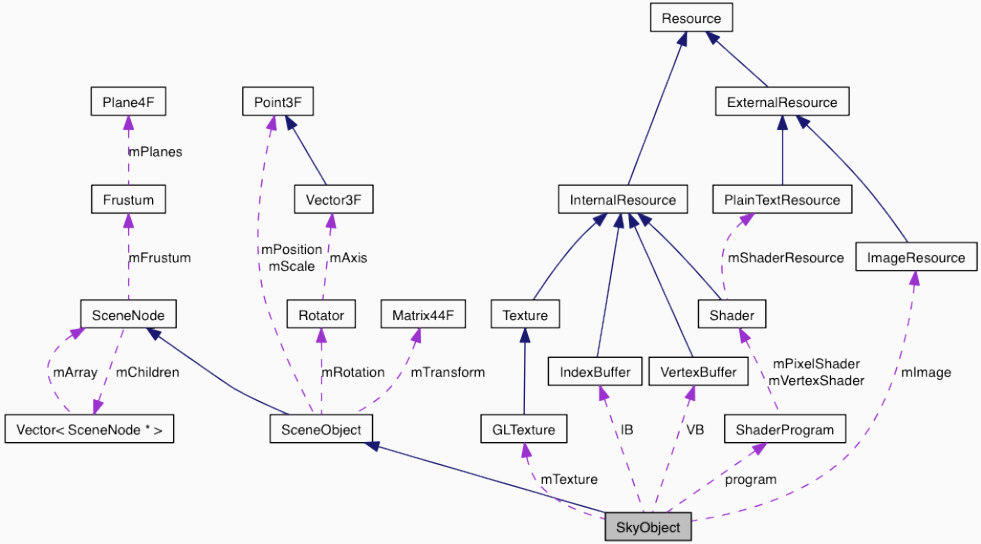
```
/**
 * @file
 * @copyright MyProject
 * license BSD3, Apache, MIT, etc.
 * @author MySelf
 * @version v3.14159265359
 * @date March, 2018
 */

/// @brief Namespace brief description
namespace my_namespace {

/// @brief "Class brief description"
/// @tparam R "Class template for"
template<typename R>
class A {
```

```
/**
 * @brief "What the function does?"
 * @details "Some additional details",
 *           Latex/MathJax: $\sqrt a$
 * @tparam T Type of input and output
 * @param[in] input Input array
 * @param[out] output Output array
 * @return `true` if correct,
 *         `false` otherwise
 * @remark it is *useful* if ...
 * @warning the behavior is **undefined** if
 *          @p input is `nullptr`
 * @see related_function
 */
template<typename T>
bool my_function(const T* input, T* output);

/// @brief
void related_function();
```


Resource
Plane4F
Point3F
ExternalResource
mPlanes
Frustum
Vector3F
InternalResource
PlainTextResource
mFrustum
mPosition
mScale
mAxis
mShaderResource
ImageResource
SceneNode
Rotator
Matrix44F
Texture
Shader
mArray
mChildren
mRotation
mTransform
IndexBuffer
VertexBuffer
mPixelShader
mVertexShader
mImage
Vector< SceneNode * >
SceneObject
GLTexture
IB
VB
ShaderProgram
mTexture
program
SkyObject

Doxygen Alternatives

`Mr.Docs`	Highly accurate Doxygen replacement
`M.CSS`	Doxygen C++ theme
`Doxypress`	Doxygen fork
`clang-doc`	LLVM tool
`Sphinx`	`Clear, Functional C++ Documentation with Sphinx + Breathe + Doxygen + CMake`
`standardese`	The nextgen Doxygen for C++ (experimental)
`HDoc`	The modern documentation tool for C++ (alpha)
`Adobe Hyde`	Utility to facilitate documenting C++

Online Tools

AI-Powered Code Completion tools help writing code faster by drawing context from comments and code to suggest individual lines and whole functions

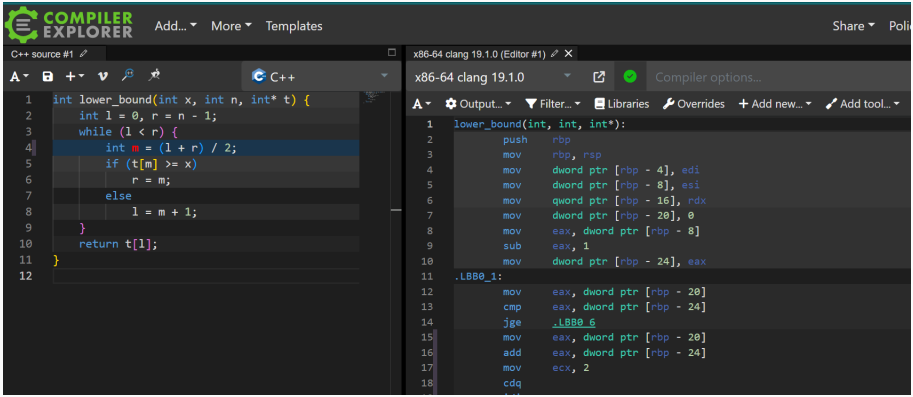
Common features:

- Semantic completion
- Recognize common language patterns
- Use the documentation to infer this function name, return type, and arguments
- Suggest bug fixes
- Generate comments, documentation, and even Pull Request text

They are commonly provided as plug-in for the most popular editors and IDE

- CoPilot
- Cursor
- WindSurf
- Cody
- TabNine
- Replit Ghostwriter
- CodeWhisperer

Compiler Explorer is an interactive tool that lets you type source code and see assembly output, control flow graph, optimization hint, etc.



Compiler Explorer allows instant C++ code writing and interaction directly from the web browser. The tool is widely used with 92 million compilations per year.

One of the most common uses of the tool is to create minimal examples for analysis and debugging. Such examples can then be shared for collaboration or education.

Support:

- Offers access to over 4,700+ compilers, including GCC, Clang, MSVC, nvcc, and nvc++
- Provides various architectures like x86, ARM, NVIDIA GPU, MIPS, and RISC-V
- Supports $\sim$ 80 programming languages

- Assembly output visualization and source code correlation
- Execution
- Code sharing
- Command line, prompt inputs, and environment variables configuration
- Static analysis with GCC, Clang, MSVC compilers and external tools such as Sonar
- Allow to include a set of predefined libraries and even GitHub URLs
- Visualize the control flow graph
- Use external tools, such as clang-format, optimization-remarks, clang-tidy, cmake, etc.

Code Transformation - CppInsights

CppInsights See what your compiler does behind the scenes

Source:

```
1  #include <cstdio>
2  #include <vector>
3
4  int main()
5  {
6      const char arr[10]{2,4,6,8};
7
8      for(const char& c : arr)
9      {
10       printf("c=%c\n", c);
11     }
12 }
```

Insight:

```
1  #include <cstdio>
2  #include <vector>
3
4  int main()
5  {
6      const char arr[10]{2,4,6,8};
7
8      {
9        auto&& __range1 = arr;
10       const char * __begin1 = __range1;
11       const char * __end1 = __range1 + 10l;
12
13       for( ; __begin1 != __end1; ++__begin1 )
14       {
15         const char & c = *__begin1;
16         printf("c=%c\n", static_cast<int>(c));
17       }
18     }
19 }
```

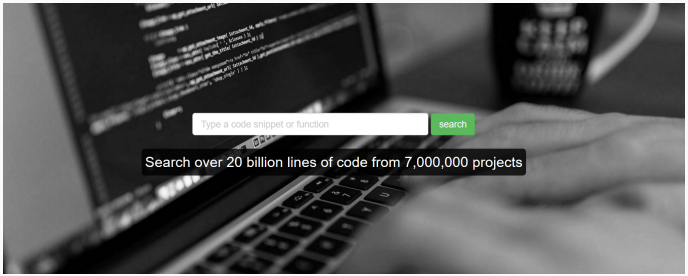
Code Benchmarking - Quick-Bench

Quick-benchmark is a micro benchmarking tool intended to quickly and simply compare the performances of two or more code snippets. The benchmark runs on a pool of AWS machines

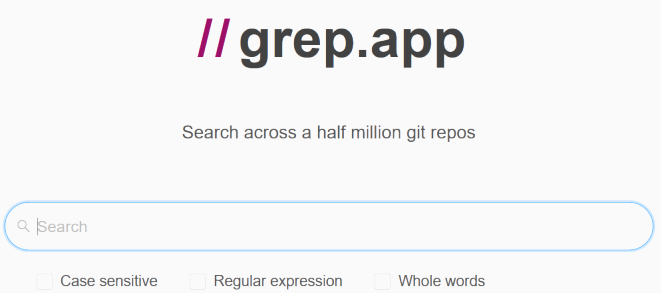
`Searchcode` is a free source code search engine

Features:

- Search over 20 billion lines of code from 7,000,000 projects
- Search sources: `github`, `bitbucket`, `gitlab`, `google code`, `sourceforge`, etc.



grep.app searches across a half million GitHub repos



Offline Tools

Code Formatting - clang-format

clang-format is a tool to automatically format C/C++ code (and other languages)

```
$clang-format <file/directory>
```

clang-format searches the configuration file .clang-format file located in the closest parent directory of the input file

clang-format example:

```
IndentWidth: 4
UseTab: Never
BreakBeforeBraces: Linux
ColumnLimit: 80
SortIncludes: true
```

`tokei` shows the number of files, total lines within those files and code, comments, and blanks grouped by language

Features: fast, accurate, support over 150 languages

Language	Files	Lines	Code	Comments	Blanks
BASH	4	49	30	10	9
JSON	1	1332	1332	0	0
Shell	1	49	38	1	10
TOML	2	77	64	4	9
Markdown	5	1355	0	1074	281
|- JSON	1	41	41	0	0
|- Rust	2	53	42	6	5
|- Shell	1	22	18	0	4
(Total)		1471	101	1080	290
Rust	19	3416	2840	116	460
|- Markdown	12	351	5	295	51
(Total)		3767	2845	411	511
Total	32	6745	4410	1506	829

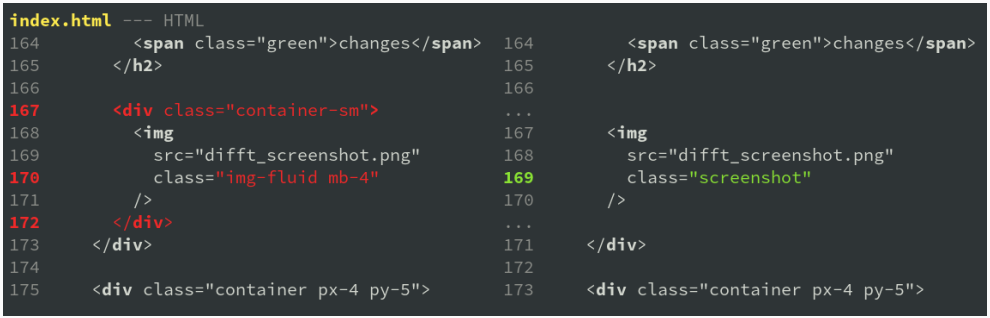
`Sloc, Cloc and Code: scc` counts the lines of code, blank lines, comment lines, and physical lines of source code in many programming languages

Additional features: Cyclomatic complexity, unique lines of code, DRYness (ratio of unique lines of code), COCOMO statistics (cost, time, people to develop)

```
-------------------------------------------------------------------------------
Language                     Files     Lines   Blanks  Comments     Code Complexity
-------------------------------------------------------------------------------
C                              419    241293    27309     41292   172692      40849
(ULOC)                                133535
-------------------------------------------------------------------------------
Total                          419    241293    27309     41292   172692      40849
-------------------------------------------------------------------------------
Unique Lines of Code (ULOC)           133535
DRYness %                               0.55
-------------------------------------------------------------------------------
Estimated Cost to Develop (organic) $6,035,748
Estimated Schedule Effort (organic) 27.23 months
Estimated People Required (organic) 19.69
-------------------------------------------------------------------------------
Processed 8407821 bytes, 8.408 megabytes (SI)
-------------------------------------------------------------------------------
```

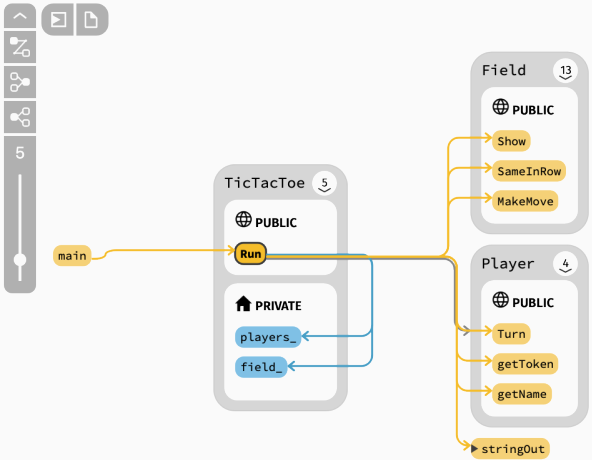
AST Diff - difftastic

difftastic is a tool that compares files based on their syntax, not line-by-line. Difftastic produces accurate diffs that are easier for humans to read.



Project Visualization - SouceTrail

SouceTrail is an open-source cross-platform source explorer that helps you get productive on unfamiliar source code



Local Code Search - `ugrep`, `ripgrep`, `hypergrep`

`ugrep`, `Ripgrep`, `Hypergrep` are code-searching-oriented tools for regex pattern

Features:

- Default recursively searches
- Skip `.gitignore` patterns, binary and hidden files/directories
- Windows, Linux, Mac OS support
- Up to 100x faster than `GNU grep`

```
[andrew@Cheetah rust] rg -i rustacean
src/doc/book/nightly-rust.md
92:[Mibbit][mibbit]. Click that link, and you'll be chatting with other Rustaceans

src/doc/book/glossary.md
3:Not every Rustacean has a background in systems programming, nor in computer

src/doc/book/getting-started.md
176:Rustaceans (a silly nickname we call ourselves) who can help us out. Other great
376:Cargo is Rust's build system and package manager, and Rustaceans use Cargo to

src/doc/book/guessing-game.md
444:it really easy to re-use libraries, and so Rustaceans tend to write smaller

CONTRIBUTING.md
322:* [rustaceans.org][ro] is helpful, but mostly dedicated to IRC
333:[ro]: http://www.rustaceans.org/
[andrew@Cheetah rust]
```

AST Search - asp-grep

asp-grep is a tool for code structural search, lint, rewriting at large scale.

```
ast-grep -p '$A && $A()' -r '$A?.()'
```

```
[TypeScript] sg -p '$A && $A()' -r '$A?.()' src/tsserver                main  *
src/tsserver/nodeServer.ts
@@ -934,7 +934,7 @@
935 935 |                case "win32": {
936 936 |                    const basePath = process.env.LOCALAPPDATA ||
937 937 |                        process.env.APPDATA ||
938     |-                       (os.homedir && os.homedir()) ||
    938 |+                      (os.homedir?.()) ||
939 939 |                        process.env.USERPROFILE ||
940 940 |                        (process.env.HOMEDRIVE && process.env.HOMEPATH && n
ormalizeSlashes(process.env.HOMEDRIVE + process.env.HOMEPATH)) ||
941 941 |                        os.tmpdir();
```

Font for Coding

Many editors allow adding optimized fonts for programming which improve legibility and provide extra symbols (ligatures)

Scope	→ ⇒ :: __	-> => :: __
Equality	= == ≠ =/= == === =/= =/=/=	== === != =/= == === != !==
Comparisons	⩽ ⩾ ≤ ≥ ⟺	<= >= <= >= <=>

Some examples:

- JetBrain Mono
- Fira Code
- Microsoft Cascadia
- Consolas Ligaturized