CMake Successor Build Systems:

A World Tour of Build Systems
Towards Better C++ Builds

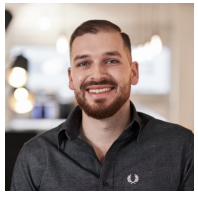
DAMIEN BUHL &
ANTONIO DI STEFANO

Cppcon
The C++ Conference

2023

October

Reliable, Fast and Safe Builds



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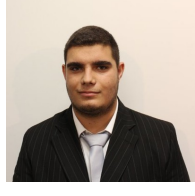

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A love ❤️ letter to CMake

Giving CMake Superpowers 🚀

Thank you CMake 🙏

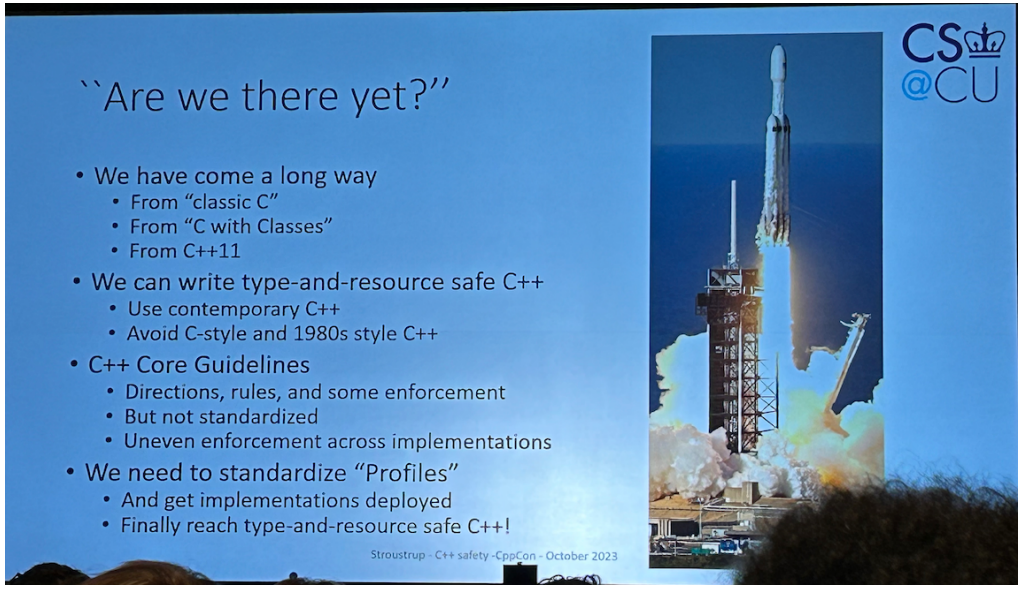
autotools, qmake and SCons almost disappeared 🎯

Safety

C++ cares about Safety

- **Keynote: All the Safeties**, Sean Parent - C++ on Sea 2023 : youtu.be/BaUv9sgLCP
- **C++ and Safety**, Timur Doumler - C++ on Sea 2023 : youtu.be/imtpoc9jtOE
- **Safety and Security: The Future of C++**, JF Bastien - CppNow 2023 : youtu.be/Gh79wcGJdTg

Are we there yet ?



Are we there yet ?

Are We "Thing" Yet	C++
Are We Web Yet	✅
Are We Game Yet	✅
Are We Async Yet	✅
Are We GUI Yet	✅
Are we stack-efficient yet?	✅
Are we safe yet?	

Are we safe yet ?

We could !

It's more configuration work 🐌

Are we safe yet ?

We should !

EUROPEAN
COMMISSION

Brussels, 15.9.2022
COM(2022) 454 final

2022/0272 (COD)

Proposal for a

REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL

on horizontal cybersecurity requirements for products with digital elements and amending Regulation (EU) 2019/1020

(Text with EEA relevance)

{SEC(2022) 321 final} - {SWD(2022) 282 final} - {SWD(2022) 283 final}

EN **EN**

National Security Agency | Cybersecurity Information Sheet

Software Memory Safety

Executive summary

Modern society relies heavily on software-based automation, implicitly trusting developers to write software that operates in the expected way and cannot be compromised for malicious purposes. While developers often perform rigorous testing to prepare the logic in software for surprising conditions, exploitable software vulnerabilities are still frequently based on memory issues. Examples include overflowing a memory buffer and leveraging issues with how software allocates and de-allocates memory. Microsoft® revealed at a conference in 2019 that from 2006 to 2018 70 percent of their vulnerabilities were due to memory safety issues. [1] Google® also found a similar percentage of memory safety vulnerabilities over several years in Chrome®. [2] Malicious cyber actors can exploit these vulnerabilities for remote code execution or other adverse effects, which can often compromise a device and be the first step in large-scale network intrusions.

Commonly used languages, such as C and C++, provide a lot of freedom and flexibility in memory management while relying heavily on the programmer to perform the needed checks on memory references. Simple mistakes can lead to exploitable memory-based vulnerabilities. Software analysis tools can detect many instances of memory management issues and operating environment options can also provide some protection, but inherent protections offered by memory safe software languages can prevent or mitigate most memory management issues. NSA recommends using a memory safe language when possible. While the use of added protections to non-memory safe languages and the use of memory safe languages do not provide absolute protection against exploitable memory issues, they do provide considerable protection. Therefore, the overarching software community across the private sector, academia, and the U.S. Government have begun initiatives to drive the culture of software development towards utilizing memory safe languages. [3] [4] [5]

U/OO/219936-22 | PP-22-1723 | NOV 2022 Ver. 1.0

NATIONAL CYBERSECURITY STRATEGY

MARCH 2023

THE WHITE HOUSE
WASHINGTON

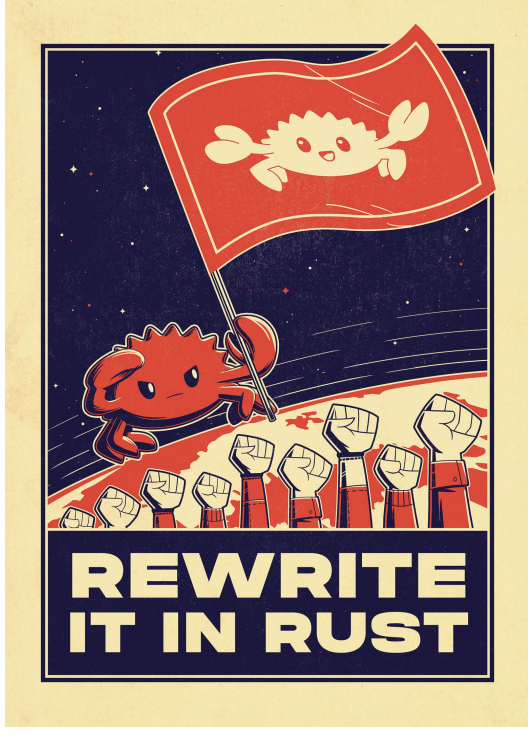
What is Safety ?

- Type Safety
- Memory Safety
  - Lifetime safety
  - Bounds safety
  - Initialization safety
- Object access safety
- Thread Safety
- Arithmetic safety
- Definition safety

Software Supply Chain Safety ?

- Reproducibility
- Traceability
- Release delivery time

YOU DON'T NEED TO



Achieve safety in C++ today

Achieve safety in C++ today with the CppCoreGuidelines

Achieving safety in C++ today with **CMake**, **Clang Tidy** and the **CppCoreGuidelines**

```
set(CMAKE_CXX_CLANG_TIDY
    clang-tidy -checks=-*,cppcoreguidelines-*)
```

Clang Tidy Checks

Achieving safety in C++ today with CMake

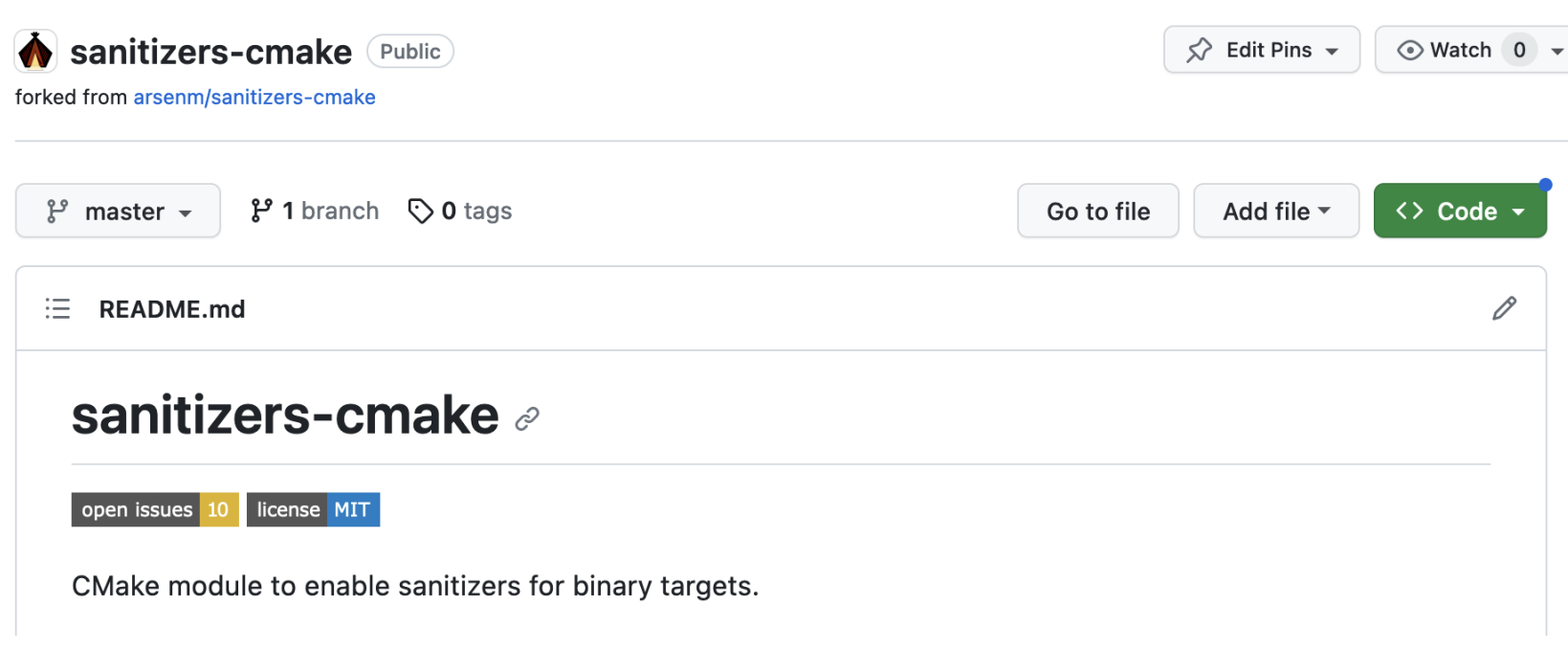
Achieving safety in C++ today

Let's tackle first

- Memory Safety
- Arithmetic Safety

Sanitizers for C++ builds with CMake

github.com/tipi-build/sanitizers-cmake



Sanitizers for C++ builds

- AddressSanitizer (ASan)
- UndefinedBehaviorSanitizer (UBSsan)
- ThreadSanitizer (TSan)
- LeakSanitizer (LSan)
- MemorySanitizer (MSan)

Using LLVM Sanitizers in your CMake

```
project(safepp)

find_package(Sanitizers MODULE REQUIRED)

add_executable(use-after-free test/use-after-free.cpp)

# enable sanitizers
add_sanitizers(use-after-free)
```

So we done ?

ASan, TSan, UBSan are incompatible with each others ❌

Multiple builds and test runs

Separate CMake toolchain files

sanitize-ub.cmake :

```
set(SANITIZE_UNDEFINED TRUE CACHE BOOL "" FORCE)
```

sanitize-address.cmake :

```
set(SANITIZE_THREAD TRUE CACHE BOOL "" FORCE)
```

Multiple builds and test runs

Separate CMake toolchain files

sanitize-memory.cmake :

```
set(SANITIZE_MEMORY TRUE CACHE BOOL "" FORCE)
```

sanitize-thread.cmake :

```
set(SANITIZE_THREAD TRUE CACHE BOOL "" FORCE)
```

We want to run these Sanitizers

on each key strokes

That requires a decent amount of CPU power

Let's look at other build systems

Learning from other build-systems

Parallelism

How many independent targets can a build system run concurrently at most?

Parallelism

Level 1 - Gradle

```
.
├── app
│   ...
│   └── build.gradle
├── lib
│   ...
│   └── build.gradle
└── settings.gradle
```

Parallelism

Level 1 - Gradle

Sub-project level parallelism. It is very limited as projects have very low granularity and are limited in numbers. It is disabled by default

Parallelism

Level 2 - Make, FASTBuild

Targets are more granular and the size of the job pool can be specified by a flag (-j/--jobs)

Parallelism

Level 3 - Bazel

Same as the level before, but resource-intensive targets can reduce the level of parallelism on-demand

Parallelism

Level 4 - Ninja

You can define separate job-pools each of which with a different size (eg: link=1 and cc=16)

Will it CMake?

Job pools can be used when compiling...

```
set_property(GLOBAL PROPERTY JOB_POOLS
      compile=16
      link=1
      codegen=16)

set_property(TARGET atarget
      PROPERTY JOB_POOL_COMPILE compile)

set_property(TARGET atarget
      PROPERTY JOB_POOL_LINK link)

add_custom_target(protocgen
      COMMAND protoc --cpp_out=./out server.proto
      JOB_POOL codegen
```

Will it CMake?

... and linking ...

```
1  set_property(GLOBAL PROPERTY JOB_POOLS
2        compile=16
3        link=1
4        codegen=16)
5
6  set_property(TARGET atarget
7        PROPERTY JOB_POOL_COMPILE compile)
8
9  set_property(TARGET atarget
10       PROPERTY JOB_POOL_LINK link)
11
12 add_custom_target(protocgen
13       COMMAND protoc --cpp_out=./out server.proto
14       JOB_POOL codegen
```

Will it CMake?

... and pretty much anywhere else 😁

```
set_property(GLOBAL PROPERTY JOB_POOLS
      compile=16
      link=1
      codegen=4)

set_property(TARGET atarget
      PROPERTY JOB_POOL_COMPILE compile)

set_property(TARGET atarget
      PROPERTY JOB_POOL_LINK link)

add_custom_target(protocgen
      COMMAND protoc --cpp_out=./out server.proto
      JOB_POOL codegen
```

Reproducibility

Given the same inputs and configuration, a target should yield identical outputs

Reproducibility

Level 1 - Make, Ninja, FASTBuild

Provide no real facility to ensure reproducibility and, thus, hermeticity is something that the developers have to take care of

Reproducibility

Level 2 - Meson

Allows you to query and introspect tools during a build and configure them to get reproducibile results as well as define toolchains

Reproducibility

Level 3 - Gradle

Predefines robust and easy to configure toolchains out of the box. This way builds do not normally rely on any system-wide installed tools/libraries that can change between different workstations

Reproducibility

Level 4 - Bazel

Toolchains are treated as normal inputs. This trivially allows defining custom toolchains whilst keeping the same level of reproducibility

Will it CMake?

Actually, yes! But we have a few problems to fix

Will it CMake?

Problem 1: file ordering matters

Building `a.cpp` and `b.cpp` can yield different results from building `b.cpp` and `a.cpp`!

Will it CMake?

Problem 1: file ordering matters

Luckily CMake forces you to write input sources manually, so ordering is guaranteed!

Will it CMake?

Problem 2: __DATE__ and __TIME__ macros

Will it CMake?

Problem 2: __DATE__ and __TIME__ macros

MSVC

```
add_link_options("/Brepro")
```

Will it CMake?

Problem 2: __DATE__ and __TIME__ macros

GCC (via an environment variable)

```
SOURCE_DATE_EPOCH=1621012303
```

Will it CMake?

Problem 2: __DATE__ and __TIME__ macros

GCC + Clang

```
# Rewrite __DATE__
add_definitions(-D__DATE__="May  14 2021")
add_definitions(-D__TIME__="17:11:43")
add_compile_options(-Wno-builtin-macro-redefined)
```

Will it CMake?

Problem 3: Randomness when using `-flto` with GCC

LTO on GCC will produce random symbols

Will it CMake?

Problem 3: Randomness when using `-flto` with GCC

```
set(APP_SOURCES
  app.cpp
  lib.cpp)
foreach(_file ${APP_SOURCES})
  file(SHA1 ${_file} sha1sum)
  string(SUBSTRING ${sha1sum} 0 8 sha1sum)
  set_property(SOURCE ${_file}
    APPEND_STRING PROPERTY
    COMPILE_FLAGS
    "-frandom-seed=0x${sha1sum}")
endforeach()
```

Will it CMake?

Problem 4: __FILE__ macro

The __FILE__ macro is very likely to change between different workstations and thus produce different results

__FILE__ macro and path prefix

- Just build in the same environment
- At the same path
- But how ?

Let's merge Git and Ninja !

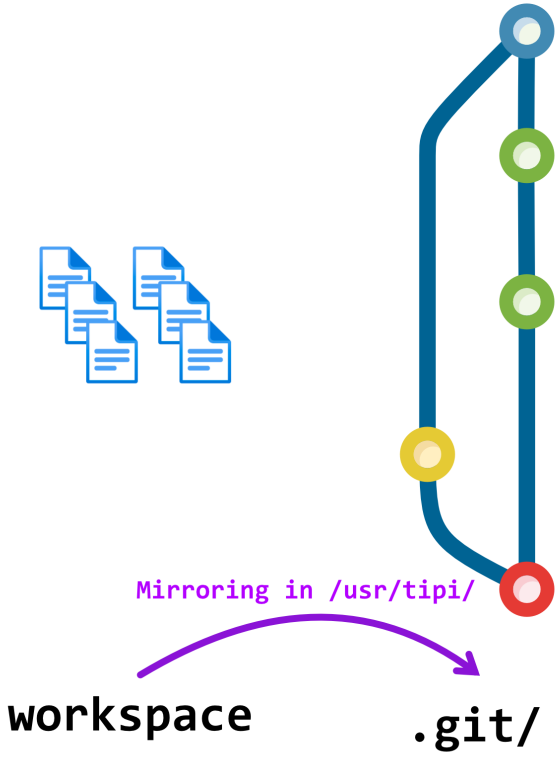
Because we can use Git :

- Content Addressable Filesystem ✅
- to clone sources and build trees in invariant paths ✅
- to **track changes** ✅

Stores code in an invariant path

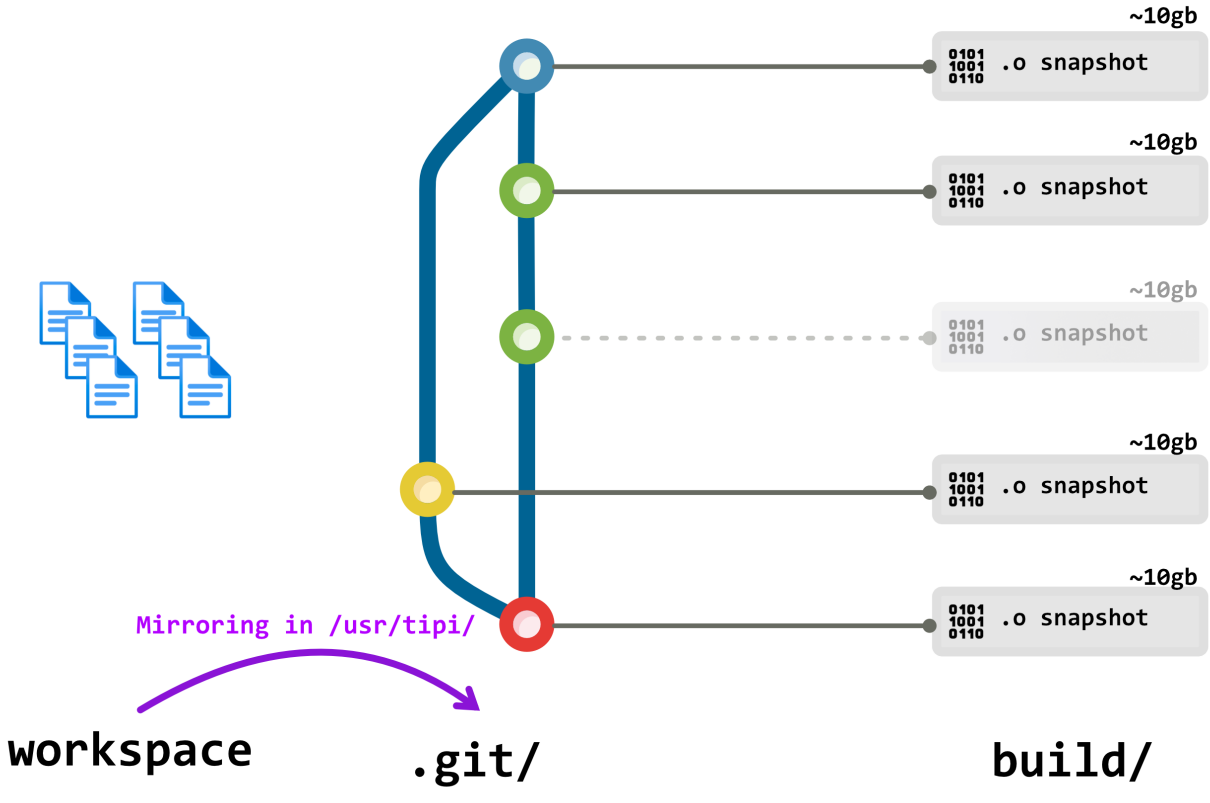
workspace

git based sources mirroring



Cache id based on the repository origin

commit-id addressable builds


~10gb
.o snapshot
~10gb
.o snapshot
~10gb
.o snapshot
~10gb
.o snapshot
~10gb
.o snapshot
Mirroring in /usr/tipi/
workspace
.git/
build/

Git + Ninja + cache packs ✅

__FILE__ problem solved 👈

Caching

How many targets can a build system avoid rebuilding?

Caching

Level 1 - Gradle

Once again the low level of granularity means that even small changes will rebuild very large targets

Caching

Level 2 - Make, Ninja

Check timestamps on the individual input files and rebuild targets if any change. Caching is completely file-system based and uses the mtime of a file to detect if it has changed since the last build

Caching

Level 3 - FASTBuild

Supports the same type of file-system caching as the previous level and adds support for distributed caching

Caching

Level 4 - Bazel

Supports file-system and distributed caching as with the previous level, but based on the digest of the input files' content rather than mtime. Bazel also has an in-memory cache for large build graphs

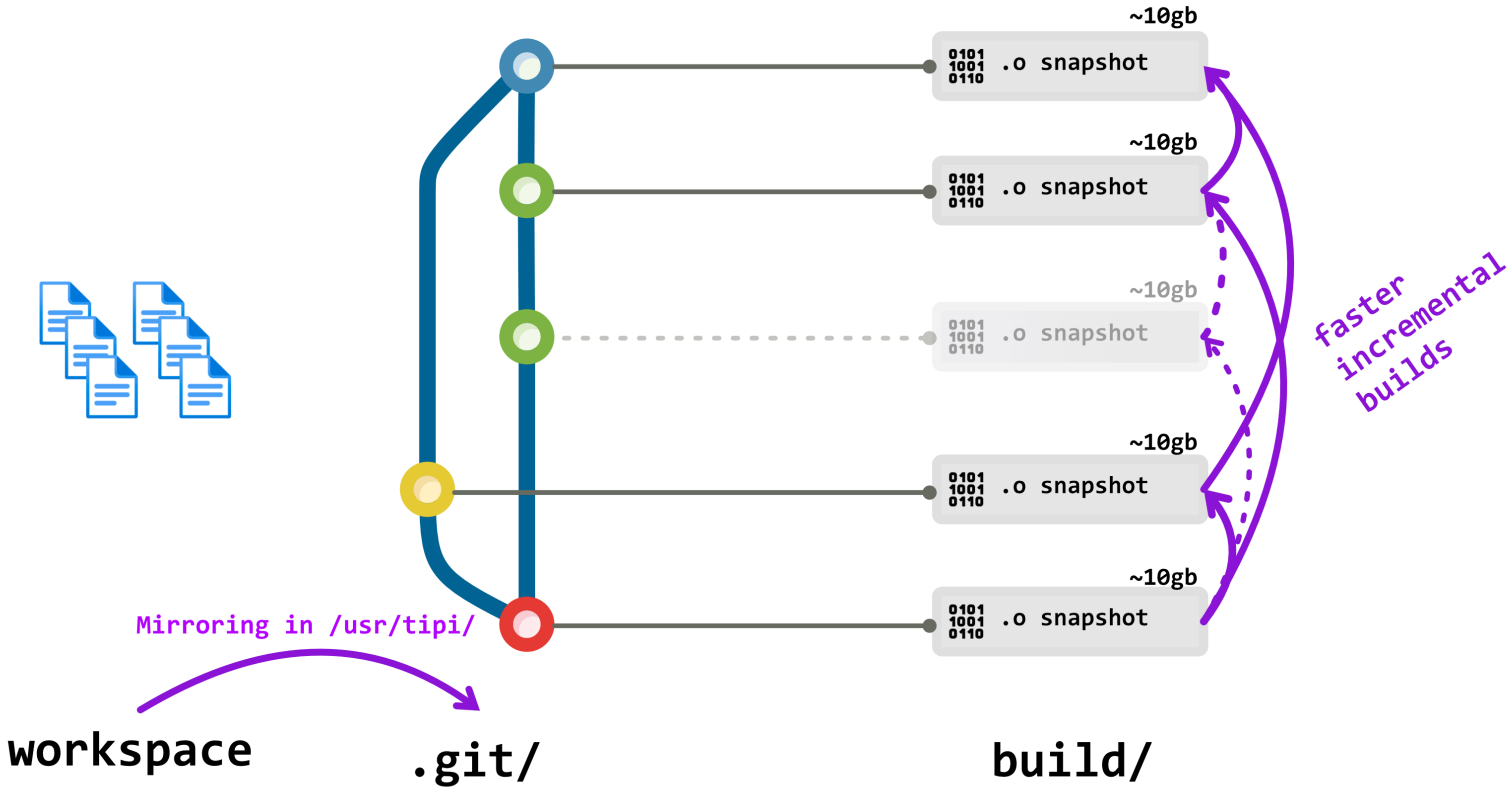
Will it CMake?

By using Make or Ninja we get file-system caching out-of-the-box

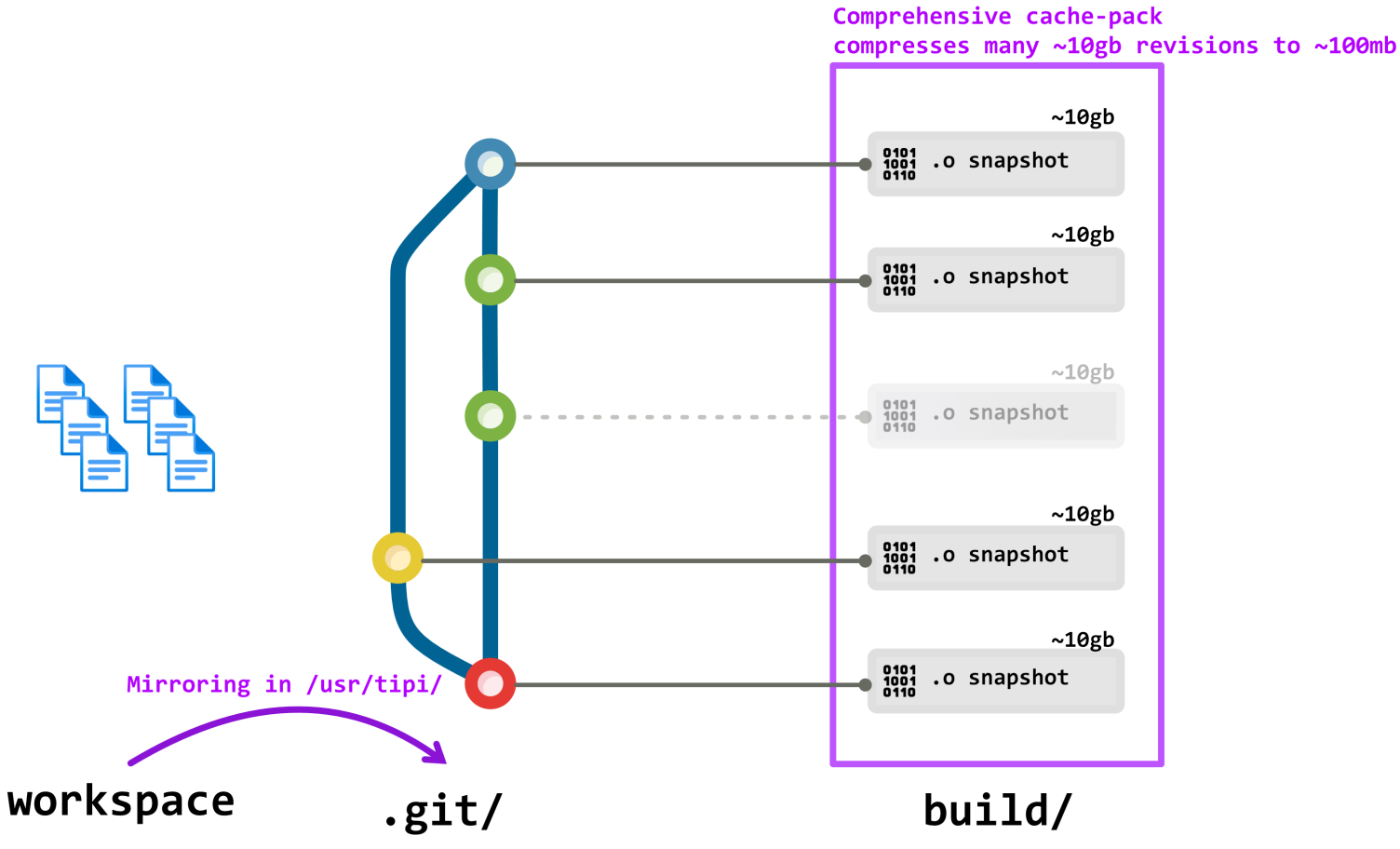
Will it CMake?

However, we can replace the standard CMake client with tipi. Engflow and Tipi partnered to bring remote execution and caching to CMake!

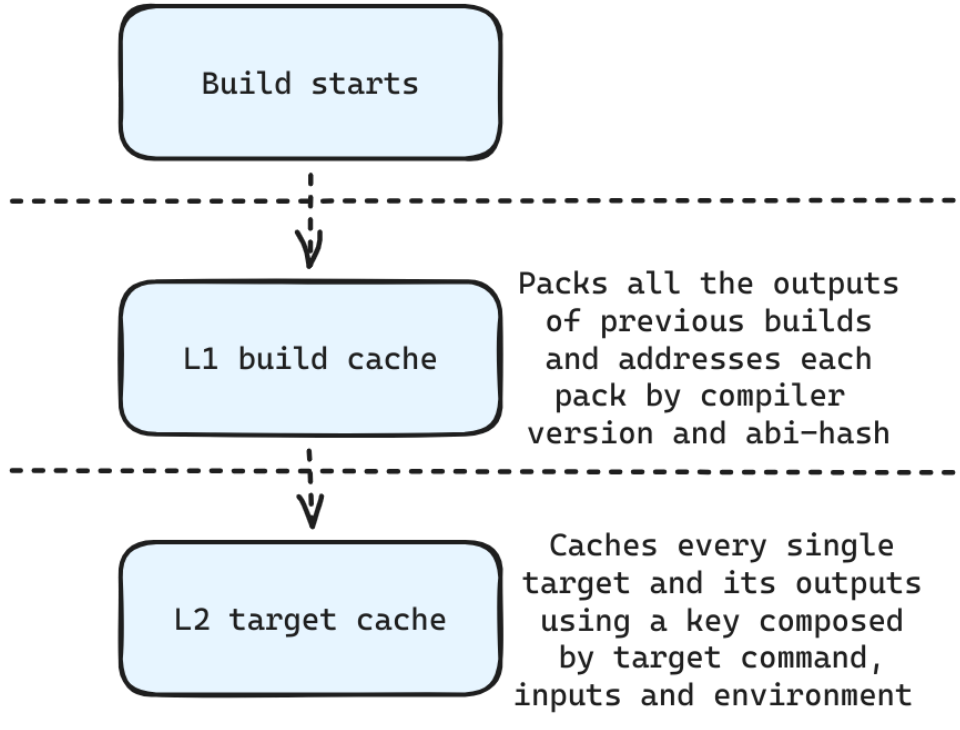
L1 Cache


~10gb
.o snapshot
~10gb
.o snapshot
~10gb
.o snapshot
~10gb
.o snapshot
~10gb
.o snapshot
faster incremental builds
Mirroring in /usr/tipi/
workspace
.git/
build/

L1 Cache


Comprehensive cache-pack
compresses many ~10gb revisions to ~100mb
~10gb
0101 1001 0110 .o snapshot
~10gb
0101 1001 0110 .o snapshot
~10gb
0101 1001 0110 .o snapshot
~10gb
0101 1001 0110 .o snapshot
~10gb
0101 1001 0110 .o snapshot
Mirroring in /usr/tipi/
workspace
.git/
build/

L2 Cache


Build starts
L1 build cache
Packs all the outputs of previous builds and addresses each pack by compiler version and abi-hash
L2 target cache
Caches every single target and its outputs using a key composed by target command, inputs and environment

Rationale

- L1 cache
  - permits fast build / install tree clean restore
- L2 cache
  - less cores required for parallel CI jobs

Dependency management

How a build system handles 3rd-party code

Dependency management

Level 1 - Make, Ninja, FASTBuild

No support at all, the developer gets to decide how to handle dependencies

Dependency management

Level 2 - Gradle

Dependency management focuses on handling jars but is very crude everywhere else

Dependency management

Level 3 - Meson, Bazel

Both provide somwhat extensible mechanisms to resolve dependencies for multiple languages and both provide centralised repositories of dependencies tweaked to better work with the respective build systems

Will it CMake?

But package management in C++ is 

Actually we have a good solution

- CMake is the de-facto standard
- It has FetchContent ❤️

FetchContent

```
Include(FetchContent)
FetchContent_Declare(
    Boost
    GIT_REPOSITORY https://github.com/boostorg/boost.git
    GIT_TAG        boost-1.80.0
)
FetchContent_MakeAvailable(Boost)
find_package(boost_filesystem CONFIG REQUIRED)

target_link_libraries(app Boost::filesystem)
```

FetchContent is kinda slow

FetchContent is kinda slow

- ⚡ No problem : we can optimize it
- Let's use CMake **SET_DEPENDENCY_PROVIDER**

Intercept FetchContent calls

```
macro(tipi_provide_dependency method package_name)
  set(oneValueArgs
    GIT_REPOSITORY
    GIT_TAG
  )

  cmake_parse_arguments(
    ARG "${options}" "${oneValueArgs}"
    "${multiValueArgs}" ${ARGN} )

  # Do something with ${ARG_GIT_REPOSITORY}

  FetchContent_SetPopulated( ${package_name} )
endmacro()
```

Install dependency provider

dependency_provider.cmake

```
cmake_language(
  SET_DEPENDENCY_PROVIDER tipi_provide_dependency
  SUPPORTED_METHODS
    FETCHCONTENT_MAKEAVAILABLE_SERIAL
)
```

```
list (APPEND CMAKE_PROJECT_TOP_LEVEL_INCLUDES
   dependency_provider.cmake)
```

Let's install Boost

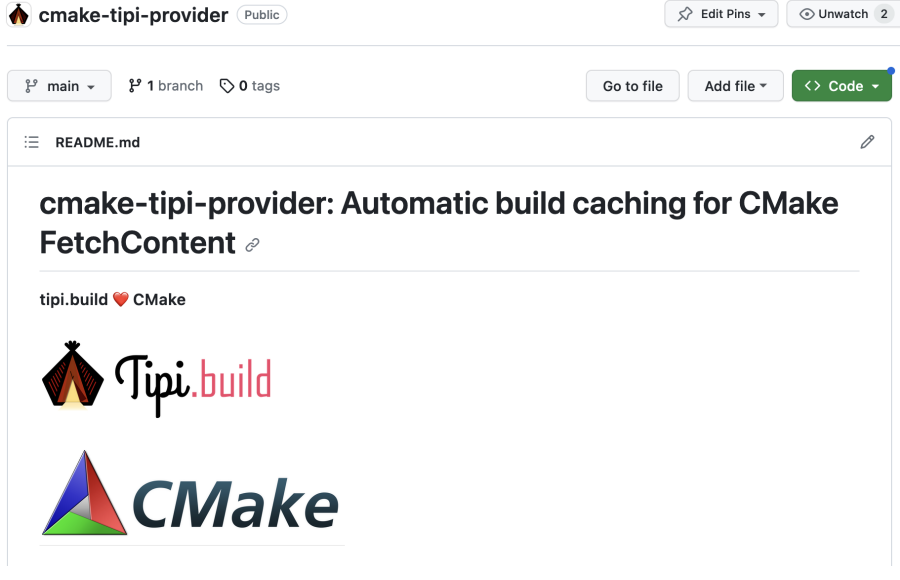
```
Include(FetchContent)
FetchContent_Declare(
    Boost
    GIT_REPOSITORY https://github.com/boostorg/boost.git
    GIT_TAG        boost-1.80.0
)
FetchContent_MakeAvailable(Boost)
```

Advantages

- No lock-in, pure CMake
- Rebuild from sources if needed
- Efficient and secure build caching

Automatic CMake Packages Caching

github.com/tipi-build/cmake-tipi-provider



Build Provenance & Traceability

SBOMs

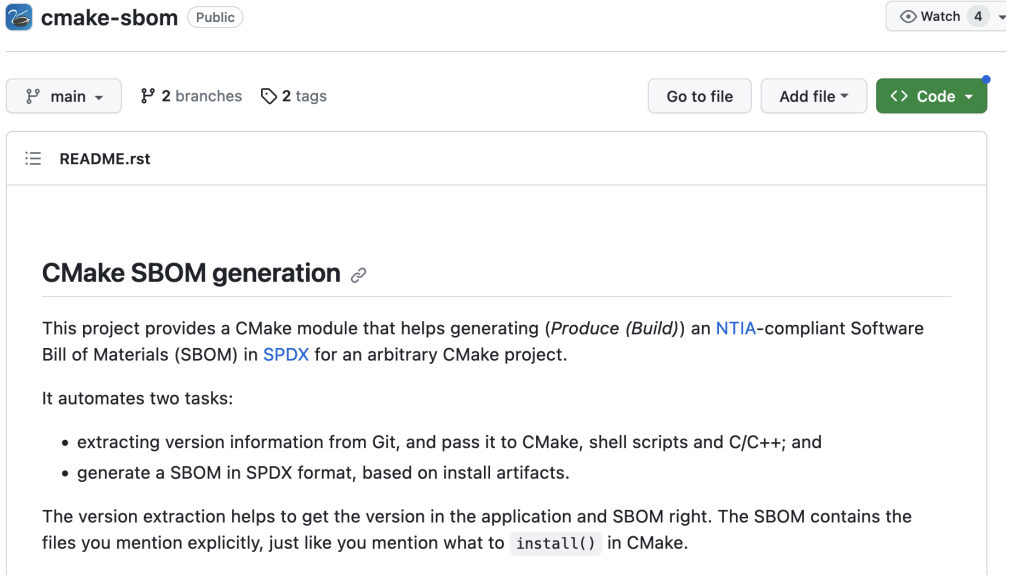
Build Provenance & Traceability

SBOMs

- Software Supply Chain Safety
- SPDX Format
- NTIA Compliance Validation

Manual Guided SBOM Generation

github.com/DEMCON/cmake-sbom



SBOMs generation

```
include(sbom)

sbom_generate(
  OUTPUT
    ${CMAKE_INSTALL_PREFIX}/sbom-${GIT_VERSION_PATH}.spdx
  LICENSE MIT
  SUPPLIER tipi
  SUPPLIER_URL https://tipi.build
)

reuse_spdx()

add_executable(app app.cpp)
```

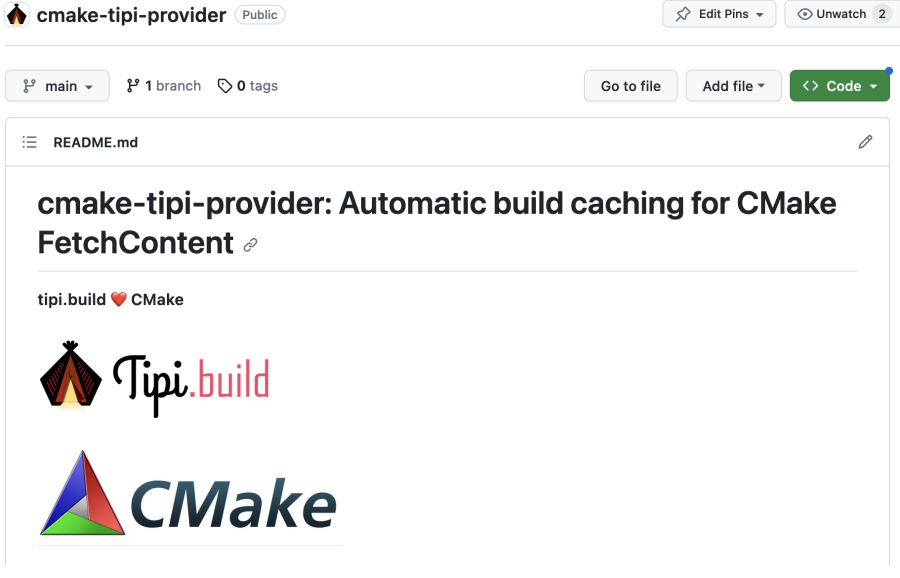
Automated SBOMs generation

```
install(
    TARGETS app
    EXPORT "${targets_export_name}"
    RUNTIME DESTINATION "bin"
)
sbom_add(TARGET app)

sbom_finalize()
```

Automatic SBOM Generation for your dependencies

github.com/tipi-build/cmake-tipi-provider



Build Cache Registry

View SBOMs, Dependencies, Cached builds

Distributed/remote builds

The ability of a build system to cache and/or run targets on a shared distributed system

Distributed/remote builds

The ability of a build system to cache and/or run targets on a shared distributed system

* also known as the thing that pays my salary :)

Distributed builds

Level 1 - Make, Ninja, Meson

No distributed caching or execution out of the box, everything runs locally

Distributed builds

Level 2 - Gradle

Has support for remote caching, but no remote execution of build targets. Once again the low level of granularity negatively impacts the potential of this feature

Distributed builds

Level 3 - FASTBuild

Supports both distributed execution and caching, however it is limited to just a list of well-known compilers when it comes to remote execution

Distributed builds

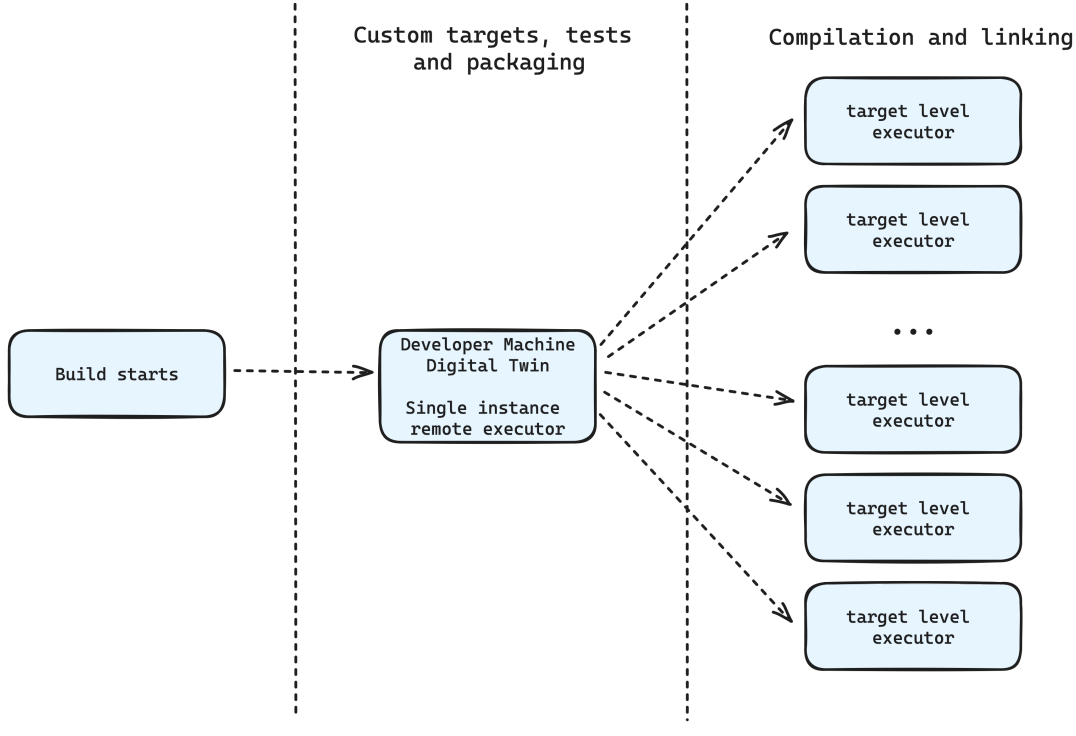
Level 4 - Bazel

Supports both distributed builds and caching for arbitrary tools, including compilers, linkers, tests and whatever you can think of

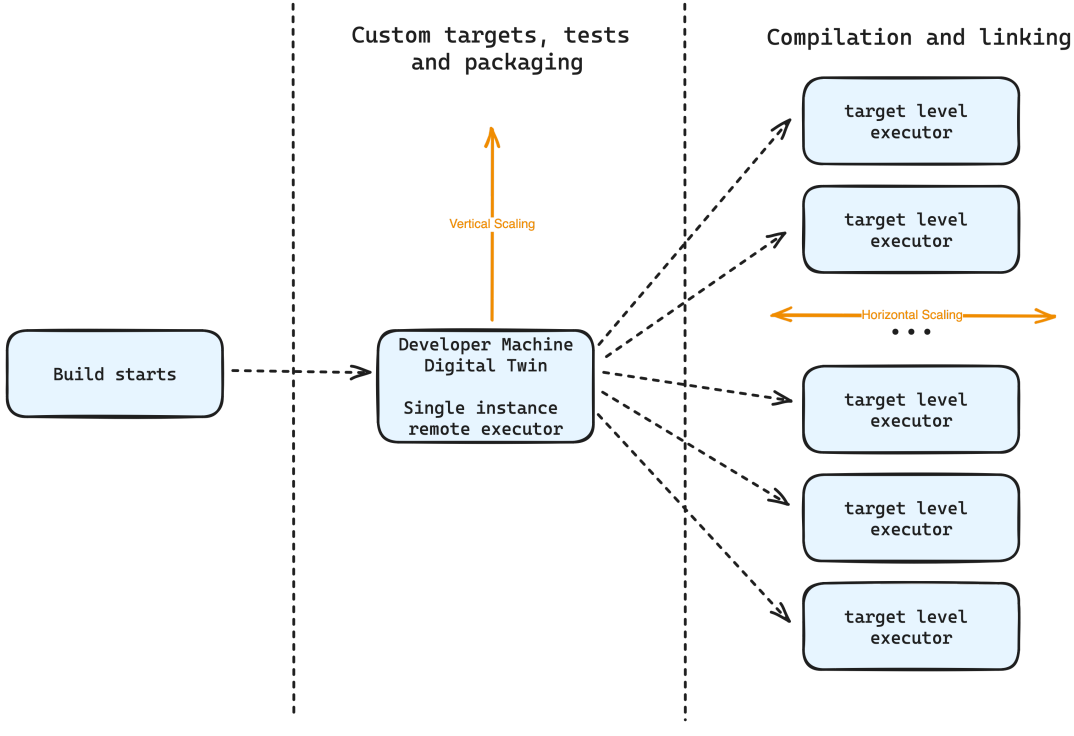
Will it CMake?

100%! We can combine Engflow's Remote Execution, which uses the same RE level protocol Bazel adopts, and tipi's single instance approach.

Will it CMake?



Will it CMake?



Let's check !

Thank you !

Request access to the BETA

https://tipi.build/cmake-re

https://engflow.com/cmake-re