Creating an LLVM Runtime

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Outline

Introduction

Let’s Create a Runtime

Are We Done Yet?

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Outline

Introduction

Why This Tutorial?

History

Rationale

Goal

Let's Create a Runtime

Are We Done Yet?

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About Me

- At AMD since 2024
- Working on
  - Fortran
  - OpenMP®
  - GPGPU Offloading
  - Loops
- Converted Flang's runtime to use the `LLVM_ENABLE_RUNTIMES` system

https://youtu.be/AGrInJLxJOQ

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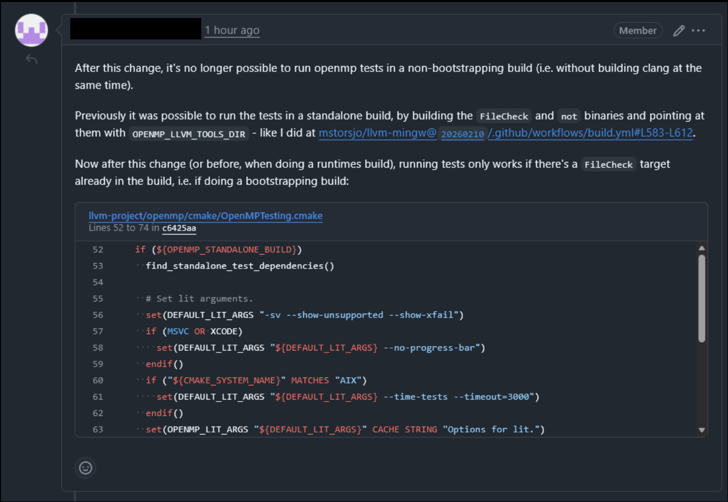
Why This Tutorial



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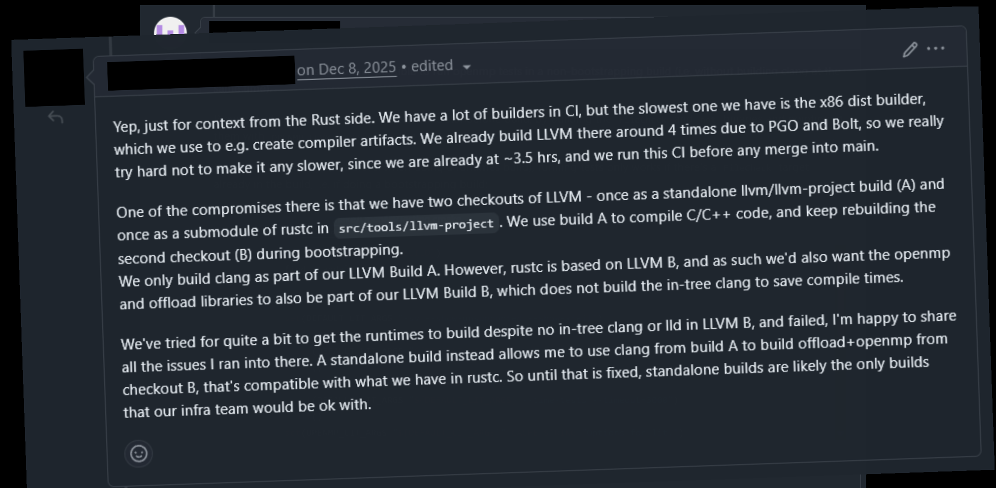

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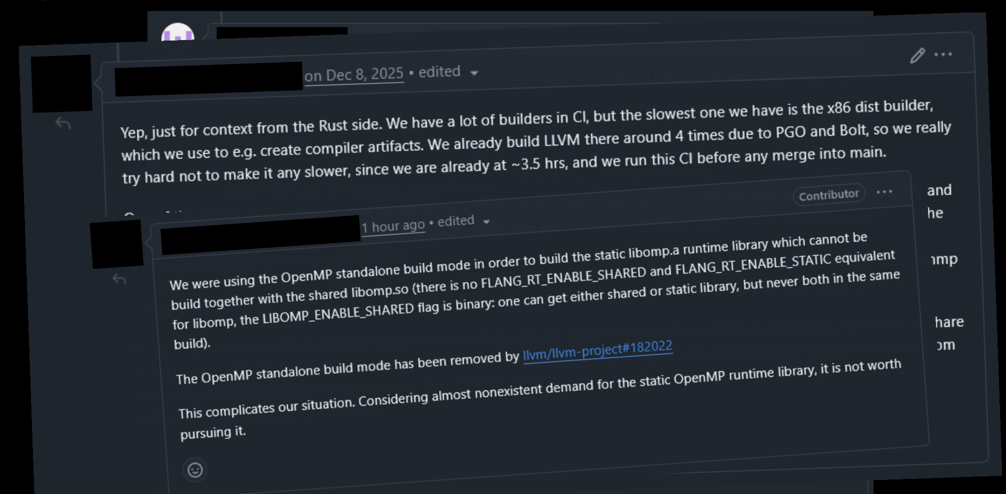

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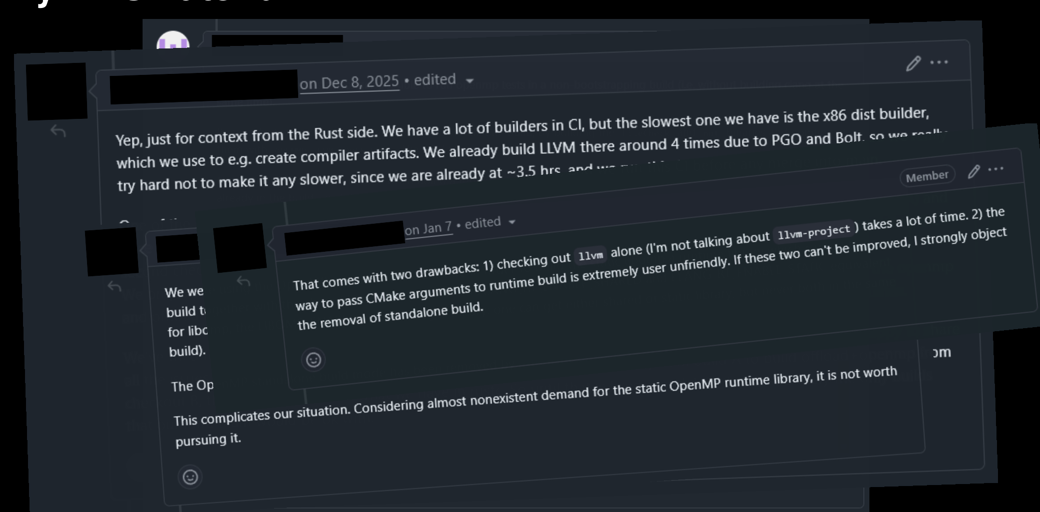

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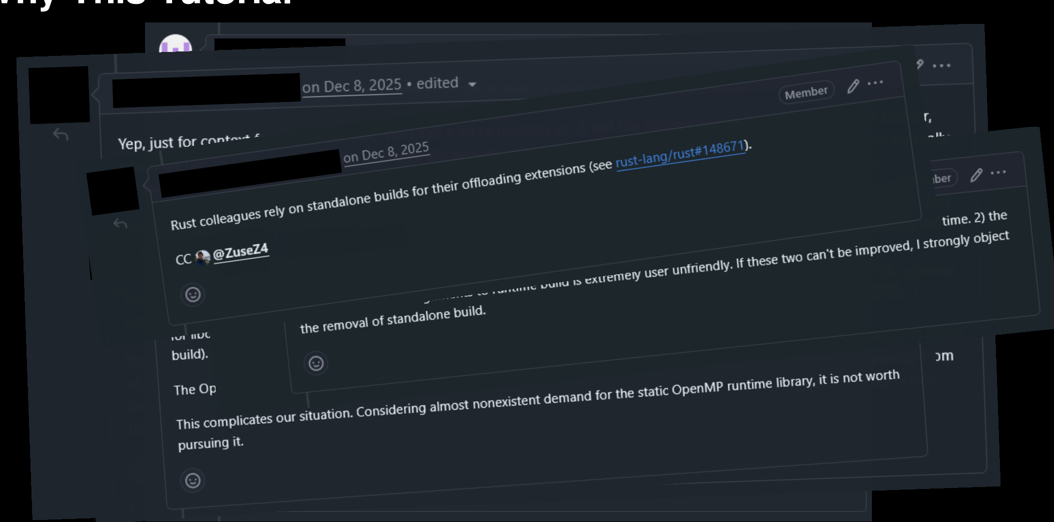

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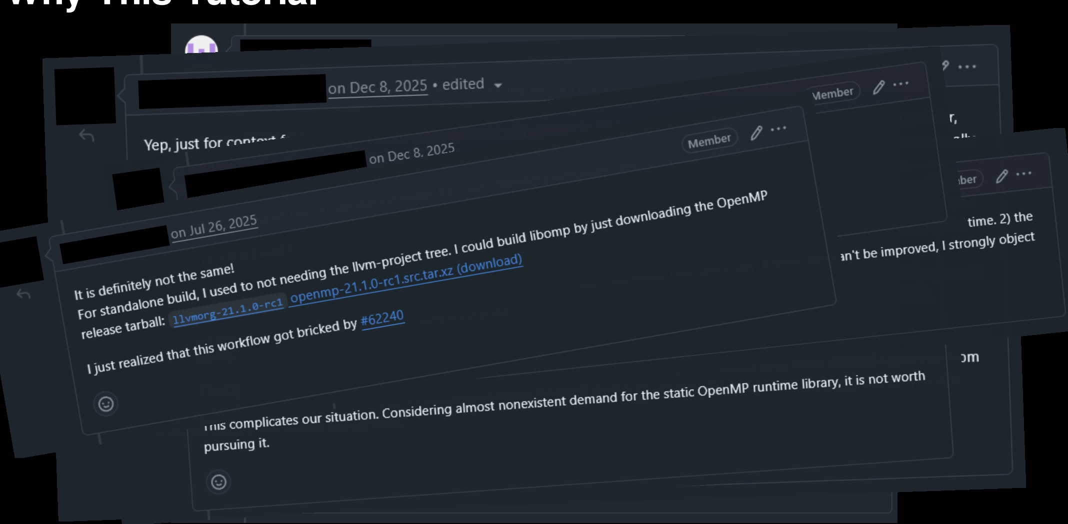

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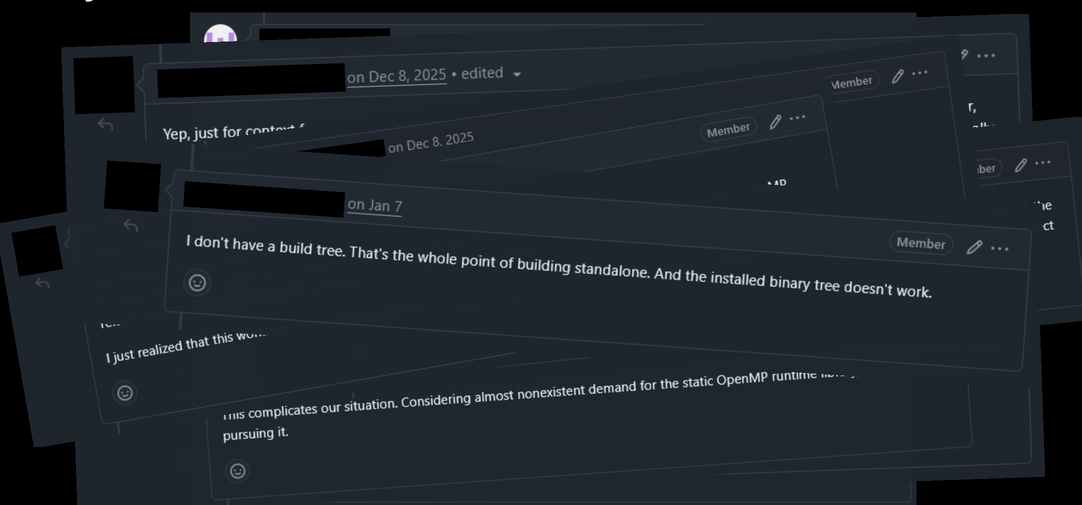

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History

1. Initially, each subproject had its own SVN repository
   - Subprojects categorized as “tools” (clang: 2009), “runtime” (libprofile), and “projects” (e.g., llvm-gcc)
   - An example project boilerplate existed

[1] https://reviews.llvm.org/D20992

[2] https://lists.llvm.org/pipermail/llvm-dev/2020-October/145997.html

[3] https://reviews.llvm.org/D26365

[4] https://reviews.llvm.org/D132478

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   - Somewhat different from compile-time utils/tools/compilers

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4. Introduction of `LLVM_ENABLE_PROJECTS`[3] (2016)
5. Introduction of `LLVM_ENABLE_RUNTIMES`[4] (2022)
   - First for libc++

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Rationale

Why `LLVM_ENABLE_RUNTIMES`?

Build Host	Cross-Compile Target	Compiler Target
The system we build on ▶ `cmake`, `ninja`, `cc`, … ▶ `llvm-tblgen`, `mlir-tblgen`, …	Where Clang will run ▶ `clang`, `opt`, `lld`, … ▶ `LLVMSupport{.a/.so}`, `LLVMPolly.so`, …	What Clang will compile for ▶ `a.out` ▶ compiler-rt, `libc`, `libc++`, …

- Automate multiple build-steps
  - Instead of: Build clang → build compiler-rt for x86_64 → build compiler-rt for arm64 → …
- Reduce per-runtime boilerplate/differences between build modes
- Runtimes compiled (Stage 2) using just-built Clang

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Why `LLVM_ENABLE_RUNTIMES`?

Build Host	Cross-Compile Target	Compiler Target
The system we build on	Where Clang will run	What Clang will compile for
▶ `cmake`, `ninja`, `cc`, ... ▶ `llvm-tblgen`, `mlir-tblgen`, ...	▶ `clang`, `opt`, `lld`, ... ▶ `LLVMSupport{.a/.so}`, `LLVMPolly.so`, ...	▶ `a.out` ▶ compiler-rt, `libc`, `libc++`, ...

Stage 1 (Build Host + Cross-Compile Target)

Stage 2 (Compiler Target)

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Tutorial Runtime

What is our tutorial runtime going to do?

Our Runtime

```
void _dublin_hello_world() {
  puts("Dia daoibh, a dhomhain!\n");
}
```

- Use LLVM™ best-practices
- Linux® only
- Prioritize conciseness and principles over
  - … features
  - … comments
  - … unrelated boilerplate
- Point out shortcomings of the current system

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Outline

Introduction

Let's Create a Runtime

- Setup
- Step 1: Register with the LLVM™ Build System
- Step 2: Build a Library Artifact
- Step 3: An Example That Uses the Library
- Step 4: Build Modes
- Step 5: CMake Cache Files
- Step 6: Artifact Output Location
- Step 7: Installation
- Step 8: Shared and Static Libraries
- Step 9: Regression Testing
- Step 10: Unittests
- Step 11: Sphinx Docs
- Step 12: Doxygen Docs
- Step 13: Cross-Compilation
- Step 14: Accelerator Offloading
- Step 15: Depending on Other LLVM™ Libraries / C++

Are We Done Yet?

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Setup

https://github.com/Meinersbur/llvm-dublin/tree/dublin-0-main

- README.md
  - Update Readme for tutorial
- .gitignore
  - Make git ignore install* subdirs (like build* already is)

$HOME/bin/cmake

```
/usr/bin/cmake -G Ninja                                    \
               -D CMAKE_C_COMPILER_LAUNCHER=ccache         \
               -D CMAKE_CXX_COMPILER_LAUNCHER=ccache       \
               -D CMAKE_DISABLE_PRECOMPILE_HEADERS=ON      \
               "$@"
```


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Register with the LLVM™ Build System

`https://github.com/Meinersbur/llvm-dublin/tree/dublin-1-basic`

- `llvm/CMakeLists.txt`
- `runtimes/CMakeLists.txt`
  - Allow `LLVM_ENABLE_RUNTIME=dublin`
- `dublin/CMakeLists.txt`
- `dublin/CODE_OWNERS.TXT`
- `dublin/LICENSE.TXT`
  - Subproject boilerplate

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Step 2: Build a Library Artifact

- `lib/Dublin/dublin.c`
- `include/dublin/Dublin/dublin.h`
  - Library sources
- `lib/Dublin/CMakeLists.txt`
  - Build instructions for `libdublin.a`

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Standard Subproject Layout

```
subproject
├─ docs
│  └─ *.rst, *.md
├─ examples
│  └─ Example1
│     └─ *.c, *.cpp
├─ test
│  ├─ Unit
│  │  └─ lit.cfg.py, lit.site.cfg.py.in
│  ├─ Component1
│  │  └─ *
│  ├─ Component2
│  │  └─ *
│  └─ lit.cfg.py, lit.site.cfg.py.in
├─ unittests
│  ├─ Component1
│  │  └─ Component1Test.cpp
│  └─ Component2
│     └─ Component1Test.cpp
├─ cmake
│  ├─ Modules/modules
│  │  └─ *.cmake
│  └─ caches
│     └─ *.cmake
├─ include
│  └─ subproject
│     ├─ Component1
│     │  └─ component1.h
│     └─ Component2
│        └─ component2.h
├─ lib
│  ├─ Component1
│  │  ├─ component1.c
│  │  └─ component1-internal.h
│  └─ Component2
│     └─ component2.c
└─ utils
   └─ utility
      └─ utility.cpp
```


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An Example That Uses the Library

`https://github.com/Meinersbur/llvm-dublin/tree/dublin-3-example`

- `examples/dublin-hello/dublin-hello.c`
  - Example source
- `examples/dublin-hello/CMakeLists.txt`
  - Example build instructions

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Common What To Build Options

- `DUBLIN_INCLUDE_<component>`
  - Executes `add_subdirectory(<component>)`
  - `ninja <component>` can be used
  - Defaults to `LLVM_INCLUDE_<component>`
- `DUBLIN_BUILD_<component>`
  - `ninja all` also builds `<component>`
  - Generally, steers which target use `ALL`/`EXCLUDE_FROM_ALL`
  - Defaults to `LLVM_BUILD_<component>`

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Build Modes

- `CMakeLists.txt`
  - Detect unsupported legacy build modes

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Build Modes

Legacy Build Modes

As project: `cmake -S <llvm-project>/llvm -D LLVM_ENABLE_PROJECTS=dublin`
Standalone: `cmake -S <llvm-project>/dublin`

- Intended to be superseded by runtimes build modes[1]
- If your build infrastructure still uses this, please consider updating
- Even “standalone” mode needs files from sibling directories

  A consequence of the monorepository

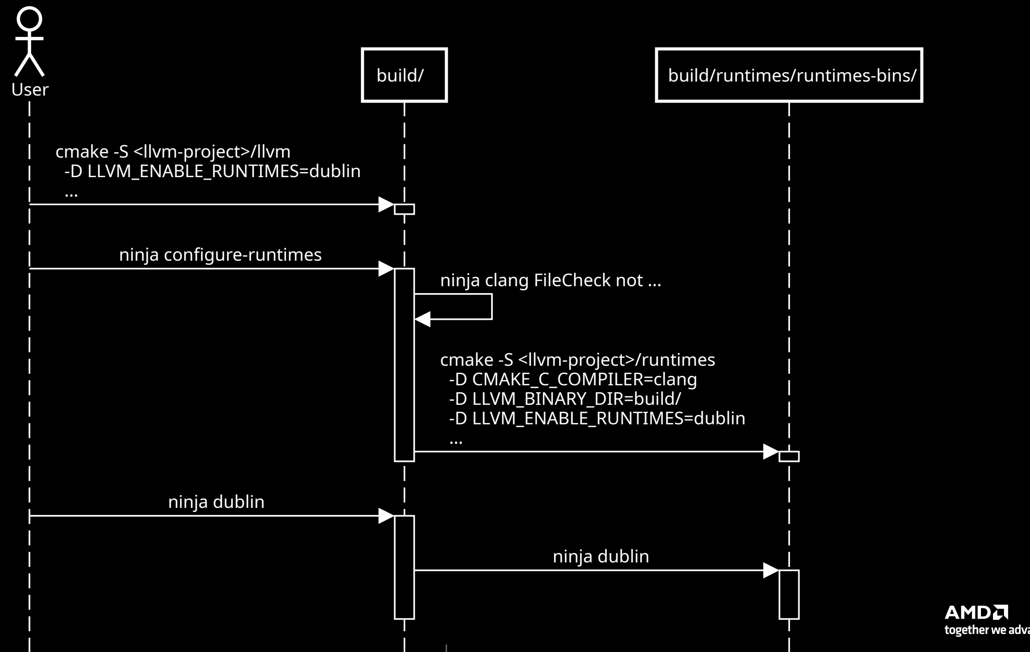
Runtimes Build Modes

Bootstrapping: `cmake -S <llvm-project>/llvm -D LLVM_ENABLE_RUNTIMES=dublin`
Default/Standalone: `cmake -S <llvm-project>/runtimes -D LLVM_ENABLE_RUNTIMES=dublin`

- Shared boilerplate code in `<llvm-project>/runtimes/CMakeLists.txt`

[1] https://lists.llvm.org/pipermail/llvm-dev/2020-October/145997.html

Bootstrapping Runtimes Build Mode



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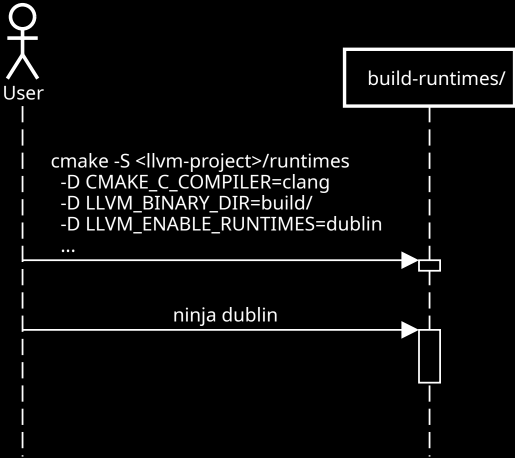
Default/Standalone Runtimes Build Mode

Skip the Middleman



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Default/Standalone Runtimes Build Mode

runtimes/CMakeLists.txt

```
project(Runtimes C CXX ASM)

find_package(LLVM HINT ${LLVM_BINARY_DIR})
# more boilerplate code

foreach (runtime ${LLVM_ENABLE_RUNTIMES})
  add_subdirectory(${runtime})
endforeach ()
```


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CMake Cache Files

`https://github.com/Meinersbur/llvm-dublin/tree/dublin-5-cachefiles`

- `cmake/caches/runtimes-bins.cmake`
  - Pre-populated CMake parameters as a bootstrapping build would set them

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Artifact Output Location

`https://github.com/Meinersbur/llvm-dublin/tree/dublin-6-location`

- `CMakeLists.txt`, `cmake/Modules/GetToolchainDirs.cmake`
  - Determine standard locations
- `lib/Dublin/CMakeLists.txt`
  - Set artifact output location

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Library Locations

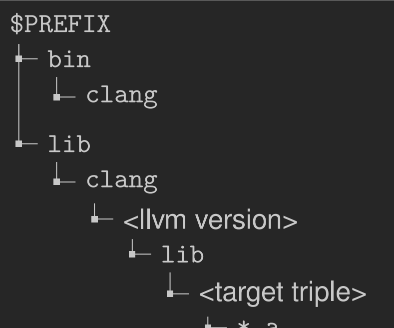
`LLVM_ENABLE_PER_TARGET_RUNTIME_DIR=ON`

Installation Prefix Dir

```
$PREFIX
├─ bin
│  └─ clang
└─ lib
   └─ <target triple>
      └─ *.so, *.a
```

- Accessible to any compiler when installed (including e.g., gcc)

Resource Dir



- Accessible to only this version of Clang (and Flang)

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Installation

`https://github.com/Meinersbur/llvm-dublin/tree/dublin-7-install`

- `CMakeLists.txt`
  - Set install output location
- `lib/Dublin/CMakeLists.txt`
  - Library installation
- `include/CMakeLists.txt`
  - Header installation

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Shared and Static Libraries

`https://github.com/Meinersbur/llvm-dublin/tree/dublin-8-shared`

- `cmake/Modules/AddDublin.cmake`
  - If building Shared and Static library, use an OBJECT library
  - Wrapper around CMake's native `add_library`
  - `AddLLVM`'s `llvm_add_library` main service is linking to LLVM™ libraries
    Target triple confusion. Do not use.
- `lib/Dublin/CMakeLists.txt`
  - Use `AddDublin.cmake` instead of `add_library`

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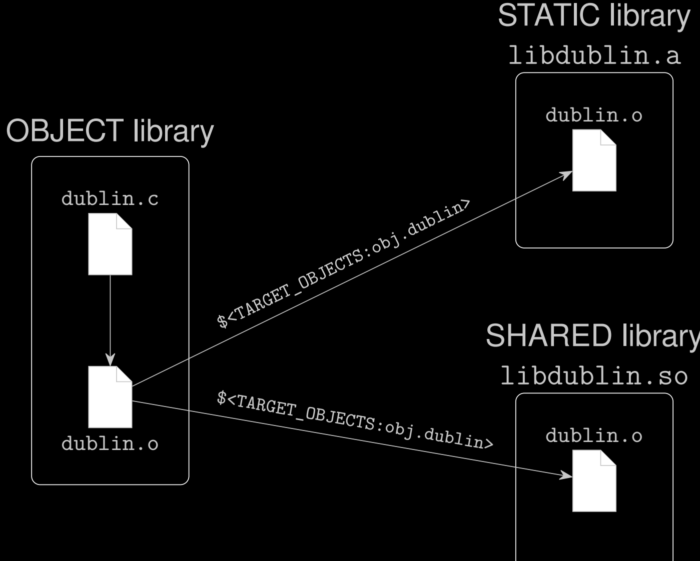
OBJECT Libraries



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Regression Testing

`https://github.com/Meinersbur/llvm-dublin/tree/dublin-9-test`

- `dublin/test/Dublin/dublin-hello.c`
  - The regression test:
    - Build the source
    - Link to `libdublin`(`.a`/`.so`)
    - Run
    - Expect output: “Dia daoibh, a dhomhain!”
- `dublin/test/CMakeLists.txt`
  - Testing boilerplate
- `dublin/test/lit.cfg.py`
- `dublin/test/lit.site.cfg.py.in`
  - `llvm-lit` configuration
    - How to find regression tests (`lit.formats.ShTest`)
    - Setup execution environment
    - Forward build configuration

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Unittests

`https://github.com/Meinersbur/llvm-dublin/tree/dublin-10-unittest`

- `unittests/Dublin/DublinTest.cpp`
  - Google Test-based test code
- `test/Unit/lit.cfg.py`
- `test/Unit/lit.site.cfg.py.in`
  - `llvm-lit` configuration
    How to find unittests (`lit.formats.GoogleTest`)

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Sphinx Docs

`https://github.com/Meinersbur/llvm-dublin/tree/dublin-11-docs`

- `docs/index.md`
  - The documentation
- `docs/conf.py`
- `docs/CMakeLists.txt`
  - Sphinx configuration
- `docs/_theme`
  - HTML boilerplate

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Doxygen Docs

`https://github.com/Meinersbur/llvm-dublin/tree/dublin-12-doxygen`

- `lib/Dublin/dublin.c`
  - Add Doxygen comment
- `docs/doxygen-mainpage.dox`
  - Doxygen frontpage content
- `docs/doxygen.cfg.in`, `docs/CMakeLists.txt`
  - Doxygen configuration

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Cross-Compilation

`https://github.com/Meinersbur/llvm-dublin/tree/dublin-13-cross`

No modifications necessary !

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Cross-Compilation

- `-D LLVM_RUNTIME_TARGETS="default;aarch64-linux-gnu"`
  Compile runtimes also for arm64
- `-D RUNTIMES_CMAKE_ARGS=-DLLVM_USE_LINKER=lld`
  Ubuntu's default `ld.bfd` does not support arm64

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Cross-Compilation

```
$builddir/
└─ runtimes/
   ├─ runtimes-bins/
   │  └─ CMakeCache.txt
   └─ runtimes-aarch64-linux-gnu-bins/
      └─ CMakeCache.txt
```

- `LLVM_RUNTIME_TARGETS=default`
  - ≈ `x86_64-unknown-linux-gnu`
  - Executable on host
  - NOT necessarily same ABI as LLVM™ (e.g., incompatible `LLVMSupport.a`)
- `LLVM_RUNTIME_TARGETS=aarch64-linux-gnu`
  - Cross-compilation target

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Accelerator Offloading

`https://github.com/Meinersbur/llvm-dublin/tree/dublin-14-offload`

- `CMakeLists.txt`
- `cmake/Modules/AddDublin.cmake`
  - Accommodate limitations of GPGPU targets
- `examples/dublin-openmp`
- `examples/dublin-hip`
- `examples/dublin-cuda`
  - Use of GPGPU-side `libdublin.a` from various offload languages

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Depending on Other LLVM™ Libraries / C++

`https://github.com/Meinersbur/llvm-dublin/tree/dublin-15-deps`

- 🗋 `lib/Dublin/dublin.cpp`
- 🗋 `include/dublin/Dublin/dublin.h`
- 🗋 `examples/dublin-hello/dublin-hello.cpp`
  - ► Convert to C++
- 🗋 `cmake/Modules/AddDublin.cmake`
- 🗋 `../third-party/unittest/CMakeLists.txt`
  - ► Link to libc++, regardless of compiler default

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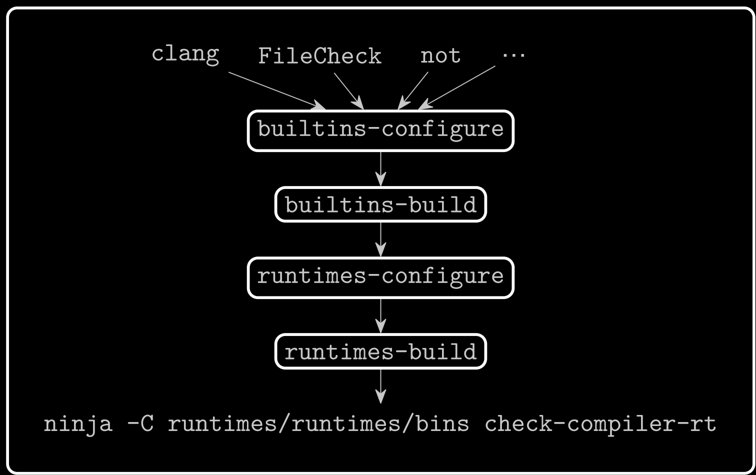
Compiler-RT Builtins



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Outline

Introduction

Let's Create a Runtime

Are We Done Yet?

- More Topics
- Build System Improvements

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Not Covered Topics

- Platform Introspection
  `check_source_compiles`
- Platform Support
  Windows®/MacOS/AIX/Fuchsia/…
- Multilib
  `lib32/lib64`
- Versioning
  `libdublin.a.1.1`
- Export libraries
  `find_package(Dublin)`
- Continuous Integration
- Fortran
- …

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Potential Runtimes Build Improvements

- Inform LLVM™ developers and OS distributions
  (Build modes) developer documentation missing, runtime template

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- Make `RUNTIMES_*` options discoverable

  ```
  set(RUNTIMES_CMAKE_ARGS "" CACHE STRING "Help")
  ```


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  Boilerplate diverged significantly since the SVN days

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  - GPGPU targets
  - `LLVM_RUNTIME_TARGETS=default`
  - Compiler-RT “builtins”

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- Writing runtimes in C++

  Option whether to use default stdlib or libc++

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- Get rid of `LLVM_ENABLE_PER_TARGET_RUNTIME_DIR`
- QEMU (`CMAKE_CROSSCOMPILING_EMULATOR`)
- …

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