

Building the LLVM and GCC Translation Systems, with Amake

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RESEARCH ARTICLE – TECHNOLOGY

Building the LLVM and GCC Translation Systems, with Amake

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This paper describes the author’s exploratory experience of porting the build systems of two large software distributions, the LLVM and GCC programming-language translation systems, to the Amake build tool. Amake is an enhanced derivative of the very popular GNU Make. Amake adds automatic language-independent dependency analysis and site-wide heterogeneous target caching. Amake also supports GNU Make’s parallel-build capabilities. This experience included (mostly) expected changes to both of these build systems, but somewhat surprising changes to Amake’s design and implementation. A description of the former changes is hoped to encourage developers to migrate their build systems to Amake. The latter changes showcase Amake’s most recently added features.

KEYWORDS:

software engineering, maintenance, and tools; computer-aided software engineering

1 | INTRODUCTION

Amake extends GNU Make¹ with automatic dependency analysis, multiuser target caching, and other valuable features. This paper describes two case studies, showing how Amake can replace GNU Make to build LLVM² and GCC.³ It also describes recent design and implementation changes that were made to Amake, the need for which was discovered while trying to build these complex systems.

Amake has evolved, over many years. Previous papers describe foundational topics, and earlier stages of the project.^{4,5,6}

Amake has built other software systems. An early, pre-cache, version has built the Linux kernel. This version builds the Bash distribution. And, of course, Amake builds itself. This paper shows that full-featured Amake can build complex, real-world systems, not just toy programs.

Amake currently extends version 4.3 of GNU Make. Porting Amake’s extensions to a new version of GNU Make is easy: Three function calls are added to `job.c`, one to `read.c`, and five to `remake.c`. One member is added to the structure named `dep`, marking detected dependencies. Ten members are added to the structure named `file`, for a variety of purposes. Amake’s source code is freely available.⁷

1.1 | Related Systems

Amake, like many other build tools, is a derivative of the original Make.⁸ Following the tradition of login shells (`ash` – `zsh`), these derivatives are often named by prefixing a letter of the alphabet. But Amake wasn’t named to be first in the phone book. Rather, its “A” is for “access,” due to its initial deployment. Amake was adopted at Hewlett-Packard’s Boise facility, circa 2007,⁴ to build what HP calls “firmware” for personal-sized laser printers. (Mainly, it’s software that rasterizes a file sent to the printer.) A preloaded shared library was used to detect certain kinds of filesystem access. The name stuck. Amake is most closely related to three programming-language independent, dependency-analysis, target-caching tools: Bazel,⁹ Clearmake,¹⁰ and Vesta.¹¹ All of these are very powerful computer-aided software-engineering tools. Albeit, Amake provides only software-build functionality, but it has advantages in that niche.

Clearmake is the build tool for the proprietary Clearcase configuration-management system.¹² Vesta is also a full-featured system, but open source. Both have outstanding build tools, but they are coupled to integrated version-control systems, requiring special filesystems, implemented as a customized kernel or loadable kernel module. Automatic dependency-analysis is performed only for versioned items (e.g., not `/bin/gcc`).

Clearmake has nothing like Amake's "top targets," but Vesta does, with its "shipped derived objects." A Clearmake build is controlled by an enhanced dialect of makefile. A Vesta system model is specified in a very elegant domain-specific functional language.

Google's Bazel (née Blaze) is a more recent arrival, at least to the public. Unlike with Clearmake and Vesta, I lack real-world industrial experience with Bazel. However, the similarities between Amake and Bazel, at least in the target-cache arena, are striking. Both use "digests" (i.e., checksums). Both also support configuring a server as a remote cache for build outputs (early external releases of Bazel did not support a cache). Both split their cache into two parts. With Bazel: An "action cache" maps action hashes to action-result metadata. This is like Amake's target-cache index daemon (`tid`), in Figure 1. A "content-addressable store" of output files holds the rest. This is like Amake's target-cache filesystem, in Figure 1. Bazel supports many "backends" that can be used for a remote cache, such as `nginx` (a popular web server), `bazel-remote` (a bespoke HTTP server), and Google Cloud Storage (a managed service).

As with Clearmake and Vesta, "Bazel does not track tools outside a workspace." This is a glaring omission of a very important capability, by all three systems. Furthermore: "Bazel tries very hard to ensure hermeticity by requiring the user to explicitly declare input files to any build rule." Thus, its automatic dependency analysis does not encompass discovery, only enforcement. Bazel does not yet support a feature like Amake's "top targets," but proposes to "optimize the remote cache," by fetching only "the final build artifacts."

1.2 | Outline

Section 2 presents build-system and Amake terminology, while Section 3 has additional Amake background needed for this paper. Section 4 discusses subtleties of top builds. Sections 5–7 contain the main contributions, presenting two case studies: building the LLVM and GCC distributions with Amake. During this work, new requirements surfaced, leading to design and implementation changes. They were general in nature, part of Amake's evolution. Amake was not "customized" for LLVM or GCC. These changes are discussed, as well as build-process changes needed for LLVM and GCC. These sections also give timing results, compared to GNU Make. Section 8 concludes the paper, with suggestions for future projects. Appendix A describes a cache-maintenance tool, which was also a very valuable debugging aid. Appendix B documents the two-server computing environment used for most of this work.

2 | TERMINOLOGY

A makefile specifies a software product's *build system*, an implementation of its *system model*. The makefile's rules specify *build commands* (e.g., compiler invocations) and file relationships (e.g., preprocessor inclusions). A file can be a target, a sibling, a dependency, or a combination of those.

A *target* is the file produced as the primary result of executing a rule's sequence of build commands. GNU Make allows non-file targets, but Amake's extensions require a target to be a plain readable file (or a symlink to one), but not a directory (nor a symlink to one). A `.PHONY` target (e.g., `clean`) is ignored by Amake's extensions, as well.

A *sibling* is a non-target file produced as a coincidence, or side effect, while executing a target's build commands.

A *derived file* is a target or sibling.

A *dependency* is a file read, but not written, while executing a target's build commands.

Like a target, a sibling or dependency must be a plain file (or a symlink to one), but not a directory (nor a symlink to one).

A sibling is distinguished from a dependency in that a sibling is written, but a dependency is only read, while executing a target's commands. A sibling produced while updating one target might also be a dependency of a different target. If a makefile explicitly lists such a dependency, an improvement to that makefile would be to, instead, list the first target as the dependency. This is because a sibling cannot be updated directly, but only during an update of its target.

A target may have multiple siblings and/or dependencies. However, a sibling must have exactly one target. That is, a sibling is created during the build of exactly one target. A build system that can produce a single sibling (or target, for that matter) in two different ways is inherently inconsistent. The distinction between sibling and dependency, and indeed between sibling and target, is muddied in a build system where the build tool executes itself as one of a target's commands (a so-called "recursive make"). This is clarified in Section 7.2.3, where real-world examples are considered.

A target that is neither a sibling nor a dependency is a *top target* (aka, a *goal*): an end product of the build system.

A dependency that is also a target of some other rule is called both an *intermediate dependency* and an *intermediate target*. This naturally partitions dependencies into *direct dependencies* and *transitive dependencies*, and is the basis for computing the closure of a target's dependencies.

A non-target dependency is a *source dependency*, the result of a manual process, such as editing by a human.

Perhaps surprisingly, updating a dependency does not necessarily require updating its targets. For example, a source-file edit, compiling to unchanged object code, need not be relinked into an executable file.

A top target differs from an intermediate target by being what a developer actually wants, not just a means to an end (e.g., an executable file, distributed to customers). Vesta calls it a “shipped derived object.” The set of top targets can vary over time, even minute by minute. For example, GNU Make, and Amake, let a developer specify any target on the command line, thereby making it a top target for that build. Therefore, any special treatment of top targets must persist only until the next build. Ultimately, the purpose of a build tool, and a build system, is to update a set of top targets from source and intermediate dependencies, while conserving computing resources.

3 | PREVIOUS AMAKE MILESTONES

Amake extends GNU Make, with features to improve correctness and time/space performance. Amake performs automatic language-independent deduction of file and non-file dependencies, storing them in text files, which can also be forensic aids to a build engineer. Its enhancements are described below:

- While updating a target, several kinds of dependency are automatically detected and recorded (in its `.dep` and `.cmd` files): files accessed, commands executed, script and binary programs executed, shared-libraries opened, and specified environment-variable values (other variables are unset).
- A rule updating a target may create/write other files. Such siblings are also automatically detected and recorded, in its `.sib` file.
- Filesystem timestamps are ignored. Instead, checksums of file content are compared. This is accelerated by a workspace host’s checksum-cache daemon.
- Heterogeneous targets and siblings are cached in a multi-user, multi-host, and multi-platform database. If a target needs updating, and a suitable candidate is cached, execution of the commands to rebuild the target is avoided.
- If a top target needs to be updated, and a suitable candidate is in the cache, updating of its non-goal dependencies is avoided. This is called a *top build*, which can save a huge amount of time and space. However, correctness requires appropriately constructed makefile rules. So, this feature must be explicitly enabled, via a makefile variable. Top-build correctness is examined in Section 4, below.

GNU Make is a single executable program, which executes as a single process (of course, it can `fork` subprocesses to execute shell commands). Amake is more complex, a collection of communicating programs, including daemons and a “preloaded” shared library.

A daemon (aka, server) is an independent process, that communicates with other processes via sockets. A long-lived daemon is started independently from Amake, and has no particular termination time. This is the traditional kind of daemon. A short-lived daemon is started by Amake, and is terminated by the end of the build.

These are Amake’s components:

- A short-lived target-cache daemon (`tcd`) provides a single build with access to the target cache.
- A long-lived (i.e., traditional) daemon (`tld`) provides `tcd` daemons with multi-user and multi-host access to the target cache. The target cache has two parts: an index and the entries. The index is an off-the-shelf database, run-time selectable as: SQLite,¹³ Berkeley DB,¹⁴ GNU DBM,¹⁵ or MySQL.¹⁶ The choice is made thread safe, with a homebrew concurrency wrapper. The entries are stored in any ordinary, but network, filesystem (e.g., NFS¹⁷ or AFS¹⁸). An entry is a `tar` file and some makefile fragments.
- A checksum-cache daemon (`ccd`) avoids unneeded recalculation of file-content checksums. Its use is optional. As files change, Inotify¹⁹ helps `ccd` invalidate entries.
- Several cache-query scripts aid cache maintenance and debugging. These compose the cache-maintenance tool, of Appendix A.

Amake’s shared library, `libaccess.so`, employs the GNU C library’s `LD_PRELOAD` mechanism, to intercept and audit several standard shared-library function calls (e.g., `open`). Each preloaded function records its arguments, and then calls the real function. Of course, this idea isn’t novel. For example, Automake’s manual,²⁰ when discussing dependency analysis, suggests:

Rather than use the file system, one could write a special library to intercept `open` and other syscalls. This technique is also quite powerful, but unfortunately it is not portable enough for use in Automake.

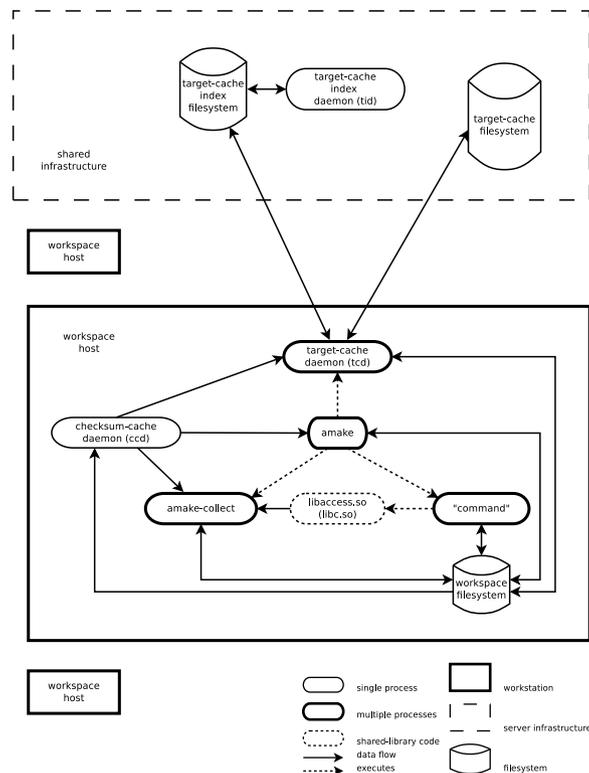


Figure 1 Overall System Structure

In contrast, Clearmake and Vesta use a custom filesystem, implemented as part of the operating-system kernel, either as a compiled-in subsystem, or as a dynamically loadable module. This is the “syscalls” approach. Amake’s approach is a “special library.” For LLVM and GCC, Amake’s shared library was upgraded for the (relatively) new family of `*_at` functions (e.g., `open_at`), which mitigate a race condition between following a path to a file and actually opening it. This addressed the GCC build process’s predilection for building targets in distant directories.

A system like this can be configured in multiple ways. Figure 1 shows a reasonable arrangement, for an installation with multiple developer workstations, each with local compute and storage resources, and sharing centralized storage resources. Such sharing can be as simple as NFS.

4 | TOP-BUILD RISKS

This section reviews Amake builds, focusing on top builds, in order to characterize the risk of using top builds. Eliminating the risk is straightforward, once understood. We begin with an illustrative build scenario; discussion follows.

For example, consider the makefile in Figure 2. In particular:

- Variable definitions enable Amake features. The `SPECIAL` variable (and C-preprocessor macro) chooses between hypothetical “regular” and “special” compilations. The `?=` form of definition specifies that the default is regular compilation. The shared source file, `f.c`, simply prints the name of the executable file it was linked into, and whether it was compiled regular or special.
- The pattern rule specifies that an object file depends on its C source file, and the compilation command.
- The rule for `a11` specifies dependencies needed to build both executable files. Its command also runs both executable files, quietly.
- Two rules specify that both executable files depend on the same object file, and the two commands to link them. The difference between the commands will highlight the top-build risk.
- The `include` directive includes the content of Amake-generated files, from the previous build.

```

1 SHELL:=/bin/bash
2 ACCESS_ENABLE:=1
3 ACCESS_CHKSUM:=1
4 ACCESS_CACHE:=1
5 ACCESS_TOP:=1
6 SPECIAL?=0
7 opts:=-DSPECIAL=$(SPECIAL)
8 %.o: %.c
9     gcc -c $< $(opts)
10 .PHONY: all
11 all: foo bar
12     @foo ; bar
13 foo: f.o
14     gcc -o $@ $^
15 bar: f.o
16     gcc -o $@ $^ $(opts)
17 sinclude *.dep
    
```

Figure 2 Top-Build Example Makefile

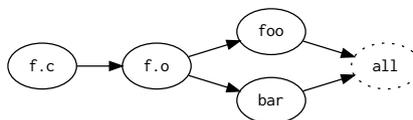


Figure 3 Top-Build Example System Model

```

1 $ amake
2 gcc -c f.c -DSPECIAL=0
3 Cache put: f.o
4 gcc -o foo f.o
5 Cache put: foo
6 gcc -o bar f.o -DSPECIAL=0
7 Cache put: bar
8 foo: regular
9 bar: regular
    
```

Figure 4 Top-Build Example (1 of 7)

Using the terminology of Section 2, the targets are all, foo, bar, and f.o. The dependencies are foo, bar, f.o and f.c. The top targets are all, and because all is phony, foo and bar. The intermediate target/dependency is f.o. The source dependency is f.c. The dependency part of the system model is shown in Figure 3.

In the following examples, we assume that previously built files have been removed from the workspace, before the build (e.g., via amake clean).

For our first example, in Figure 4, suppose we are in a new workspace, with an empty target cache, and compile regular. All targets are built, and put into the cache.

The next example, in Figure 5, is a non-top regular build: All targets are fetched from the cache.

Compare this to a top regular build, in Figure 6. Unlike the previous build, in Figure 5, only the top targets are fetched from the cache. After the

```

1 $ amake ACCESS_TOP:=
2 Cache get: f.o
3 Cache get: foo
4 Cache get: bar
5 amake: Nothing to be done for 'all'.
6 foo: regular
7 bar: regular

```

Figure 5 Top-Build Example (2 of 7)

```

1 $ amake
2 Cache top: foo
3 Cache top: bar
4 amake: Nothing to be done for 'all'.
5 foo: regular
6 bar: regular

```

Figure 6 Top-Build Example (3 of 7)

```

1 $ amake SPECIAL:=1
2 Cache top: foo
3 gcc -c f.c -DSPECIAL=1
4 Cache put: f.o
5 gcc -o bar f.o -DSPECIAL=1
6 Cache put: bar
7 foo: regular
8 bar: special

```

Figure 7 Top-Build Example (4 of 7)

build, the intermediate target, `f.o`, does not exist in the workspace. In a large software system, with thousands of source files, the time and space saved by avoiding rebuilding, or even copying, files like this would be huge.

At this point, the cache contains only regular targets. We demonstrate the risk, by performing a special build, in Figure 7. Although `bar` is built correctly, `foo` is not. The next paragraph explains what worked, while the sequel deconstructs what went wrong with `foo`.

The command for `bar` differs from the command that built the cached `bar`. But, before `bar` can be relinked, its dependencies must be considered. The command to build `f.o` also differs from the command that built the cached `f.o`. So, `f.o` is recompiled, `bar` is relinked, and they are added to the cache.

The command for `foo` is the same as the command that built the cached `foo`. Furthermore, the source dependencies are the same as those used to build the cached `foo`. The source dependencies are `f.c`, as well the many automatically detected files, programs, and libraries that participated in that build. The intermediate dependency, `f.o`, is not considered, because it is not in the workspace. So, an incorrect `foo` is fetched from the cache.

One might be tempted to call this a "bug" that needs to be fixed. However, trying to do so would just take you most of the way back to a non-top build. Fetching `f.o`, for consideration, would undermine the whole point of a top build.

Of course, a non-top special build produces correct executable files, as seen in Figure 8. Now, the cache contains a full set of regular and special targets. However, both the regular and special `foo` entries were built with exactly the same command. They cannot be distinguished, without analyzing intermediate dependencies. Of course, a non-top regular build is still correct, as seen in Figure 9.

However, the top regular build in Figure 10 exposes an even more subtle form of risk. While trying to fetch an acceptable `foo` from the cache, the `tid` provides the `tcid` with two, potentially acceptable, paths to the target-cache filesystem. One path is for the regular entry; the other is for the special entry. The `tid` finds them both acceptable, because their commands are the same. The `tcid` would also find both acceptable, due to their source dependencies, making either entry completely acceptable. But, since the `tid` orders paths from newest to oldest, in a heuristic attempt to speed-up fetches, the `tcid` succeeds after the most recent `foo` entry, which turns out to be the wrong one.

To summarize, the makefile in Figure 2 builds `bar` correctly, but `foo` incorrectly, in Figure 10, because the command to link `bar` contains the value of `$opts`, even though the linker doesn't need that value. A top build ignores intermediate dependencies, thereby ignoring the commands that

```

1 $ amake ACCESS_TOP:= SPECIAL:=1
2 Cache get: f.o
3 gcc -o foo f.o
4 Cache put: foo
5 Cache get: bar
6 foo: special
7 bar: special

```

Figure 8 Top-Build Example (5 of 7)

```

1 $ amake ACCESS_TOP:=
2 Cache get: f.o
3 Cache get: foo
4 Cache get: bar
5 amake: Nothing to be done for 'all'.
6 foo: regular
7 bar: regular

```

Figure 9 Top-Build Example (6 of 7)

```

1 $ amake
2 Cache top: foo
3 Cache top: bar
4 amake: Nothing to be done for 'all'.
5 foo: special
6 bar: regular

```

Figure 10 Top-Build Example (7 of 7)

would build them. The computation of the leaves of the transitive closure (i.e., the source dependencies) skips them. A careful makefile designer, hoping for correct top builds, needs to promote those command dependencies to the target, duplicating them, even if only as a comment on a command line.

5 | LLVM AND GCC

LLVM and GCC are well known programming-language translation systems. LLVM is more of a framework for translation and optimization, but it comes with a compiler (i.e., `clang`). GCC is more of a set of translator frontends and backends, providing a cross-product of compilers and standalone libraries. This work was done with LLVM 6.0.1 and GCC 9.2.0.

LLVM's build system employs CMake,²¹ to process over 400 `CMakeLists.txt` files, producing a tree of makefiles. CMake is cross platform: it can target a dizzying zoo of build tools. Here, we use its Unix Makefiles platform, for GNU Make.

GCC's build system employs GNU Autotools,^{20,22} to process about 100 `Makefile.am` and `configure.ac` files, producing a tree of `configure` scripts, which produce a tree of makefiles. GNU Make and Libtool²³ do the rest.

While both systems employ generated makefiles, which greatly simplifies scripted makefile tweaking, the CMake makefiles are less brittle. GCC's makefile-generation tools allow arbitrary content to flow through, verbatim. Thus, scripts to manipulate the resulting makefiles must be finely tuned.

GCC's build system uses Autotools in a surprising way. In most systems (e.g., Bash), the `configure` step produces *all* of the makefiles. With GCC, it produces one, top-level, makefile. The rest of the build, as directed by that makefile, produces the rest of the makefiles. Thus, makefiles are not available for tweaking, until compilation/linking is underway. In short, configuration is interleaved with translation.

Two techniques can address this. In simple cases, such a makefile can be effectively modified by creating its directory and adding a wrapper, named `GNUmakefile`. For example:

```

1 some content here
2 include Makefile
3 more content here

```

GNU Make's `makefile-search` order allows this wrapper to override parts of the real makefile. In other cases, a wrapper script, here named `wrap`, can perform arbitrary operations, at very particular times, before forwarding its command-line options, in `$$@`, on to the real `make`. For example:

```

1 #!/bin/bash
2 case $PWD in
3   where) action ;;
4 esac
5 exec amake MAKE:=$0 "$@"

```

Thus, `wrap` can use the working directory and makefile target to selectively: clear the checksum cache, modify makefiles and/or scripts, and/or override makefile variables. It is executed for a top-level build, and for each recursive build. Here, LLVM was built with a 35-line `wrap`. GCC's `wrap` was 75 lines long.

The first step in porting a system's build process to Amake is to understand, and disable, its ad-hoc dependency-analysis efforts. Their ubiquity is a testament to the importance of automatic dependency analysis. Examples are everywhere: simple makefile-generation scripts, X11's `imake`,²⁴ GNU Autotools, the Linux kernel's `Kbuild` system,²⁵ or even just GCC's `-MMD` option.³ They all strive to increase accuracy and reduce manual labor. Most techniques simply try to approximate files-accessed dependencies, but some also attempt commands-executed dependencies (e.g., `Kbuild`).

A detailed description of the ad-hoc dependency-analysis, employed by the LLVM and GCC builds, follows. Mainly, both builds try to detect files-accessed dependencies via file-inclusion analysis. Consequently, both are severely hampered by what can be gleaned from preprocessor directives in C/C++ source code. LLVM's build scans the source code itself. GCC's build asks the preprocessor to do it, which performs actual file and conditional inclusion. Neither method works for other languages, such as \LaTeX , or one read by a homebrew translator. This form of incompleteness is a common failing of build systems.

Both build processes can also build a set of software-development utilities, the so-called "binary utilities" (e.g., `nm`). They are distributed as part of LLVM, but separately from GCC.

6 | LLVM

This section describes the build changes and Amake modifications needed to build the LLVM distribution. A few build times are also cited.

6.1 | LLVM-Build Changes

Starting from scratch, the LLVM and Clang distributions are untarred, or checked-out, creating a "source" directory, and CMake is executed in an empty "build" directory. One command-line argument is the source-directory path; another specifies "a build system generator" of `Unix Makefiles`. CMake is again executed to "set the build tree" to the current directory, and the build directory is populated with `build.make` makefiles, ripe for subsequent tweaking.

As mentioned in Section 5, CMake implements build avoidance, which overlaps and interferes with some of Amake's features, and must be disabled. The first such change removes many dependency-analysis `$(MAKE)` commands from CMake's `Makefile2`. Then, most absolute paths in `build.make` makefiles are made relative. These changes could have been accomplished by modifying CMake's makefile generator. Finally, the two `build.make` files that build the `libclang` and `LTO` shared libraries, as siblings of library-versioning symbolic-link top targets, are changed, to also build the libraries as top targets.

Amake, via `wrap`, is then executed, with a command-line argument of `--jobs=4`, for a 4-job build. This low degree of parallelism avoids thrashing during linking. A higher value can be used during compilation, but not linking. GNU Make has a command-line argument to throttle the number jobs based on load average. It needs one to do the same based on memory pressure.

6.2 | Amake Changes, for LLVM

Only one modification to Amake was required. It was surprising, but easy to implement. Referring to Figure 1, the target cache has two parts: the index and the `cachedir` directories that hold entries. Since the cache is shared, between processes and hosts, it is thread safe, in two ways. The index is protected by a typical readers/writers concurrency wrapper, implemented with mutexes and condition variables. The entries are protected by

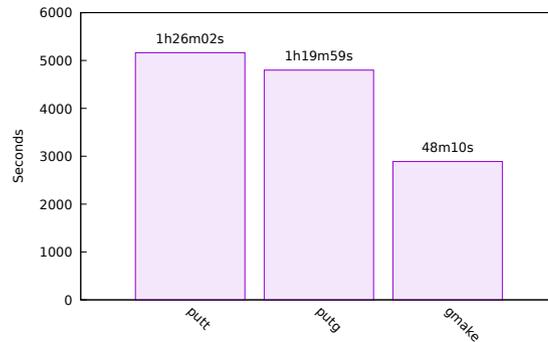


Figure 11 LLVM No/Empty Cache Builds

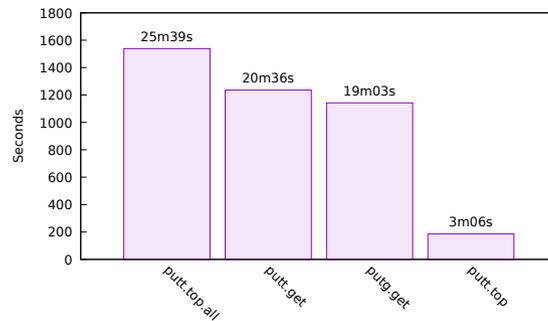


Figure 12 LLVM Cache Builds

writing them to directories named to prevent concurrent access, constructed from: username, hostname, date, time, PID, and filename. Originally, the time granularity was seconds. However, LLVM's build was observed writing two distinct targets, with the same name but to different workspace directories, within one second of each other, causing them to be cached in the same cachedir. Such collisions were avoided by simply refining the granularity, from seconds to microseconds.

6.3 | LLVM-Build Times

A comprehensive build-performance analysis, even just for the time domain, is challenging, since there are so many build scenarios (e.g., in an empty workspace, in an up-to-date workspace, and after a single source-file edit). Furthermore, the content of the cache makes a huge difference. Therefore, only a few comparisons are drawn here.

First, consider Figure 11. In an empty build directory, a GNU Make build requires 0:48:10 (hours:minutes:seconds). In an empty build directory, with an empty target cache, Amake top and get builds require 1:26:02 and 1:19:59 (resp.), 179% and 166% more than GNU Make. The overhead is mainly for filling the cache, for later builds. The top build also has to compute transitive closures and write `.top` files. Note that, with an empty cache, a top build still has to build *all* of the targets, to build the top targets.

Next, consider Figure 12. With a cache of qualified candidates (a common scenario), times are much better. In an empty build directory, sans CMake progeny, an Amake get build requires 0:25:39 to fetch all 2453 targets. Comparable top builds require 0:20:36 and 0:19:03 to fetch 504 top targets, including 242 `lib/` and 83 `bin/` files. The multitude of top targets are due to CMake's generated makefiles. Indeed, top builds are slower than corresponding get builds, due to redundant dependency checking, across so many top targets. When `wrap` selects just the "important" 106 top targets, 9 `lib/*.so` and the same 83 `bin/` files, Amake requires only 0:03:06.

Compared to the first-mentioned "from scratch" build, Amake's cached workspace-filling build requires only 53% of the time required by GNU Make. If only the important top targets are needed (e.g., for testing), this drops to a miniscule 6% of that required by GNU Make.

The most common scenario, shown in Figure 13, starts with an almost up-to-date workspace, and a cache of mostly acceptable target candidates (e.g., after a developer has just made changes to one source file). This scenario is accurately approximated with a completely up-to-date workspace (i.e., just after one of the previously discussed builds). A GNU Make up-to-date build, albeit with rudimentary dependency checking, requires 4

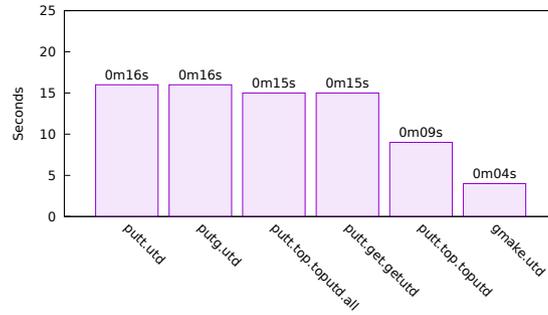


Figure 13 LLVM UTD Builds

seconds. Amake up-to-date builds (permutations of top/get and uncached/cached) require about 16 seconds, 4 times more. If only the the important top targets are needed, the aforementioned shared-library and executable files, Amake requires 9 seconds, only 5 seconds more than GNU Make.

7 | GCC

This section describes build and Amake modifications needed to build the GCC distribution. As in the previous section, a few build times are cited.

7.1 | GCC-Build Changes

Compared to LLVM's build process, many more changes are required to build GCC with Amake. This is because LLVM's CMake-generated makefiles enjoy the uniformity of algorithmically produced code, while GCC's generated makefiles contain much handcrafted code. The remainder of this subsection describes these changes.

Starting from scratch, the GCC distribution is untarred, or checked-out, creating a "source" directory. This directory's `configure` script is then executed, from an empty "build" directory. The first change is to execute this script with a command-line argument to disable Automake's `depcomp` script. According to a comment in the script, it "understands how to coax many different C and C++ compilers into generating dependency information in the format it requires." While `-disable-dependency-tracking` sounds promising, further ad-hoc build-avoidance techniques must be disabled. After `configure` deduces its source directory, it creates a single makefile, in the build directory, ripe for such tweaking. Further configuration is performed by rules in that makefile.

The second change involves `wrap`. As described in Section 5, `wrap` can redefine a makefile's variables, changing what the makefile does. But, it can also change scripts and makefiles generated by that makefile, just before they are (later) used. The `gcc`, `libcpp`, and `libgcc` subsystems get this treatment. In short, the soon-to-be tree of about 30 `configure` scripts will later generate makefiles, which will even later execute `wrap/amake`, rather than `make`, by overriding the value of `$(MAKE)`, eventually updating *real* targets (e.g., object files). In this way, `wrap` quashes the remaining ad-hoc build-avoidance techniques (e.g., use of a compiler's `-MMD` command-line argument).

After the configuration step, `wrap` is executed, with a command-line argument of `--jobs=$(nproc)`, launching a 24-job build (for the computing environment described in Appendix B). Upon entering a GCC subsystem for the first time, the `configure/wrap/amake` interleaving occurs, eventually updating real targets.

The other build-process changes fall into several, related, categories.

7.1.1 | The Righteous Path

Names in a makefile have two facets. First, they are simply character strings that look like they *could* be paths to filesystem objects. They might contain slashes and dots, but they are just targets and dependencies, with no connection to files and directories (e.g., `all` and `clean`). Second, they might *also* be paths to filesystem objects, which have filesystem metadata (e.g., timestamps).

A name that is also a path is fragile. Mostly, GNU Make compares names as strings. However, a file has multiple paths, without even considering hard-link and symbolic-link trickery. For example, `foo`, `./foo`, and `/x/y/z/foo` are unequal names, but may be equal paths. Since Amake records target and dependency paths, by writing them to files (e.g., `.dep` files), it must decide which form to use.

When GNU Make and Amake compare names that are paths, *some* filesystem resolution is needed. GNU Make attempts superficial filesystem resolution, but it is easily discouraged. For example, if a target's dependency is `./prg`, GNU Make recognizes the target named `prg` (and vice versa). Curiously, `$(<` drops the leading `./` and, thereby, activates `$PATH` search. But if `dir` is a directory, and the dependency is `dir/./prg`, GNU Make doesn't realize that it's also `prg` (and vice versa).

Beyond GNU Make's half-hearted attempts at resolution, Amake tries harder. Its code, and that of `libaccess`, leaves paths as is. However, `wrap` converts absolute paths to relative paths (e.g., for GCC's `VPATH`). In contrast, `amake-collect` resolves paths fully, for equality, but preserves relativity. Relativity is critical for inter-workspace caching and GCC's staging directories. A "canonical" absolute path (e.g., according to `realpath`) is fine for one workspace, but others might be located at different *levels* (i.e., distances from `/`), whether on this workstation or another. Indeed, a workspace might even be remounted at a different level. Levels also matter because GCC's build writes the "same" target to multiple directories, at different levels. For example, `gengtype` is written to `../gcc/build` in stage 1, but to its parent directory in later stages, by different rules, by the same makefile. Amake's target cache must accommodate this.

Amake's code preserves absolute paths. Such paths might have been typed by a human, or generated by a program. Notably, GCC's makefiles also use absolute paths for `VPATH` and `vpath`. But to allow sharing between GCC workspaces, `wrap` performs absolute/relative path conversion.

7.1.2 | Thick and Thin

An absolute path embedded in a target file can also interfere with inter-workspace caching. GCC's build employs a crossbred feature of the `ar` librarian, producing a file with traits of both static and dynamically-linked libraries. A "thin archive" is built with a `-T` argument, and "contains a symbol index and references to the original copies of the member files of the archive." Amake has no trouble tracking its files-referenced dependencies, but embedded paths can be fragile, with respect to cache fetches. Also, while a static or shared library can be a top target, a thin archive cannot: it's worthless without its referenced files. An `ar` wrapper avoids these problems: `-T` is simply ignored. Further, `-D` is added, to "operate in deterministic mode" (e.g., no timestamps), allowing checksums to match. Even further, `-u` is replaced by `-c`, always creating a new archive, rather than updating it, to preserved member order.

7.1.3 | A Timeless Way of Building

The fundamental algorithm of GNU Make, as well as most Make variants, is to update a target if and only if one or more files upon which it depends is changed (i.e., written to). Since the beginning (circa 1979), makefile authors have needed/wanted to avoid this behavior. They have tried to write some makefile rules whose targets would always be up to date, and some whose targets would always be out of date.

GNU Autotools uses files and directories to record build state (e.g., `config.cache`). Some are always to be updated. For those, `wrap` sets Amake variables, which disable automatic-dependency and caching features, simply treating the files as GNU Make would. Some of these files are scripts, which are not thread safe. A makefile comment laments: "Serialization dependencies: Host configures don't work well in parallel to each other, due to contention over `config.cache`. Target configures and build configures are similar." By the way, Autotools should not hardcode file descriptors 5 and 6. Bash, at least, can allocate a free file descriptor, and assign its number to a variable (e.g., `exec {fd}<foo`).

Another ad-hoc build-avoidance trick is known as a "stamp," which records when an event occurred, to prevent target updates. A stamp is just a file, often empty, created to indirectly record time-of-last-modification metadata (e.g., with a simple `>$@`). The makefile in GCC's `gcc` subsystem contains a well-written 35-line comment, explaining the trick's evolution. Basically, "Make must be deceived into thinking `...`" that a file has changed if and only if its *content* has changed. Since Amake's checksum comparisons do just that, `wrap` transforms these numerous and complex stamp rules, into fewer and simpler rules.

7.2 | Amake Changes, for GCC

Building LLVM required just one small change to Amake, as described in Section 6.2. Building GCC required several significant changes to: target-cache entries, the checksum-cache daemon, and automatic makefile-variable values (e.g., `$-`).

7.2.1 | Target-Cache Content

Earlier build-with-Amake projects (e.g., for Bash and LLVM) failed to reveal an overly optimistic assumption: an entry's `cachedir` could simply hold the target itself, its siblings (if any), and its metadata. However, some GCC makefile rules write files to directories other than that in which the build was started; they can't just be stored in the `cachedir`. A rule that writes a file to a subdirectory poses no problem: it can be stored in a `cachedir` subdirectory. But, a rule that writes a file to a parent directory is trickier. Its path could be either relative (e.g., `../bin/foo`) or absolute (e.g., `/bin/foo`), and these two cases cannot be unified, by path conversion, because different workspaces might be located at different levels (i.e., distances from `/`). Nor can such a file just be stored in its `cachedir`, according to its path; it might end up outside of the `cachedir`. Removing a path prefix could

cause collisions, and would prevent determining destinations of future fetches. So, a cache entry's target and siblings are combined into a `tar` file, which is stored in the `cachedir`. Fetching an entry is just a `tar` extract operation. To avoid a spawning a process for each fetch, `tcld` links against a `tar` library,²⁶ which also offers compression.

Prior to the adoption of `tar` files as cache entries, an entry was simply a set of plain files and directories: whatever was being cached. This simplified cache debugging, analysis, and maintenance. With `tar` file entries, the familiar Unix toolbox of `find`, `grep`, `diff`, and others cannot be used directly. To address this, a cache-analysis tool was developed, as described in Appendix A.

Using `tar` solves the problem of a target's rule storing files in arbitrary directories, but only if the rule doesn't create the directory. At first, such a directory seemed like it should be treated as a sibling of that target. However, a different target's rule might also create that directory, for *its* files. If the directory was treated as a sibling of both such targets, it would be added to both of their `tar` files, along with all of its contained files. This is wrong. Those files must be partitioned between the targets' `tar` files. Otherwise, fetching either entry would extract siblings (and targets) of both targets. Subsequently, fetching the other entry would overwrite those same files. Parallel builds, started with the `-j` or `--jobs=` command-line option, exacerbate this interference. Indeed, if a directory could be a target, Amake would need to compute its checksum. A directory could be opened with `open` and its `O_DIRECTORY` flag, then the directory's raw bytes could be read and checksummed. However, two directories containing identical files and subdirectories could easily have different checksums, which would interfere with caching.

Therefore, a directory is never a sibling, nor a target, but its contained files can be either or both. Fetching those files might create the directory, in the workspace, as a side effect of extracting from the `tar` file. This supports the invariant from Section 2: A sibling belongs to exactly one target.

The foregoing analysis applies to "install" targets, in general, and GCC's staging targets, in particular. Their commands spray siblings all over a filesystem. Caching such a target doesn't make sense. Consider a blatant example, `install-leaf`, which is unconditionally updated after GCC's `libgcc` subsystem has built its targets:

```

1 all: all-multi
2     $(MAKE) install-leaf ...
3
4 install-leaf: ...
5     $(mkinstalldirs) ...
6     $(INSTALL_DATA) libgcc.a ...
7     chmod 644 ../libgcc.a
8     $(RANLIB) ../libgcc.a

```

The `libgcc` makefile says: "Now that we have built all the objects, we need to copy them back to the GCC directory. Too many things (other in-tree libraries, and DejaGNU) know about the layout of the build tree, for now." Therefore, caching is disabled for this target, with an Amake target-specific variable. Similarly, because directories containing them are renamed as a new stage begins, automatic-dependency detection on the previously built tools (e.g., `xgcc`) is disabled during the new stage, with another Amake variable.

Amake stores a target's command sequence in a `.cmd` file, typically in the same directory as the target. A target whose rule creates its destination directory originally surfaced as a problem because a `.cmd` file was originally computed and stored *before* executing the commands. Early command-sequence analysis makes sense, because commands need to be compared when deciding to update a target, but it is a chicken/egg problem. So, commands are now computed before, kept in memory during, and stored *after*, a target's update.

This directory analysis may seem esoteric and pedantic. However, the GCC build's reliance on Libtool forces our focus on these details. For example, while building the `libstdc++` subsystem, Libtool builds targets whose siblings are stored in a shared (between targets) `.libs` directory. This directory is created by the targets' commands, as needed. For example, a library of interfaces to the C and C++ front ends, named `libcc1`, which is linked into GDB,²⁷ is also part of the GCC distribution. Three of its deliverables are shared libraries (e.g., `libcc1.so`), but the makefile does not build them as targets. They are built as siblings of their respective "libtool library file" targets (e.g., `libcc1.la`). Each such target has a makefile rule with a command like:

```

1 ./libtool --tag CXX --mode=link ... -o ...la

```

It writes the target to the working directory, but the deliverable, the sibling, is stored in a subdirectory named `.libs`, which is created as needed by `libtool`, a generated 9300-line `sh` script. Considering `libcc1.la` as a single example, its cache entry is `libcc1.la.tar`, containing:

```

1 libcc1.la
2 libcc1.la.cmd
3 libcc1.la.dep
4 libcc1.la.sib
5 libcc1.la.top
6 .libs/libcc1.la -> ../libcc1.la
7 .libs/libcc1.la.cmd
8 .libs/libcc1.lai
9 .libs/libcc1.lai.cmd

```

```

10 | .libs/libcc1.so -> libcc1.so.0.0.0
11 | .libs/libcc1.so.cmd
12 | .libs/libcc1.so.0 -> libcc1.so.0.0.0
13 | .libs/libcc1.so.0.cmd
14 | .libs/libcc1.so.0.0.0
15 | .libs/libcc1.so.0.0.0.cmd

```

This content demonstrates important points. Files written by a target's commands can be to directories other than that in which the build was started. Siblings of other targets are not in this entry, thereby avoiding cache-fetch collisions. Absolute and relative symbolic links are supported, whether the destination exists or not. Amake metadata (e.g., a target's `.cmd` file) is stored too, so it can be fetched into the correct directory. A sibling also has a `.cmd` file, as discussed in 7.2.3.

Commands for a target can write files to directories other than the one in which a build was started, as discussed above, but a different problem occurs when commands *change* to a different directory before writing files. Suppose Amake is started in directory *A*, and a target `foo` is being updated. Referring to Figure 1, way back in Section 3, the `amake-collect` process for `foo` is, therefore, also executing in *A*. However, a command to update *A/foo* could be executing as a process in directory *B*. When that command calls a library function like `open`, the call is intercepted by the corresponding `libaccess` function, and the path is relative to *B*. That path is piped to the `amake-collect` process, executing in *A*, to be written to *A/foo.dep*. Indeed, a single `amake-collect` process might be receiving paths from multiple processes using `libaccess` in multiple directories. Later, when another Amake process is started in directory *A*, it reads the relative paths in *A/foo.dep*, but cannot access the files they refer to, because they are relative to directories other than *A*. To solve this problem, `libaccess` functions transform a relative path to an absolute path, before piping it to `amake-collect`. The directory parameter of the family of `*_at` functions, is also involved. Then, `amake-collect` transforms it to a relative path, before writing it to a `.dep` file. Similarly, when `amake-top` computes the transitive closure of dependencies, from multiple `.dep` files, from different directories, it also transforms relative paths appropriately.

Another possibility is that one of a target's commands might change to a different directory, before executing a program. This impacts the design of `.cmd` files. Recall that a target's `.cmd` file records the sequence of commands that created the target. The solution is to simply parenthesize each command in the sequence, causing it to be executed within a subshell. Now, a target's command-sequence checksum is computed after adding: a prologue of environment-variable `export/unset` commands, aforementioned parentheses, and aesthetic indentation. In addition, an initial `set -e` allows manual execution, without placing `&&` between parenthesized commands, effecting a makefile rule's stop-on-error behavior.

Finally, because a build's targets (and metadata) might be stored in multiple directories, locating and reading their `.dep` files, at the start of a subsequent build (i.e., via GNU Make's `include` directive), can be challenging. Those `.dep` files can be anywhere in a workspace, and they must be included selectively. A makefile cannot just `include` all of the `.dep` files in a workspace. A solution is to accumulate the set of directories in which targets are stored, during builds, and store the set in a file, specified by a makefile variable. A subsequent build, using the same makefile, reads the set of directories from that file, and then reads the `.dep` files in those directories.

7.2.2 | Checksum-Cache Daemon

As seen in Section 3, file checksums are computed locally, never over a network. Checksums might be *compared* remotely, but they are merely 40-byte ASCII strings. Nevertheless, local checksumming takes time, and is a perfect candidate for caching. Perhaps surprisingly, building GCC forced design-level changes to `ccd`, Amake's checksum-cache daemon. Originally, a file's checksum-cache entry was invalidated only when the operating system's `Inotify`¹⁹ facility reported a change to the file. `Inotify` makes sense for source files, which change infrequently, but derived files must also be checksummed, and changes must be noticed immediately. So, Amake operations that create files now perform checksum-cache entry invalidation. This approach still ignores latency for source-file changes, but a developer who changes a source file, during a build, deserves the consequences.

A distinctive feature of the GCC distribution is that it builds *itself*, in stages. First, a native compiler builds GCC, then GCC builds GCC, and then another self-build ends with object-file comparison (as a sort of test). Each stage is stored in a set of carefully named, and renamed, subdirectories. These names allow each stage to treat itself as the final deliverable. Unfortunately, all this renaming wreaked havoc on the cache-checksum daemon, rendering per-entry checksum-cache invalidation insufficient. Each new stage needs a complete checksum-cache invalidation. The solution is for `wrap` to request its local `ccd` to clear the *entire* cache between stages.

7.2.3 | Nested Builds

Section 2 warned of confusion, when a target's rule executes `$(MAKE)`, on either the same makefile or a different one, in either the same directory or a different one. Such a build, a nested or hierarchical build, is often called a "recursive" build, due in part to a paper criticizing the practice.²⁸ Yet, they are common, and often very modular. The name suggests a misunderstanding of the concept: they seem no more recursive than a process calling `fork`. Consider the makefiles in Figure 14. They are not equivalent, but similar enough to allow refinement of terminology. A similar chunk of GCC makefile is in Figure 15. In Figure 14 (upper), `bar` is a dependency of `foo`, and `zap` is a sibling of `bar`. In Figure 14 (lower), `bar` and `zap` are

```

1 foo: bar
2     cp bar $@
3 bar:
4     >zap
5     >$@

```

```

1 foo:
2     $(MAKE) bar
3     cp bar $@
4 bar:
5     >zap
6     >$@

```

Figure 14 Non-Nested and Nested Makefiles

```

1 stmp-fixinc: gyslimits.h ...
2     ...
3     cd ../prev-gcc && \
4         $(MAKE) ... DESTDIR=../gcc ...
5     ...
6     $(STAMP) stmp-fixinc

```

Figure 15 A GCC Nested Makefile

siblings of `foo`, and `zap` is also a sibling of `bar`. The split affinity of `zap` does not violate our invariant that “a sibling must have exactly one target,” because it occurs only across separate, albeit nested, builds. Each target has a `.cmd` file, a Bash script that records how it was built, and how to rebuild it. A developer might also want to rebuild a sibling. A sibling’s `.cmd` file simply executes its target’s `.cmd` file, thereby rebuilding the sibling as a side effect. For Figure 14 (lower), `zap.cmd` executes either `foo.cmd` or `bar.cmd`, depending on which target built the sibling last. In a nested build, this means the outer build, an application of the Principle of Least Surprise. Figure 15 is like Figure 14 (lower): `stmp-fixinc` is a real file, a stamp. The rule’s commands copy a slew of header files, from the previous stage back into the current stage. They are all siblings of the stamp. So, when the stamp is fetched from cache, the header files are fetched, too. This must be, since a fetch (by definition), does not execute commands, and thus does not perform the nested build. Fortunately, such rules are rare. To that makefile author’s credit, “Yuck” is in a nearby comment, which also hints at struggling with such rules, while using Ccache, a compiler-cache tool.²⁹

7.2.4 | `$(<`, `$(?)`, `$(^)`, `$(+)`, and `$(!)`

Mixing automatic-dependency analysis and automatic variables presents challenges, as was discovered almost immediately after Amake’s debut. At first, simple makefile workarounds sufficed, but GCC’s build needed a wholesome solution, which, in turn, entailed non-trivial design changes. All of the automatic variables are impacted, but in the same way. Consider `$(^)` (“dollar caret”), a target’s dependencies, without duplicates, often used to link object files into an executable file. For example:

```

1 foo: $(objs)
2     gcc -o $@ ... $^

```

Detected dependencies, written to `foo.dep`, and soon read via `include` by a makefile, cause two problems: Since `foo` depends on `gcc`, as a programs-executed dependency, `gcc` tries to link itself into the target. And, since `foo` also depends on various library and object files (e.g., `libc.so` and `crt.o`), as files-accessed dependencies, Amake tries to update them, using builtin rules. Regardless of which happens, the build fails spectacularly. The forementioned workaround simply replaces `$(^)` with `$(objs)`. While the order of dependencies in `$(^)` can affect linking, `$(<`, the “first” dependency, is even more sensitive to dependency order. That’s why, originally, an `include *.dep` had to be at the end of a makefile.

The obvious solution is to omit detected dependencies from `$(^)` and company. This must be done on a per-target basis, because a detected dependency for one target might be explicit for another. Since a detected dependency produces an ordinary makefile rule, albeit without commands, distinguishing detected and explicit dependencies requires more information. The solution is provenance. When reading makefiles, GNU Make saves a rule’s location as its target’s `fileloc`. Amake now does the same for dependencies. Now, `$(^)` for `foo` contains `bar` when the `fileloc` of

`bar` is other than `foo.dep`. Often, a file is explicitly listed *and* implicitly detected, resulting in a duplicate dependency. For example, an object file is explicitly listed, to link it into an executable file, then detected when linked, resulting in a `.dep` rule. Amake uses provenance to omit the detected one from `$^`.

A target's `$^` is also very important because it helps determine the command sequence to execute, to update the target. This has four facets. First, the commands help decide if a workspace file is already acceptable. Second, they help decide if a cache entry is acceptable. Third, they specify how to build an acceptable file. The fourth facet is a refinement of the third: automatically detected dependencies can select the rule, among implicit alternatives, thereby determining `$^` and thus the command sequence. This is surprising, since a target can have only one explicit rule with commands. And, as GNU Make's manual says, "explicit prerequisites do not influence implicit rule search." However, implicit prerequisites *can* influence implicit rule search. For example, in the fragment below, an initially absent `tgt.bar` causes the second rule to be selected, creating `tgt.bar`, but a subsequent build selects the first rule, because both dependencies exist.

```

1  %: %.foo %.bar
2      >$@
3
4  %: %.foo
5      test -f $*.bar
6      >$@
7
8  tgt:
9
10 tgt.foo:
11     >tgt.bar
12     >$@

```

GNU Make's `VPATH` features can also interact with automatically detected dependencies to determine rule selection, `$^`, and thus the commands. For example, in the fragment below, a present `foo/tgt.zap` and initially absent `bar/tgt.zap` causes the second rule to be selected, creating `bar/tgt.zap`. A subsequent build selects the first rule, because both dependencies exist (as the same file).

```

1  VPATH=bar:foo
2
3  %: %.zap bar/%.zap
4      >$@
5
6  %: %.zap foo/%.zap
7      >bar/$*.zap
8      >$@
9
10 tgt:

```

Another subtlety is the possible effect of automatically detected dependencies on parallel builds. A makefile may contain a carefully (or coincidentally) crafted set of explicit dependencies, resulting in an acceptable degree of concurrency, and an acceptable sequence of concurrent compilations. For example, one "tool" might need to be built before it can be used to build another tool. This happens in GCC's `gcc/build` subsystem, with its `GTFILES` family of makefile variables. A makefile comment and rule makes this clear: "In order for parallel Make to really start compiling the expensive objects from `$(OBJ)`s as early as possible, build all their prerequisites strictly before all objects."

```

1  $(ALL_HOST_OBJS):| $(generated_files)

```

An automatically detected dependency can also cause a target to be updated later than otherwise. This can cause its commands to execute concurrently with, and interfere with, another target's commands, especially when temporary-file names are poorly constructed, allowing collisions. The solution is to choose better names.

Evidently, GNU Make's maintainers have also thought about partitioning dependencies. Version 4.3, has a `.EXTRA_PREREQS` variable:

Words in this variable are considered prerequisites of targets but they are not added to any of the automatic variable values when expanding the recipe. This variable can either be global (applies to all targets) or a target-specific variable.

At first, this new variable, as well as variable inheritance, was seen as a potential way to help Amake partition dependencies. However, employing one or the other would render the feature unavailable to a user. As stated above, dependency provenance, the file containing a dependency's definition, provides a general solution.

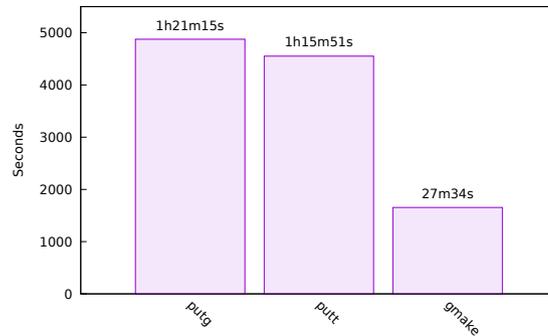


Figure 16 GCC No/Empty Cache Builds

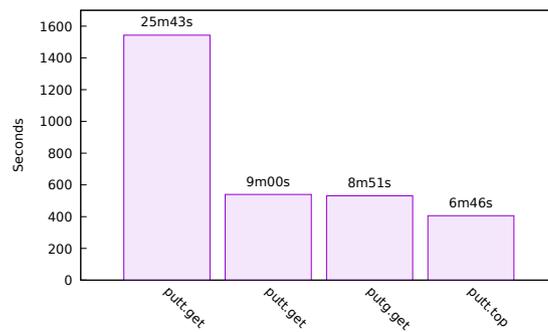


Figure 17 GCC Cache Builds

7.3 | GCC-Build Times

As with LLVM, only a few comparisons are drawn here.

First, consider Figure 16. In an empty build directory, a GNU Make build requires 0:27:34. Likewise, and with an empty target cache, Amake get and top builds require 1:21:15 and 1:15:51 (resp.), 295% and 275% more than GNU Make. The overhead is mainly for filling the cache, an investment for later. The cache doesn't help at first, but it fills as the build progresses. Later stages fetch top-build entries, making the top build faster than the get build. Indeed, whereas the get build fetches 2299 targets, the top build fetches only 924 targets. This speedup occurs despite the top build computing transitive closures, and writing them to files.

Next, consider Figure 17. A more satisfying, and common, scenario starts in an empty build directory, as before, but with a cache of acceptable candidates. A get build takes 0:08:51 to fetch all 7959 targets. The top build takes 0:06:46 to fetch the 1301 top targets. Thus, Amake's cached workspace-filling build takes only 33% of the time required by a "from scratch" GNU Make build. If only top targets are needed (e.g., for testing), this drops to 25% of that required by GNU Make. The leftmost two builds also fetch all 7959 targets. The leftmost one is much slower because the only prior cache-filling build was a top build: 1381 targets were not added to the cache; the leftmost one adds them. Rerunning the build in an empty workspace produces the second from the left.

The most common scenario, depicted in Figure 18, approximates a developer changing one source file. It starts with an up-to-date workspace and a cache of acceptable candidates (with Amake). GNU Make, with its simple dependency checking, takes just 0:00:09. Amake get builds take 0:01:26 – 0:01:19, while top builds take 0:00:39 – 0:00:26, depending upon how the cache was filled. For times below 90 seconds, percentages make less sense than absolute differences: A developer waiting to test a build probably wouldn't mind an extra 30 seconds.

8 | CONCLUSION AND FUTURE WORK

We've seen that Amake can build large-scale software systems efficiently, with only minor build-process modifications.

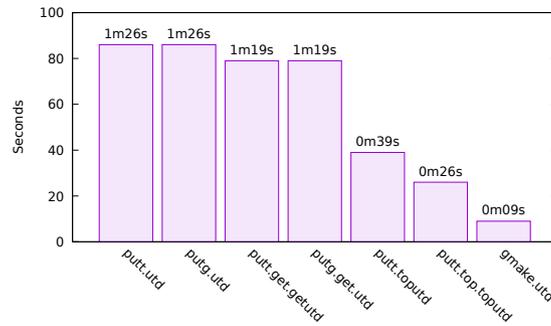


Figure 18 GCC UTD Builds

An underlying performance assumption of the organization shown in Figure 1 is that there are benefits to copying a target from a remote cache, compared to rebuilding the target locally. This benefit would be magnified with a local cache (somehow still shared). Since the cache is essentially a database, distributed-database technology should be investigated.

Expecting performance benefits from a distributed database seems reasonable, due to both spatial and temporal locality. If a target is built in a workspace on a particular host once, it seems likely that it will also be needed in other workspaces on the same host. This would happen, for example, on an “integrate and test” machine, where branches are incrementally merged, previously uncached targets are built (then, subsequently fetched), and “smoke tested” prior to baselining. A developer merging changes between multiple “task” branches, sprouted from the same baseline, might see similar benefits from a local cache. Recall that the target cache has two parts: an index and its entries. The index is treated as a key/value database, even with an underlying SQL implementation. So, a distributed key/value database (e.g., Cassandra³⁰, CockroachDB³¹, or CrateDB³²) should be investigated. The entries compose a directory-oriented filesystem. So, a distributed filesystem, (e.g., Andrew File System¹⁸ or Coda File System³³) should be investigated.



APPENDIX

A CACHE TOOL

Amake’s target cache now stores entries in `tar`²⁶ files, rather than as plain Unix directories, files, and symbolic links. This hampers cache browsing, debugging, and maintenance, for both developers and users of Amake. They can’t directly use their typical Unix toolbox of: `find`, `grep`, `diff`, and others. A cache-analysis tool, named `ct`, is available to help with such forensics, circumventing the stickiness of `tar`. It’s one of those programs with (abbreviatable) subcommands, rather than traditional command-line options:

```

1 f|find <entry>
2 ct|chksumtgt <entry>
3 cd|chksumdep <entry>
4 cc|chksumcmd <entry>
5 ok|depok <entry>
6 da|diffall <entry>
7 d2|difftwo <dir1> <dir2>

```

Most of the subcommands take an entry filename, without slashes, as an argument (e.g., `f.o.o`). They print the absolute paths to each cache-entry `cachedir` for that entry, sorted by creation date, as mounted on the local workstation. The `find` subcommand might be used to prune old or “bad” entries. A bad entry could result from a build command that violates exit-code protocols. The `chksumtgt` subcommand also prints the file-content checksum for the target file in each of those `cachedirs`. This can help in understanding a cache miss. Two entries for the same target can have the same checksum if, for example, they depend on superficially different versions of the same source file. The `chksumdep` subcommand also prints the checksum for the target’s `.dep` file, in each of those `cachedirs`. This can help in understanding, for example, the scenario from the previous paragraph. The `chksumcmd` subcommand also prints the checksum of the commands that built the target, in each of those `cachedirs`. This can also help with the above scenario. The `depok` subcommand is like `chksumdep`, but actually compares checksums. For each of the entry’s `cachedirs`,

for each dependency in the target's `.dep` file, the dependency's checksum is compared to the checksum of the corresponding workspace file (if it exists). This checks whether a cache entry is acceptable, with respect to files, programs, and libraries in the current workspace. The `diffall` subcommand pairwise compares all of the entries for a given filename, printing those that are identical. Duplicate entries indicate a problem. The `difftwo` subcommand takes two `cachedirs` as arguments, printing, in `diff` format, differences. This can help in understanding why different workspaces build differently. It forms the body of the `diffall` loop.

B DEVELOPMENT ENVIRONMENT

The builds described and timed, in Sections 6 and 7, were performed on two identical Supermicro X8DTH-iF computers. Each has two 2.8GHz Intel 5660 CPUs (6 cores per CPU, 2 hyperthreads per core, 32KB L1 cache, 256KB L2 cache, 12MB shared L3 cache), 24GB RAM, a single 3.0Gb/s disk drive, and Gigabit Ethernet LAN. One of the computers served as the “shared infrastructure” of Figure 1. The other played the role of a “workspace host” capable of parallel builds. This isn't exactly cutting-edge hardware, but caching makes the most sense in an environment with slow processors, and fast communication and disks.

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