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The Vesta Approach to Software Configuration Management

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Abstract

Vesta is a system for software configuration management. It stores collections of source files, keeps track of which versions of which files go together, and automates the process of building a complete software artifact from its component pieces. Vesta's novel approach gives it three important properties. First, every build is *repeatable*, because its component sources and build tools are stored immutably and immortally, and its configuration description completely specifies what components and tools are used and how they are put together. Second, every build is *incremental*, because results of previous builds are cached and reused. Third, every build is *consistent*, because all build dependencies are automatically captured and recorded, so that a cached result from a previous build is reused only when doing so is certain to be correct. In addition, Vesta's flexible language for writing configuration descriptions makes it easy to describe large software configurations in a modular fashion and to create variant configurations by customizing build parameters. This paper gives a brief overview of Vesta, outlining Vesta's advantages over traditional tools, how those benefits are achieved, and the system's overall performance.

1 Introduction

This paper describes Vesta, a software configuration management (SCM) system for managing and building software, designed to extend from small systems to very large ones (tens of millions of lines of source code).[1] Vesta addresses the following four core SCM problems:

Version management. Version management is the process of assigning names (typically sequential numbers) to a series of related source files and supporting retrieval of those files by name.

Source control. Source control is the process of controlling or regulating the production of new versions of source files. Operations commonly associated with source control include *checkout* and *checkin*, which respectively reserve a new version and supply the data for a previously reserved version. Source control may be coupled with concurrency control as well, so that checking out a particular version limits the ability of other users to check out related versions.

System modeling. A system model is both a static description of a system's configuration and a recipe for producing a software artifact. It names the (versions of) software components that are to be combined to produce larger components or entire systems, names the tools that are to be used to combine them, and specifies how the tools are to be applied. System models are also sometimes called *configuration descriptions*.

Building. Building is the process of evaluating a system model so as to construct a complete system according to the model's instructions. It may also include other activities, such as running regression tests on the resulting artifact.

Version management, source control, system modeling, and building are four parts of the larger SCM problem. Considered broadly, SCM is often taken to include such areas as process management, software life-cycle management (e.g., bug tracking, testing), and even the specific tools used to develop and evolve software components. We hold the view that these aspects of SCM, although important to the overall software development process, are secondary to the core issues listed above. We have therefore focused the Vesta project on solving those core problems, constructing a solid base upon which we believe solutions to the other problems can be built.

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[1] Throughout this paper we use the name "Vesta" to refer to Vesta-2, the second complete SCM system based on the Vesta approach. Vesta-1 was implemented in the early 1990's and saw extensive use within our research center [2, 3, 8, 14]. Vesta-2 is a complete redesign and reimplementation based on our experience with Vesta-1, retaining the same fundamental approach but correcting the deficiencies of the earlier system.

Some form of SCM is almost always a necessary part of software development. SCM is useful whenever multiple source files, multiple developers, or multiple releases and/or target platforms are involved. Moreover, the larger the number of source files, developers, or releases, the larger the configuration management problem.

A good SCM system can greatly reduce these problems. Version management can ease the problem of managing multiple source files by keeping related versions of files together. Source control can help multiple developers work productively in parallel. Together, system modeling and building can help manage multiple releases by accurately selecting the right sources to use for each release and by automatically managing the machine-generated files created during a build (*derived* files), so that users need only concern themselves with source files.

Several difficulties stand in the way of designing and implementing an SCM system that addresses these problems. First, handling large-scale software is difficult, because it usually involves large numbers of source files and developers. The rapid growth of today's software makes this an even more pressing problem. Unlike most other SCM systems in use today, Vesta was specifically designed to work with very large projects—millions of lines of code and beyond. Second, with larger numbers of developers comes the need to support parallel development across sites that are often geographically separated, which introduces the problem of keeping replicated copies consistent. Finally, for building to be efficient, it must work incrementally, re-using the results of previous builds whenever possible. However, when multiple versions, multiple target platforms, and multiple releases are involved, sound incremental building is a non-trivial problem.

The rest of the paper is organized as follows. We first consider the strengths and weaknesses of several widely-used SCM systems. Section 3 then describes the Vesta approach, focusing on the main ideas in the Vesta system and the benefits they provide. In Section 4, we describe how those ideas are realized in practice, with an emphasis on the user's view of the system. We describe the performance of our implementation in Section 5. Finally, Section 6 lists some additional technical issues that could not be presented fully in this brief paper, summarizes our experience in using the system, and offers our conclusions.

2 Previous Approaches

In this section, we review related work by assessing several popular SCM systems. Some systems, like the Revision Control System (RCS) and the Concurrent Version System (CVS) address only version management and source control, while others like Make address only system modeling and building. RCS, CVS, and Make are rather old, of course, but they remain useful points of comparison for Vesta for two reasons: they are still widely used, and many newer systems approach the core SCM problems in essentially the same way that they do. We also consider ClearCASE, which takes a more ambitious, integrated approach to solving the core SCM problems.

2.1 RCS and CVS

RCS is a system for maintaining multiple versions of individual files [16, 17]. Its main strengths are that it is easy to use, well-understood, and well-documented. Its main disadvantages are two. First, it does not provide transparent access to individual file versions. That is, an explicit checkout step is required to access an older version of a file. Hence, to build an older version of a system, the developer must first explicitly check out the correct versions of each source file required by the build. Second, sources are versioned at the granularity of individual files. Although RCS provides tagging facilities for grouping related files, those facilities are awkward to use.

Like RCS, CVS is relatively easy to use and well-supported [6]. It also suffers RCS's problem of not allowing transparent access to file versions. However, unlike RCS, CVS allows related files to be grouped together into *modules*. CVS also includes an optimistic concurrency control methodology that allows multiple developers to work on the same file *concurrently*. However, allowing concurrent modifications is not without its costs, since conflicting edits must be detected and resolved. CVS's conflict detection is simple-minded (i.e., purely line-based), so semantic conflicts between changes in disjoint lines may go undetected. When conflicts occur, they must be resolved manually, which can be a time-consuming process.

2.2 Make

Make is a widely-used tool for building software [4]. It is easy to use and the syntax of its system models (i.e., Makefiles) is simple, if somewhat cryptic. Moreover, Make can also be used for tasks other than building software, such as running regression tests. Many extended versions of Make have been developed over the years, but few have addressed the shortcomings we discuss in this section.

There are several major problems with the Make approach to software construction. In this approach, dependencies between derived files and the inputs used to produce them must be specified explicitly by the user, and Make relies on timestamps to decide when it is safe to reuse a derived file in a subsequent build. A build based on incorrect dependency information or incorrect timestamps can produce an *inconsistent* result, in which parts of the resulting system incorrectly include stale derived files. Inconsistent builds can produce programs that fail to link or run, or that exhibit bizarre, unexplainable bugs. Developers often must resort to performing a scratch build to correct such problems.

Inconsistent builds are not uncommon in Make. Specifying dependencies explicitly is an inherently error-prone task. There are tools such as *makedepend* for generating certain kinds of dependencies automatically, but again, such tools must be run by hand, so they may not be run as often as necessary. Another problem is that some dependencies are inexpressible or too costly to express. For example, dependencies on the values of environment variables cannot be expressed in Make, and dependencies on the Makefile itself are too costly because they would result in a scratch build whenever the Makefile was changed. Make's use of timestamps is also problematic. For example, when building a system from older sources, Make may incorrectly conclude that the system is up-to-date because the timestamps associated with the older file versions are in the past; again, a scratch build is often the developer's only recourse in such situations.

Finally, Make scales poorly. Make does its dependency analysis from the leaves of the build tree, working its way up to the final result. Hence, the cost of an incremental build in Make is proportional to the total number of sources contributing to the build, not the number of sources that have changed. Moreover, although it is possible to structure a software system hierarchically by arranging for Make to invoke itself recursively on sub-components, doing so is awkward and performs poorly.

Bell Laboratories' Nmake [5] addresses most of these problems with Make, as well as others, though it does not fully solve them. Nmake includes a built-in static dependency generator that does its own parsing of source files (looking, for example, for `#include` statements in C code); this greatly reduces the likelihood of omitted dependencies, but the dependencies generated can be overly conservative, increasing the amount of rebuilding work needed, and new parsing support has to be written whenever Nmake is used on code written in a new language. Nmake includes an improved timestamp checking algorithm that fails only when an erroneous system clock gives two different versions of a file the same timestamp, and it caches timestamps and other state to speed up its dependency analysis somewhat.

2.3 ClearCASE

Perhaps the biggest problem with the systems discussed so far is that they are not integrated. Building a particular version of a system requires two steps: checking out the correct versions of the sources, and then building them. As described previously, the first build of an older version must be performed from scratch, since

Make does not have any knowledge about which versions it is building, so it cannot tell when it is safe to reuse a derived file from a different build.

ClearCASE is a commercial SCM system that integrates version management with building, and that addresses many of Make's shortcomings [1]. It is based on many of the ideas in the earlier DOMAIN Software Engineering Environment (DSEE) system [12, 13].

ClearCASE provides access to file versions primarily through its *view* mechanism. A view is a set of rules that transparently map unversioned file names to versioned names. The rules governing a view can be specified in a variety of ways. They include provisions for always accessing the latest version of a file, the latest version along a specified branch of development, the version current as of a specified time, and others.

For building, ClearCASE provides its own version of Make called *clearmake*. Thus developers do not have to learn a new system modeling language, and their existing Makefiles continue to work. Unlike Make, clearmake does automatic (although somewhat incomplete) dependency detection by monitoring and recording the files accessed during a build. It also manages derived files for potential later reuse.

There are several problems with ClearCASE. The problem with the view approach to version management and building is that the meaning of a name can change over time. In particular, the actions taken by *someone else* can cause one's own build to suddenly fail; for example, when your view is configured to use the latest version of a file, someone else may check in a new version with changes that are incompatible with your work. This shortcoming is an impediment to effective parallel development. There are also problems with the clearmake builder. First, because clearmake is Make-based, it suffers from the same scalability problems as Make. Second, because its dependency detection is incomplete, clearmake can produce inconsistent builds. Third, clearmake's mechanism for allowing developers to reuse the derived files produced by others—called *winking in*—is based on heuristics that can fail to capitalize on valid reuse opportunities. Finally, anecdotal evidence suggests that the overheads introduced by clearmake are large, so some development organizations choose to use ordinary Make for improved performance, despite Make's shortcomings.

3 The Vesta Approach

As described earlier, Vesta's goals are to address the core SCM problems of version management, source control, system modeling, and building. It is meant to provide a firm technical base on which solutions to the other SCM problems can be built. Vesta is also explicitly designed to scale up to large code bases, which means it must effectively support parallel development. Of course, it must be an open system that works with standard development tools. Finally, it must perform well and be easy to use.

The Vesta approach is based on the following foundations:

- Immutable, immortal, versioned storage of all sources and tools. Unlike ClearCASE, Vesta uses explicit version numbers rather than views.

- Complete, source-based configuration descriptions. By *complete*, we mean that the descriptions name *all* elements contributing to a build. Every aspect of the computing environment, including tools, libraries, header files, and environment variables, is fully described and controlled by Vesta.[2] By *source-based*, we mean that configuration descriptions specify how to build a system from scratch using only immutable sources (i.e., non-derived files). The descriptions themselves are versioned and immutable sources, and their meaning is constant; a particular top-level description always describes precisely the same build using the same sources, even after new versions of sources and descriptions have been created.

- Automatic derived file management. The storage and naming of derived files is managed automatically by the Vesta storage repository, thereby easing the burden of building multiple releases or building for multiple target platforms.

- Site-wide caching of all build work. Vesta features a shared site-wide cache of build results so developers can benefit from each others' builds.

- Automatic dependency detection. The Vesta builder dynamically detects and records all dependencies, so none can be omitted by human error. By *dynamically*, we mean that the builder detects which sources are actually used in the process of constructing a build result and records dependencies only on them. Vesta's dependency analysis does not make use of any knowledge of how the build tools work; it is thus *semantics-independent* in the terminology of Gunter [7]. For example, if a compiler reads file foo.h in the process of compiling file foo.c, Vesta will assume that the compiler's output depends on all of foo.h, even though a tool with knowledge of C might be able to find individual items in foo.h that could be changed without changing the result of the compilation.

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[2] Ultimately, of course, every build is also dependent on the operating system platform on which it is performed, and it is possible in principle to write tools that depend on features of the operating system that we do not encapsulate. However, we have not encountered any such dependencies in the standard construction tools we have used.

At this point, the reader may well be wondering what it is like to use Vesta in practice. How can any sources be edited if all sources are stored immutably? If system models must name the version of every source file, isn't the overhead of maintaining those references overwhelming? We address these questions and other practical aspects of using Vesta in Section 4 below.

We first point out that these foundations provide several valuable benefits:

Repeatable builds. The immutability and immortality of sources combined with the completeness of build descriptions together mean that every Vesta build is *repeatable*. That is, any build performed in the past can be exactly reproduced at any time in the future.

Incremental builds. Although the system models describe how to build a software system from scratch, the Vesta builder uses the site-wide cache of previous builds to avoid redoing work, so good incremental build performance is the norm. The time required to perform an incremental build is generally proportional to the amount of new work to be done, not to the size of the system being built.

Consistent builds. Because every build is conceptually performed from scratch, and because Vesta's automatic dependency detection means that a cached result is used only when it is correct to do so, all Vesta builds are guaranteed to produce consistent results. Hence, there is never any need to do scratch builds to correct for an errant build in which a stale derived file was used.

Parallel development. Several features of the Vesta system enable parallel development. For one, the Vesta repository supports concurrency control, version branching, and partial replication across geographically distributed sites. But perhaps more important is the fact that a user must take explicit action to build with a newer version of someone else's code. Hence, it is impossible for one developer's action to break another's build. This feature makes developers more productive by allowing them to work independently.

The entire Vesta system was designed and implemented with an eye toward scalability. Our design goal was to support systems containing 20 million lines of code or more. This emphasis is visible in several respects. To organize the construction of large-scale software, system models can be arranged as a modular hierarchy. During a build, caching is done top-down rather than bottom up. Hence, cache hits often occur on larger units of work than individual tool invocations, such as the construction of an entire library or collection of libraries. This top-down caching avoids the scalability problem of incremental builds suffered by Make. Finally, because the repository itself implements the file systems containing both checked-in and checked-out files, it is able to make checkout and checkin almost instantaneous, thereby eliminating one of the burdens of working with large source trees.

4 A User's View of Vesta

The discussion so far has been fairly abstract. In this section, we provide a user's view of Vesta to make the ideas more concrete. We start by describing Vesta's components. We then consider Vesta's source control tools and their effects on the repository. Finally, we present some sample system models to give a sense for Vesta's system modeling language.

4.1 Vesta Components

Figure 1 shows the main components of the Vesta system.

The bottom half of the figure shows the *repository* and *function cache* servers. One instance of each server is run at each site. The repository server manages the storage of both sources and derived files. It provides both a standard NFS interface to sources and a remote procedure call (RPC) interface that is used by other Vesta tools. The function cache server stores the results of previous builds. Both servers use a normal file system for backing storage.

The top half of Figure 1 shows the Vesta components that run on each client host. The main client programs are the *repository tools* and the *evaluator*. The repository tools provide checkout, checkin, and other source control operations. The evaluator is the Vesta builder. It reads user-written *system models* and a set of system-supplied models comprising the *standard construction environment*. Not shown in the figure are standard development tools such as text editors and the like, which can be used to access sources via the repository's NFS interface in the usual way.

During a build, the evaluator will often be called on to run an external tool like a compiler or linker. To do so, the evaluator makes a remote procedure call to a *runtool server* process. As indicated by the dashed vertical line in the figure, the runtool server may or may not be running on the same client host as the evaluator. Decoupling the runtool server from the evaluator allows for tools to be invoked on different machine platforms (e.g, for cross development), for multiple clients to share one runtool server running on a powerful machine, or for one client to use multiple runtool servers in parallel.

Before it contacts the runtool server to launch a tool, the evaluator calls the repository to create a special directory tree in which the tool will be run. The runtool server then launches the tool in an encapsulated environment that causes

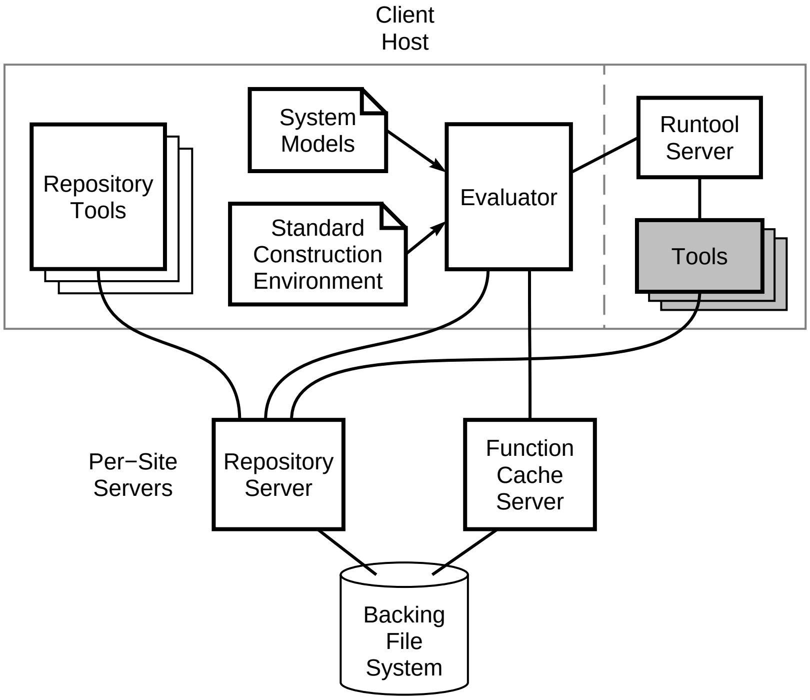

Figure 1: Vesta's main components.

all of the tool's file references to go to this tree, where they are trapped and reported back to the evaluator. The evaluator records these references as the dependencies for the tool invocation.

During the build, the evaluator also contacts the function cache server to determine if each piece of the build it is about to execute has been performed before (by any user). If so (a *cache hit*), the function cache returns the corresponding result. If not (a *cache miss*), the evaluator performs the work and then calls the cache to create a new cache entry for possible reuse in the future.

Figure 1 omits several administrative tools. Among these is a tool called the *weeder* that is used to delete unwanted derived files from the repository and unwanted cache entries from the function cache. The weeder reads a description file that says which build versions should be kept; it then uses a concurrent mark-and-sweep garbage collection algorithm to identify all derived files and cache entries that are safe to delete. The description file uses a simple but powerful pattern language; such rules as "keep builds of the last two versions" are easily expressed.

Parameterizing the weeder with an explicit instruction file gives each organization the flexibility to keep the builds it considers important. Deciding what to weed is a time-space tradeoff. Even if a useful build is inadvertently left out of the weeder instructions and deleted, Vesta's repeatability guarantees that it can be reproduced, albeit more slowly, and re-cached.

4.2 Repository Operations

The Vesta repository is a general-purpose file system with special support for immutability. It provides three types of directories, each with distinct mutability rules: *mutable*, *immutable*, and *appendable*. We will briefly explain the semantics and purpose of each type in the course of this section.

Unlike most file system implementations, the repository does not directly manage a disk. Instead, it maintains its own tree of directories, but stores the files that they point to in an underlying conventional file system. This implementation detail is not generally visible to users. The repository also maintains the site-wide pool of cached derived files, storing them in the same underlying file system.

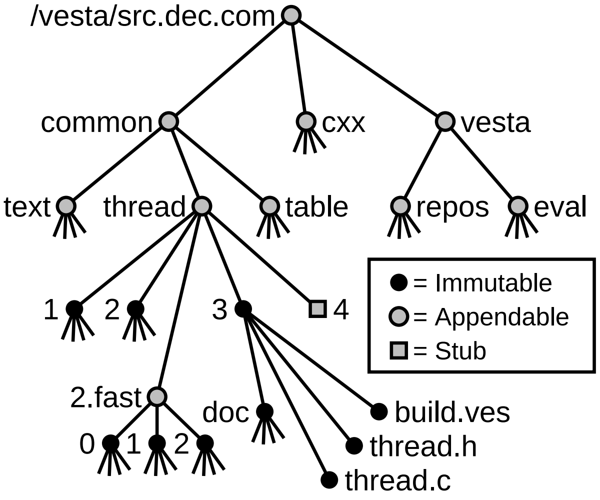

Figure 2: Naming convention assumed by the Vesta repository tools.

Figure 2 illustrates the naming convention we use for source code kept in the repository. This naming convention is imposed not by the repository server itself, but by the much smaller client-side repository tools. Thus a different source control paradigm could be implemented simply by modifying the repository tools; changes to the repository proper would not be required.

- Related sources are grouped into arbitrary directory trees called *packages*. Versioning and checkout are done at the package granularity, not on individual files. As shown in version 3 of the `common/thread` package, each package version may contain arbitrary files and nested directories.

- To support large-scale software, the package namespace is hierarchical. For example, the packages of Figure 2 are arranged in a two-level hierarchy, with package names like `common/thread` and `vesta/repos`.

- Version numbers appear as explicit pathname arcs. For example, version 3 of the `common/thread` package is named `common/thread/3`.

- The root directory of each package version is immutable. Hence, the contents of a package version cannot be changed. The directories that form the package hierarchy, such as `common` and `common/thread`, are appendable. The only operation allowed on such directories is the insertion of new items, such as new packages or package versions.

- Checkout uses pessimistic concurrency control (locking).[3] By default, checking out a package reserves the next unused version number, for use by the new version that is to be checked in later. For example, in Figure 2, a user has checked out the `common/thread` package and version 4 has been reserved for his use. If a second user tries to check out the same package, the checkout tool will report a conflict, and the user can either negotiate with the first user to check in his changes before proceeding, choose to do an unlocked scratch checkout that cannot be directly checked back in, or create a *branch* in the version sequence and check out the branch.

- Branches are exactly like new, independent packages, except that a branch is named as a subdirectory of its parent package, and its initial version (0) is identical to the version of the parent package from which it branched. In Figure 2, the branch `common/thread/2.fast` has three versions named `0`, `1`, and `2`, the first of which is an exact copy of `common/thread/2`.

As shown in Figure 3, the repository exports two NFS file systems, which are made visible to the client through two mount points, typically named `/vesta` and `/vesta-work`. The directory tree rooted at `/vesta` consists only of appendable and immutable directories, while the one rooted at `/vesta-work` is an ordinary mutable directory, in which arbitrary additions, deletions, and changes are permitted. There is a mutable directory in `/vesta-work` for each user, and edits are performed in subtrees of those directories.

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[3] However, an optimistic, CVS-like scheme where conflicts are detected only at checkin time could be implemented with only minor changes to the repository tools.

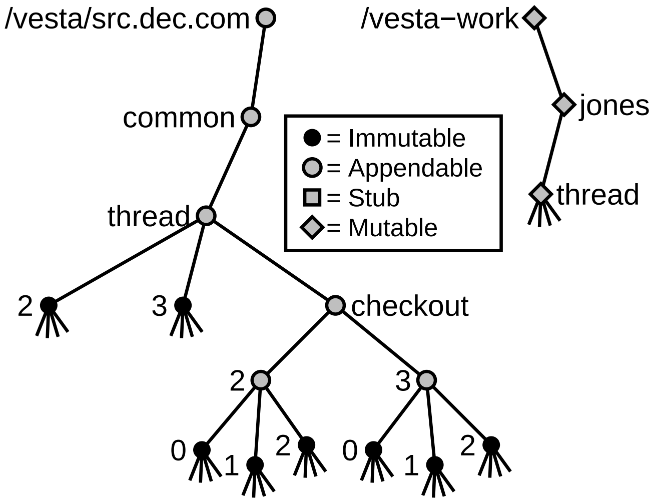

Figure 3: The working directory and checkout sessions of the `common/thread` package.

Vesta records an immutable version of a package not only when the package is checked in, but also each time the checked-out package is modified and rebuilt (and even more often, if the user chooses). It is necessary to create these intermediate versions in order to support Vesta's repeatability guarantee, which requires that *all* builds be performed against immutable sources. Thus a user does not have to carefully consider which builds might be useful in the future and be sure to check in the sources used in those builds; Vesta automatically records them all.

To avoid cluttering the namespace, the intermediate versions that are created between checkout and checkin are stored in separate directories called *checkout sessions*. Each package contains a subdirectory called `checkout` to hold such sessions. In the example of Figure 3, the subdirectory `checkout/2` holds intermediate versions leading up to version 2, while `checkout/3` holds intermediate versions leading up to version 3. Each time a package is checked out, a checkout session is created for it. The act of creating a new version within a session is called *advancing* the session.

The typical development cycle can be viewed as a nested loop:

- Check out the package using **vcheckout**
- Modify the package:
    - Edit using your favorite text editor
    - Advance the session using **vadvance**

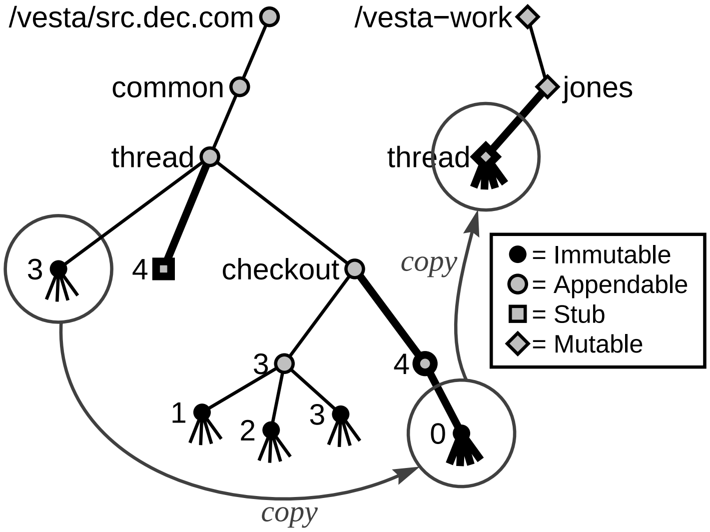

Figure 4: The effects of **vcheckout common/thread**.

  - Build the package using **vesta**
  - Test
  - Repeat as necessary

- Check in the package using **vcheckin**
- Repeat as necessary

The outer loop consists of three steps: check out the package using **vcheckout**, modify it, and check it back in using **vcheckin**. The inner loop is the familiar edit-compile-test sequence, but with the extra **vadvance** step added. This step takes a snapshot of the current state of the package and records it as a new immutable version within the current checkout session.[4] We now describe these tools and their effect on the repository in more detail.

Figure 4 shows the effects of the command **vcheckout common/thread**. In this figure and the next two, bold lines denote newly created elements. The steps of each command illustrated are perform atomically. Assuming that the latest version of the `common/thread` package was version 3, this command would first create a special element called a *stub* named `common/thread/4`. The stub reserves a name under which the package will be checked back in; attempting to check out the

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[4] Since **vadvance** and **vesta** are usually run together, we provide a simple shell script that runs them in sequence as a single command. **vadvance** can also be used independently as a means of checkpointing a user's current sources.

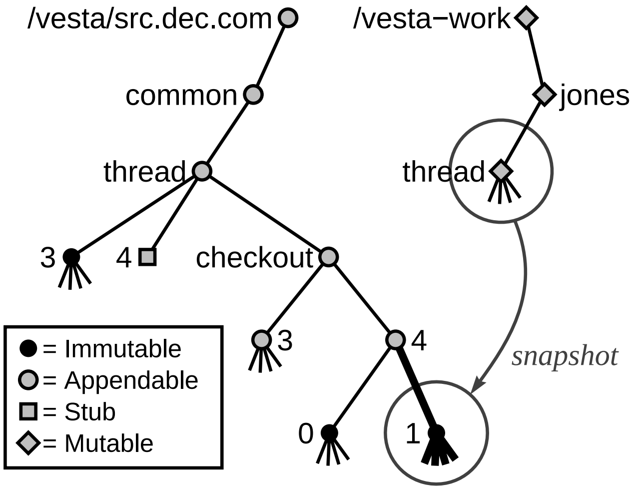

Figure 5: The effects of **vadvance**.

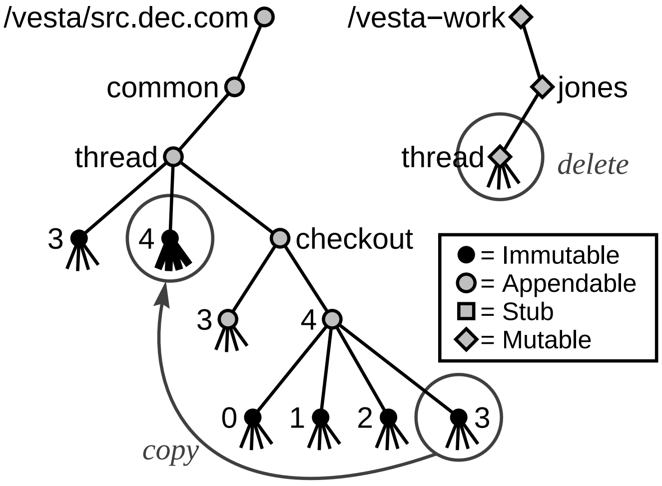

Figure 6: The effects of **vcheckin**.

package again will fail because a stub for version 4 already exists. Next, the new appendable directory `common/thread/checkout/4` is created, and the latest version of the package is copied into that checkout directory as checkout version 0. Finally, a mutable copy of the package is made in the user's working directory under `/vesta-work`.

Files in the working directory may then be freely edited. Before building them, the user invokes **vadvance**. As shown in Figure 5, **vadvance** simply creates an immutable snapshot of the working directory in the appropriate part of the package's checkout directory. Builds are then performed using these immutable sources.

Finally, once the user is satisfied with the state of the package, **vcheckin** is used to check the package back into the main line of the package version space. As shown in Figure 6, **vcheckin** replaces the previously created version stub by the latest sub-version of the checkout session, and deletes the user's working version of the package from `/vesta-work`.

We do not currently have any Vesta-specific tools for merging branches back into the main line. Our existing tools do keep careful track of the history of all versions and branches, so it would be a simple matter to write a tool that finds the common ancestor of any two versions, and either automatically merges the changes along one branch into the other (perhaps using existing Unix tools like **diff** and **patch**), or presents them to the user for manual merging (using a text-based tool like **diff3** or equivalent graphical tools).

4.3 System Modeling Language

We now consider typical client system descriptions. A complete discussion of Vesta's system modeling language is beyond the scope of this overview, so we confine ourselves to motivating and describing its main features here. We describe the language fully in a separate paper [9].

Across different development organizations, there is a rather wide variation in build processes, including the size and scope of the systems being built, the structure and methodology of the organization, and the degree of parameterization required. Vesta therefore supports varied descriptions through a general-purpose language that supports abstraction. Abstraction permits the construction of *extensions* that adapt the language to each organization's development methodology. As a proof of concept, we have built one fairly comprehensive extension called the *standard construction environment*.

The system modeling language itself is a full-fledged functional programming language with a C-like syntax. The functional nature of the language is important, since each function call represents a unit of work appropriate for caching. The language uses strong, dynamic typing: program variables do not have static types, but

```
files
  h = [ date.h ];
  c = [ date.c, calendar.c ];
{
  libs = < ./C/libc >;
  return ./C/program("cal", h, c, libs);
}
```

Figure 7: A `build.ves` system model for building a sample application.

the run-time types of arguments to all built-in operations are checked for correctness. The main aspect of the language that is specialized for software construction is a primitive to run external tools like compilers and linkers in an encapsulated environment (i.e., to invoke the runtool server of Figure 1). The language also includes an `import` statement that supports modular, hierarchical system modeling.

Figure 7 shows a sample model for building an application. By convention, the model responsible for building all the components of a package is named `build.ves`. The `files` clause binds the program variables `h` and `c` to the listed files in the package. The body of the model then binds the variable `libs` to a singleton list containing the standard C library, and returns the result of invoking the `program` function supplied by the standard environment. It is the `program` function that is responsible for compiling the necessary sources and linking the program.

Before a model like the one shown in Figure 7 can be invoked, the *environment* in which the build is performed must be created and bound to the special variable named "." (dot). The variable "." is special because it is passed as an implicit argument on all function calls. Hence, assignments or changes to "." are visible in all descendant functions of the function call graph. This feature of Vesta's function call semantics makes it easy to define customizations that affect all relevant parts of a build.

The build environment embodies not only the complete set of functions, tools, libraries, and header files needed by the build (all versioned and stored in the Vesta repository), but also any requested build customizations. Such customizations are typically injected "from the outside"; that is, a developer considers them as parameters of a particular build rather than inherent details of the system being built. It is thus appropriate to include them in the top-level (outermost) system model. Indeed, such a model does nothing more than import a particular version of the build environment, set parameter values, and invoke the build procedure for a package or collection of packages. A top-level model can therefore be readily constructed by a graphical "control panel" program: the user specifies desired customizations

```
from /vesta/src.dec.com/common import
  std_env = std_env/23/build.ves;
import
  calendar = build.ves;
{
  . = std_env()/env_build("DU4.0");
  // build customizations would go here...
  return calendar();
}
```

Figure 8: A top-level `.main.ves` model for establishing the build environment.

```
from /vesta/src.dec.com/microcommerce import
  wallet = wallet/12/build.ves;
  vendor = vendor/20/build.ves;
  broker = broker/7/build.ves;
{
  return wallet() ++ vendor() ++ broker();
}
```

Figure 9: An umbrella system model for building a collection of components and combining their results.

in the control panel window, and the program writes a stylized top-level model for the build.[5] By convention, top-level models are named `.main.ves`.

Figure 8 shows an example. The model begins with two imports. One import is of the non-local model `common/std_env/23/build.ves` (bound to the variable `std_env`), and the other is of the local model `build.ves` (bound to `calendar`). The model body consists of two statements. The first invokes the `env_build` function returned by the `std_env` model, and binds the result to the special variable ".". The second statement then invokes and returns the result of the package's own `build.ves` model shown in Figure 7. This example shows that a model can be called like a function.

Figure 9 shows a system model for building what we call an *umbrella package*. Such packages do not contain any sources or build anything directly. Instead, they import a collection of packages, build them, and then combine the results together into a single result. Umbrella packages illustrate how to structure build descriptions in a modular fashion. In this example, the umbrella package serves to record the

---

[5] We have not implemented a general-purpose control panel as yet, so we currently write our own top-level models by hand. However, an engineering group that we are working with has successfully developed a specialized control panel for their large, complex, highly parameterized application.

information that versions 12, 20, and 7 of the `wallet`, `vendor`, and `broker` components go together to make one coherent version of the `microcommerce` system.

We are now prepared to address the point raised in Section 3: If system models must name the version of every source file, isn't the overhead of maintaining those references overwhelming? Three factors make the overhead tractable. First, many references are local to the model's containing package, and hence do not require explicit version numbers; for example, the references to files in Figure 7 and the import setting `calendar = build.ves` in Figure 8. Second, we structure our models so that most explicit version numbers appear only in the small tree of umbrella models that make up the standard environment. A top-level `.main.ves` model typically contains only one import with a version number, to select a particular version of the standard environment. Third, we provide a tool called **vupdate** that a user can invoke at will to automatically update some or all of the imports in a model to the most recent versions.

The brief examples presented here cannot fully illustrate the power of the Vesta system modeling language or the wide variety of build customizations supported by the standard construction environment. The system models that make up the standard environment are rather complicated, but we believe that the investment by a modeling language "wizard" in creating them is more than offset by the resulting simplicity in the far more numerous user models.

5 Performance

If Vesta's performance were significantly worse than that of alternative SCM systems, it would be of little practical interest. We have worked hard to make the system efficient. In fact, in this section we show that Vesta's overall performance on scratch builds is as good as Make's, and that Vesta's caching makes it significantly faster than Make on incremental builds.

To compare Vesta with Make, we ran tests on the hardware configuration shown in Figure 10. Client processes (the builder and tools) were run on a 333MHz AlphaStation 500 5/333. Server processes (the repository and function cache in the case of Vesta, and the NFS server in the case of Make) were run on a 233MHz AlphaStation 400 4/233. In both cases, the server processes used the same AdvFS file system residing on a local disk, and the client and server machines communicated via a high-speed ATM network called AN2. All machines were running version 4.0D of Compaq's Tru64 Unix operating system.

We measured builds of software systems of varying sizes. The characteristics of these systems are shown in Table 1. The columns of this table indicate the total

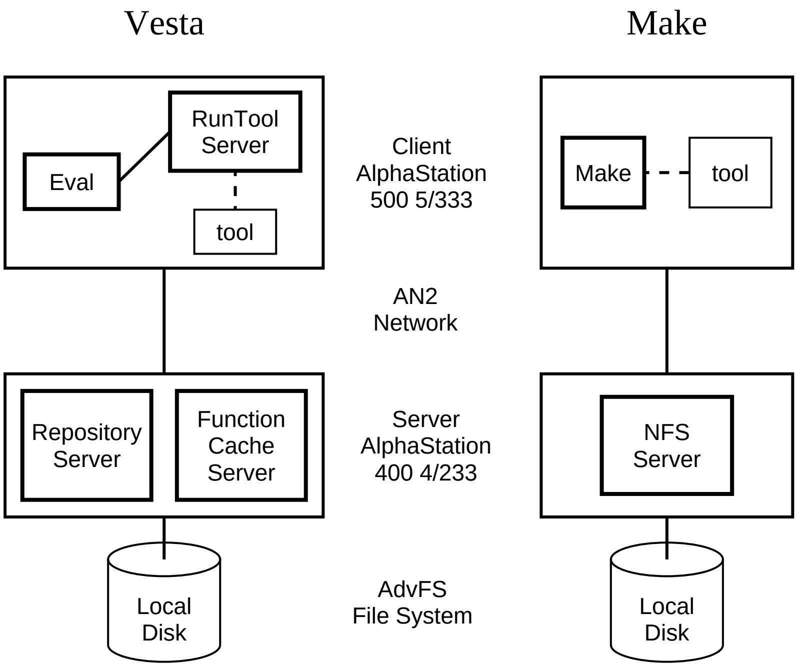

Figure 10: The experimental setup for our performance measurements.

number of lines of source code, the number of C/C++ source files to be compiled, the number of tool invocations necessary, and the number of packages across which the sources reside.

The *Hello* test is a simple "hello world" program consisting of a single 10-line source file. It requires two tool invocations: one to compile the file, and one to link it. This test is included mainly to provide a baseline measurement. The *Evaluator* test consists of building all of the Vesta libraries and the Vesta evaluator application. The sources for this test are contained in 10 library packages and the evaluator package itself. Finally, the *Release* test consists of building the entire Vesta release. In addition to building the evaluator, this includes building all the

Test	Lines	Files	Tool Runs	Pkgs
Hello	10	1	2	1
Evaluator	53,304	103	117	11
Release	119,602	255	333	16

Table 1: Characteristics of three build tests.

Test	Vesta	Make
Hello	3.3s	3.4s
Evaluator	310s	318s
Release	912s	960s

Table 2: The elapsed time in seconds required by Vesta and Make to build the three test cases of Table 1 from scratch.

Test	Vesta	Make One	Make All
Hello	3.3s	3.4s	3.4s
Evaluator	12.5s	15.1s	23.3s
Release	13.1s	15.1s	32.1s

Table 3: The elapsed time in seconds required by Vesta and Make to perform incremental builds of the three test cases of Table 1.

Vesta tools, servers, and documentation.

Table 2 shows the elapsed time (in seconds) required by Vesta and Make to perform each of the three test builds from scratch. These data show that scratch Vesta builds are somewhat faster than Make builds, but not appreciably so, since most of the time is spent compiling and linking.

To measure the time required to perform incremental builds, we modified one of the source files in each build test and rebuilt. In the case of the Release test, we modified the same evaluator source file as in the Evaluator test.

Table 3 shows the elapsed time (in seconds) to perform each incremental build. For Make builds, we report two values. The “Make One” column reports the time required to run Make in the single directory containing the modified source file. This is what developers typically do when working on a set of sources. However, if a source in another package were modified, the resulting build might be inconsistent. To get closer to a consistent build, the Make user would need to run Make in each of the other directories, or packages, contributing to the build. The “Make All” column reports the elapsed time required to run Make in all such packages. The extra time in the case of the Evaluator and Release tests is the time required by Make to determine that all the other packages were up to date. Note that Vesta provides even stronger consistency guarantees than the “Make All” approach, yet it is significantly faster, primarily due to top-down caching.

6 Conclusions

This brief overview paper has omitted discussion of many of the detailed technical issues in Vesta. We list some key points here, then go on to summarize our experience in using Vesta and present our conclusions. Additional papers [9, 11, 15] and a forthcoming book-length report [10] give a more complete treatment.

Repository. The repository is a general-purpose file system with support for Vesta-specific features, but making that file system visible via an NFS interface was non-trivial. Also, the repository supports partial replication of sources across geographically distributed sites [15]. All packages that exist in all Vesta repositories are named in a single global namespace, and each repository can store any subtree of that namespace. Replication exists when the subtrees stored by two different repositories overlap. Thus the subtree `/vesta/src.dec.com` shown in Figure 2 might be stored (in whole or in part) not only at SRC, but at other cooperating sites as well. The append-only nature of the repository simplifies the problem of defining and maintaining consistency between partial replicas.

Caching. The main challenge in caching (parts of) builds is forming cache entries whose dependencies are as fine-grained as possible [11]. For example, we do not want the compilation of a C file to appear dependent on every header file available in its environment, but only on those that were actually read when compiling it. This requires some non-trivial dynamic dependency analysis in the Vesta evaluator, as well as support for dynamic, fine-grained dependencies in the function cache. Also, to make incremental builds fast, the evaluator creates some special cache entries to get cheap high-level cache hits.

System Modeling Language. The main virtue of Vesta's system modeling language [9] is that it supports flexible, modular build descriptions that can be highly parameterized. The main challenge was designing a general-purpose language amenable to efficient execution and caching that supports a variety of methodologies and build customizations.

Overall, Vesta handles the core SCM problems of version control and building quite well. It provides repeatable, incremental, and consistent builds. It also supports parallel development through several features, such as branching, explicit versioning, and partial replication. Vesta's system modeling language is general enough to support different development organizations, and it encourages modular software descriptions. On both scratch and incremental builds of the sizes we have tested, Vesta performs better than Make, while providing much stronger consistency guarantees. Finally, we have found the system easy to use; once we switched over from building the system with Make to building it with Vesta, we never wanted to go back. The advantages provided by being able to exactly name and reproduce any past build are difficult to fully appreciate until they are available, but difficult to live without thereafter.

We have gained additional experience with Vesta over the last two years by demonstrating it to a Compaq engineering group and helping them to install and use it for their project. Vesta is currently in daily use by over 100 developers in this group. The code base they are writing is expected to exceed 700,000 lines by the time it is complete. They have adapted Vesta to their application and development environment by writing a small number of "wrapper scripts," a domain-specific control panel application to generate top-level models, and (with some initial help from us) additional system models to add their specialized build tools to the standard environment. Overall, they have found Vesta to be a substantial improvement over their previous version and build management tools; in fact, they believe that Vesta's strong support for independent parallel development has put them 3 to 6 months ahead on the first phase of their project.

However, despite these successes, there are still some open questions. The first relates to scalability. Vesta was designed to build much larger systems than we have tested it on thus far. An earlier Vesta prototype (Vesta-1) saw use by 25 programmers maintaining, extending, and porting a 1.4 million line code base for over a year [14]. We designed the current Vesta-2 system to overcome the scaling bottlenecks we observed at that time, but we have not yet used it to build anything quite so large. Our Compaq engineering users have not encountered hard scaling limits, though we have had to fix a few performance bugs in the implementation as they have ramped up their use.

Another question relates to ease of use. Our experiences have been positive, but as the developers of the system, we are obviously biased. Our users seem to be pleased as well, although their custom wrappers and control panel are undoubtedly important factors in making the system easier for them to use.

Finally, for Vesta to be adopted by any organization, some technical and non-technical hurdles must be overcome. Users of other SCM systems need to convert their code bases and descriptions to Vesta, which may require specialized tools that understand their existing development methodology. Perhaps a more substantial problem is the need to overcome the psychological barrier created by Vesta's radically different approach to SCM. New users thus require training, not just in a different set of tools, but in a different way of thinking about the software development process.

7 Acknowledgements

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