Sharpening Your Tools: Updating bulk_extractor for the 2020s.

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Abstract

Bulk_extractor is a high-performance digital forensics tool written in C++. Between 2018 and 2022 we updated the program from C++98 to C++17, performed a complete code refactoring, and adopted a unit test framework. The new version typically runs with 75% more throughput than the previous version, which we attribute to improved multithreading. We provide lessons and recommendations for other digital forensics tool maintainers.

Keywords: bulk_extractor

1. Introduction

Digital forensics (DF) is a fast moving field with a huge subject area. A digital investigator must be able to analyze "any data that might be found on any device anywhere on the planet."

As such, DF tools must be continually updated to address new file formats, new encoding schemes, and new ways that the subjects of an investigation (the "targets") use their computers. At the same time, tools need to retain the ability to analyze legacy data formats—all of them, in fact.

Many DF tools run on stock operating systems (Linux, macOS and Windows), adding another layer of complexity: operating systems are also continually evolving. Analysts who do not update their systems risk having those systems compromised by malware, which negatively impacts analyst productivity and can be used in court to discredit an analysis. This is true even for analyst workstations that are “air gapped” and not connected to the Internet, since malware in evidence can exploit bugs in forensic software.

At the same time, updating the operating system potentially causes risk for the proper execution of the digital forensic tools: although new versions of operating systems attempt to provide compatibility for software that ran on previous versions, compatibility layers are not perfect.

Surprisingly, open source software distributed in source code form faces a greater challenge when the underlying operating system is upgraded. This is because software compatibility layers typically emphasize compatibility for software that is distributed as binary executables. Software that is compiled from source, in contrast, must cope with upgrades to compilers, libraries, and file locations. Old compilers required for old source code distributions may not run on new operating systems. Legacy software may use older libraries that are incompatible with newer runtimes. Thus, after the compilers and libraries are upgraded, the older open source software may no longer compile. Colloquially this is sometimes called dependency hell and bit rot. One way around this problem is to run the old software inside a virtual machine—but older virtual machines typically won’t be protected against modern malware threats.

In theory, one advantage of open source software is that the end-user has the source code and is therefore able to update the application (or pay for a programmer to update the application). In practice, many users of digital forensic tools lack the expertise, financial resources, and time to update the collection of open source tools that they rely upon to do their jobs.

1.1. Contribution

This article presents our experience updating the digital forensics tool bulk_extractor (BE) a decade after its initial release. Forensic tool developers can benefit from the detailed discussion of how embracing features in the C++17 standard and modern software engineering practices can improve the correctness, reliability, and throughput of forensic software. Businesses and funding agencies can use this experience to help justify the substantial cost of updating and even rewriting digital forensic tools that appear to be working properly. Students will benefit from reading this article and then consulting the BE source code, which can be found on GitHub.

1.2. Outline

This concludes the introduction. In §2 we present a detailed description of BE, including the tool’s history and its use in digital forensics research and education. We
discuss why it is difficult to ascertain the extent that an open source digital forensics tool is used operationally.\footnote{Although BE version 1.5.3 is the most recent version of the program that was widely in use at the start of this project, v1.5.3 would no longer compile on modern systems. Therefore we had to separately update v1.5.3, producing versions 1.6 and 1.6.1, in addition to our rewrite that produced v2.0.}

In §3 we present how we planned the update of the tool. Included in this section is a discussion of the improvements in the C++ and Python programming languages over the past decade that might inspire others to upgrade their tools. We also discuss the design and inclusion of a test suite, including both unit tests and black-box tests.

In §4 we present the results of our effort to produce BE version 2.0 (BE2), including refactoring the code base and implementing a significant number of unit tests that were used to validate the correctness, reliability and throughput improvements of the tool.

Finally, in §5 we generalize our experience in updating BE and extract lessons that may be useful for the developers of other forensic applications.

2. Background

Although there are many models for digital evidence examination, the most common include a five step process of policy and capability development; evidence assessment; evidence acquisition; evidence examination; documentation and reporting\cite{4}. BE is designed to assist in the evidence examination stage.

Multiple strategies are employed by evidence examination tools. There are file-extraction tools that attempt to extract individual files from disk images or reassemble files from network streams using metadata; there are file carving tools, which attempt to recognize files within bulk data such as disk image and product files based solely on content recognition; and there are file analysis tools that understand file formats and attempt to extract information, such as text and Microsoft Office file metadata.

BE does not fit neatly into any of these categories. Instead, it was designed to be a so-called “find evidence button.” It is similar to a file carving tool, in that it attempts to recognize known formats in bulk data and use those data in further processing. But in addition to recognizing files such as JPEG images, BE will recognize smaller “features” such as email addresses, URLs and credit card numbers, as such information has been proven to be valuable in investigations. BE will also examine every input block to see if that block contains FAT32 or NTFS directory entries and, if any are found, report the decoded metadata. Overall, it handles dozens of data formats, all at the same time. The program then constructs normalized Unicode histograms of important strings like email addresses and Internet search queries, drawing from utf-8, utf-16be and utf-16le encoded binary. Experience has shown that this “kitchen-sink” approach—throwing every tool at every byte—finds data that other tools miss, and these data can be important in investigations. And while such analysis is computationally expensive, it is embarrassingly parallel. As a result, BE routinely utilizes all of the cores of a multi-core workstation.

Another distinguishing aspect of BE is that it performs recursive reanalysis of data blocks. That is, BE checks every byte to see if it is the start of a stream that can be decompressed, decoded, or otherwise unwrapped. If so, the resulting bytes are then recursively reanalyzed using the various BE scanners. Thus, BE’s JPEG carver finds not just ordinary JPEGs, but JPEGs that are in gzip-compressed data, JPEG’s that are in BASE64 MIME attachments, and JPEGs that were once in Windows memory but have since been compressed and written to the Windows swap file.

The combination of decoding data recursively and recognizing interesting data without regard to file system structure makes BE a powerful tool that complements traditional forensics tools. Because of its simplified data model and parallelism, BE can typically process a disk image several times faster than traditional tools, and can therefore be used for triage. BE also supports a random-sampling mode, making it possible, for example, to scan a 1TB disk image in 5 minutes and determine with 99% probability if the disk contains a specific media file from an archive\cite{5}. At the same time, BE sometimes unearthed artifacts that other tools can’t, making it useful for demanding investigations.

Because BE ignores file boundaries, the modules that it uses to recognize content, called scanners, are typically more complex than the format decoders (sometimes called dissectors) in other forensic programs. Of course each scanner checks the input to every field before using it for memory references. But BE scanners also check for end-of-memory conditions, since a scanner may be operating on a fragment of a decompressed memory block. And since BE processes memory in parallel, each block in a different thread, all scanners must be thread-safe. Some of the program’s most important scanners are large lexical analyzers written in GNU Flex\cite{6} that scan bulk data for email addresses, phone numbers, MAC addresses, IP addresses, URLs, and other kinds of formatted text strings (sometimes called selectors\cite{7}). The approach of using GNU flex for this purpose was first used by SBook\cite{8} to recognize email addresses, phone numbers, and other formatted information in free-text address book entries; the BE scanners are based on the original SBook analysis engine, meaning that some of the code in BE is now 30 years old.

2.1. History

The BE approach for bulk data analysis was first deployed to find confidential information on a set of 150 hard drives purchased on the secondary market\cite{9}. The program was refined and made multi-threaded to keep up with the increased number of hard drives and other storage devices collected during the construction of the Real Data
During development, some BE users indicated that they were excited by the project but wanted to have their own, private label, proprietary version of the program that incorporated specific non-public capabilities. Maintaining such capabilities is a complex undertaking. Instead, the decision was made to refactor the program’s code base, dividing the functionality into three parts. The core architecture of applying content-recognizing scanners to blocks of data and providing for recursive re-analysis of that data was incorporated into the somewhat improperly named bulk extractor API. This module included support for the program’s configuration, passing data to scanners, maintaining a set of scanners (the “scanner set”), and a “feature recorder” system for persisting the data found by scanners to the file system for further analysis. Because this module was introduced in version 1.3, this module was called be3_api. We have since renamed it to be2_api because of the significant incompatible changes associated with the 2.0 release.

The second part of BE was the program’s main loop and all code necessary for reading disk images. This part of the program reads data in overlapping blocks and feeds the data to the API. When a user requested the ability to have BE scan files in a file system (or contained within a cloud-based storage system), this new capability was readily added, with only a few lines of modification required to the main program.

The third part of BE was the scanners themselves. Each scanner used the same API and only the API: no scanner was privileged over any other. Written in C++, scanners can be compiled and linked with the main program and the API. Alternatively, scanners can be embedded in shared libraries (.so files on Linux and macOS, .dll files on Windows) and loaded at run-time. The scanners register not just their ability to scan data and write to feature files, but their metadata, configuration variables, and help messages: all are available using standard command-line arguments. This allowed users to create and deploy their own proprietary scanners.

BE1.6 shipped with 37 individual scanners; BE2 has 35 (hashdb and sceadan both having been removed). The amount of effort to take an existing digital forensics C or C++ library that extracts features from a block of data and turn it into a BE scanner is typically less than an hour, provided that the library is already thread-safe.

### 2.2. CLI and GUI

BE was designed to be used with a command line interface (CLI) that performs batch analysis on pretty much any kind of data that a forensic investigator might have. The command-line user interface is straightforward: one provides the input file and an output directory, and BE runs. (The program has over a hundred command-line arguments to enable or disable scanners and to set configuration variables, but all can be safely ignored in most cases.)

BE also has a graphical user interface (GUI) written in Java. Called “BEViewer,” the program’s main feature is viewing the “feature files” and carved data that BE produces. BEViewer can also run the BE program.

#### 2.3. BE in research

The original BE feature extraction code was developed to search for credit card numbers and other sensitive information on hard drives purchased on the secondary market as part of a research study[9], and the program retained its use as an apparatus for digital forensics research and experimentation for the following decade. For example, the sceadan scanner was implemented for Beebe and Maddox’s Sceadan tool[12], and a hashdb scanner was implemented for Allen’s hashdb[13]. Incorporating the experimental functionality into BE allowed testing the Sceadan and HashDB algorithms at scale, with large amounts of data, and to have the results recording using the BE feature reporting system. This may have made it faster to develop these systems.

Building Sceadan and HashDB into the BE mainstream code had negative impacts as well: doing so complicated building the program. It also added to the cost of supporting BE, since users wanted to know if Sceadan or HashDB were required for proper operation (they were not). Finally, these experimental tools were not needed by the majority of BE users. Indeed, despite multiple publications on fragment classification and hash-based carving ([14, 15]), there is no evidence that this technology was ever deployed into an operational environment.

As a result, we have removed support for these experimental systems from BE2.0. Users who need this functionality can use BE’s ability to load plugins at runtime using shared libraries. Indeed, it is unclear why the original developers of these scanners did not implement them as shared libraries.

#### 2.4. BE in education

BE has been widely used in digital forensics education, as evidenced by the more than 400 videos on YouTube that result from a search for the term “bulk extractor.” Many of these videos showcase the result of student projects using the tool.

We believe that BE is a successful tool in education because is easy to use, runs on Windows, Mac and Linux platforms, and finds a wide variety of forensic artifacts. For advanced students, BE can easily be used as inputs into a wide range of student projects.

#### 2.5. BE in operational use

Since its creation, BE has been used by government agencies worldwide and private companies. In 2011 the
program won a US Department of Defense Value Engineering Award [16].

Because BE is distributed as open source software and because most investigations are subject to confidentiality constraints, it is difficult to establish how broadly the program is used. For example, the program is included on several digital forensics software distributions, but it is not possible to know if people who run the distributions from a bootable DVD or USB memory stick actually run the BE program. We do know that the program is included as part of the Blacklight digital forensics tool[17], and has also been used incorporated into the BitCurator[18] tool used by curators in the digital humanities.

Stroz Friedberg’s DFIR consulting practice has made use of BE in some investigations. In a large incident response case, Linux servers with XFS filesystems had been attacked, and no popular forensic tools could cope with filesystem analysis of XFS. BE was used to triage these servers for relevant indicators of compromise, allowing for rapid progress in the early days of the investigation. In a well-known intellectual property theft case, Waymo vs Uber, BE was used as one of several processes to scour forensic evidence of the defendant’s engineering laptops for file names provided by the plaintiff.

In summary, BE is a powerful tool that has been used for more than a decade, with compelling anecdotes of usage, but we do not know how widely or regularly it has been used.

3. Updating BE

BE is a legacy C++ program. The technique of using GNU flex to develop large regular expression ensembles dates to an unpublished 1989 MIT Media Lab research project. The histogram engine dates to Garfinkel and Shelat’s 2003 project [9]. The producer-consumer threadpool was developed in 2008, and the underlying scanner-based architecture with recursive reanalysis was in place by 2009. All of this was done with versions of C++ based on the circa-1998 Standard Template Library (STL), well before the ratification of the C++11 standard.

Part of the BE requirements study[11] revealed that the application needed to run in a wide variety of environments, including Microsoft Windows, macOS, and several varieties of Linux. The program achieves the necessary portability through the use of GNU autoconf[19], the POSIX API, and the mingw[20] compiler suite to produce the Windows executable. The ability of these tools to provide portability to future operating systems is less well developed, however, necessitating minor changes to the configuration system or the BE source code to accommodate operating system changes such as deprecated APIs and renamed #include files.

Development of new BE features largely stopped in 2014. The one exception was an unfortunate fork of the BE codebase when a developer added support for “record carving.”[23] A significant effort to resolve the issue by publishing a new version of BE that only advertised compatibility with Python 3.

3.1. Upgrade Goals

Based on this experience, in 2018 the decision was made to embark on an orderly upgrade of BE to create version 2.0. This section describes the upgrade goals.

**Make the program easier to compile and maintain by relying on the C++ standard.** The primary reason for the BE upgrade was that the program would no longer compile on modern open source operating systems. In part, this was because BE predated the C++11 standard. Although the autoconf system is resilient, it has its limits, and after six years of abandonment, they were beginning to show.

We were especially eager to rely on the C++ standard to provide platform-independence, because the C++ standard is designed so that conforming code can compile in the future on platforms that do not exist today. It does this by specifying the *version* of the standard to use when compiling and linking the executable: C++11, C++14, C++17 and so-on.

Upgrading the existing code to a modern C++ standard required that we:

- Choose a specific C++ standard.
- Generally use C++ functionality rather than POSIX or Windows functionality.
- Remove as many #ifdef preprocessor directives as possible.

upgraded a build system, it was discovered that The Sleuthkit compiled with the MinGW cross-compiler would no longer function properly. It was discovered that between Fedora 31 and Fedora 34 the compiler’s developers had swapped MinGW’s handling of the *printf* format specifiers %a and %s, from Windows semantics[21] to POSIX semantics[22]. We avoided this problem in BE2 by deprecating the use of *printf*, relying instead on the C++17 formatting primitives which are consistent across platforms.
• Replace code that the original authors had painstakingly written, debugged and maintained with new code that used the C++ standard. This meant that we might be introducing bugs into working code, so we needed to have a better strategy for testing than the original authors.

We first chose the C++14 standard, as a complete C++17 implementations were not widely available when the upgrade started. We eventually migrated to C++17 for the std::filesystem support, and because the project had dragged on for so long that C++17 was widely available.

In 2021 we considered moving to C++20, but attempts to use specific features met with failure, so BE2.0 uses C++17.

**Improve reliability.** The single most important aspect of a digital forensics tool is that it must not crash before useful output. Ideally a digital forensics tool will not crash at all. However, if the tool does crash, there needs to be some way to get useful output first, or to restart the tool to complete the analysis.

Garfinkel’s original BE requirements study identified the need to never crash[11]. Of course, the tool did crash from time to time, so BE incorporated a system for restarting: when the command-line tool crashed, if the program was re-run with exactly the same command line arguments (by hitting up-arrow and return, for example) the tool would carry on from where it had left off, skipping the data that it was analyzing during the crash. For BE2, a goal was to improve the program’s reliability so that it really never did crash.

**Simplify the code base.** Although the internal structure of BE was sound, it was needlessly complicated in places, a result of 10 years’ evolution in the calling conventions between the API and the individual scanners. For example, scanners in the be13api took two arguments: a pointer to a structure called the scanner parameters, and a pointer to a second structure called the recursion control block. In be2_api the relevant parameters from the recursion control block were added into the scanner parameters structure, and that structure is passed to the scanner as a reference to a C++ object, rather than a pointer, because it is mandatory. Unused options were removed, and options that were always used together were combined.

**Remove experimental code from the code base.** BE was initially developed to support digital forensics research, and there was a significant amount of experimental, research code contained therein. This code was removed for BE2: experiments can continue, but they will be confined to using the plug-in system.

**Make BE run faster.** Our final objective was to decrease the amount of time that the program required to run. Initially, we wanted BE2 to run faster than BE1 on the same hardware. After further analysis, we determined that BE2 should also take better advantage of multiple processor cores without corresponding need for high-performance I/O systems: over the past ten years CPUs had enjoyed much more speedup than disk subsystems.

To increase parallelism, we redesigned the multithreading system so that recursive processing could happen in another thread. This allows utilizing more cores without requiring improvements in the underlying I/O system. We also added reference-counting garbage collection to the memory management system so that a single buffer could be processed simultaneously by multiple scanners, each in their own thread: the memory is automatically freed when it is no longer needed.

BE has the ability to process a directory of files. In BE1 each file was handled in its own thread. In BE2 all of the files are scanned in advance and then processed in order, each file being split into multiple pages, each page being processed in parallel with multiple threads. As a result, there are more opportunities for parallelism. (We also now recursively enumerate the directories and files within the specified directory using the portable C++17 methods, which further simplified the BE codebase.)

Another improvement in computing since the release of BE1 was the widespread availability of serverless computing systems such as Amazon Lambda and Microsoft Functions. Because BE effectively processes each 16MiB page independently, 1TB of evidence can be processed simultaneously on 59,605 different VMs. This would allow processing the 1TB disk image in 5 min or less without sampling, a longstanding goal of this project.³ Realizing this goal would require storing the 1TB drive on a parallelized storage system that could accommodate tens of thousands of simultaneous and independent readers. It would also require the ability to scale Amazon Lambda from 0 to 59,605 simultaneous function executions instantaneously. In practice, Amazon has configured AWS to scale gradually. So while adopting BE2 so that it could run under Amazon Lambda would allow processing a 1TB drive in 5 minutes, it would not be the first drive that received such a speedup: it would likely be the 10th or 20th. This experiment will not be realized until BE users have the need for such capability, and are willing to pay to develop it.

Finally, we wanted faster compiles for developers, which meant simplifying the GNU autoconf script, as this script runs single-threaded.

### 3.2. Improving the Code Quality

As part of refactoring the code base, we dramatically improved the code quality of the underlying C++ code.

We started by reading most of Stroustrup’s textbook[24]. More than a thousand pages long, we believe that few people read this book in its entirety. Moreover, the book only

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³The goal of processing a 1TB disk in five minutes was first proposed by a DARPA program manager in 2005.
covers through C++11, and we were using C++14 (and then C++17). However, BE was based on a version of C++ that predates the C++11 standard, and the changes between that version and C++11 are dramatic compared to those that follow. The intimate familiarity that comes with reading such a text allows one to make better use of the language’s features that are at the same time both more efficient and safer.

Next, we worked to improve the efficiency, safety and speed of BE’s fundamental memory management C++ class, the *sbuf*. This class represents a sequence of bytes that are read from evidence or decoded from another *sbuf*. The *sbuf* tracks how the contained memory was allocated (and thus, how it needs to be freed); provides accessor methods that are type-safe, memory-safe and thread-safe; has capabilities for making new *sbufs* from disk files, slices of other *sbufs*, from new memory that is passed to a codec or decompressor; and provides rich debugging capabilities.

To improve encapsulation and provide for better code re-use, we moved many functions from scanners and the BE framework into the *sbuf* class. For example, the *sbuf* can now compute its cryptographic hash in a thread-safe manner and cache the results so that they can be used elsewhere in the program: hashes are computed as needed, a form of lazy evaluation. The *sbuf* class now implements string-search and several other performance-critical functions. Implementing them within the *sbuf* class allows the arguments to be validated for memory safety *once*, and then unsafe code to be used within the *sbuf* implementation. As a result of moving functionality into the *sbuf*, we were able to eliminate virtually all raw memory references throughout the rest of BE.

Other improvements in the code base include:

- We moved common code out of the scanners and into the **be2api** framework. For example, rather than each scanner having options for setting its carve mode, the framework understands how to set them for any named scanner.
- We simplified the API, combining functions and methods with nearly identical functionality. For example, *sbuf* previously had two functions that could map a file into an *sbuf*: one that took filename already open and the open file descriptor, another that just took the filename and opened it. We eliminated the API call that took an open file descriptor, and modified the source-code so that the file was opened by the *sbuf* method, and never by the caller.
- We added explicit phases into the API where the scanners can allocate and free memory. Now scanners are expected to deallocate all memory that they allocate during the run, rather than allowing the operating system to discard the memory when the process exits. This allowed us to find memory leaks in our unit tests that otherwise would have been missed.
- Whereas previously many strings were passed by reference as `const std::string &`, there are now passed by value as a `std::string`. This necessitates a string copy, but it is not a meaningful impact on performance, especially when compared with the improved safety against possibly using an invalidated reference. This decision simplified code and resulted in the elimination of several use-after-free errors.
- We enabled *sbuf* child tracking, meaning that each *sbuf* counts how many child *sbufs* it has. (A child *sbuf* is one that shares a portion of the parent *sbuf*’s memory.) Previously this was turned off because of a bug in which not all children were properly registered when they were created and de-registered when they were deleted. Once we defined the clear policy described above, we were able to find the bug! Now we assume that all allocated *sbufs* are freed and throw an exception if that is not the case, which allows memory leaks to be rapidly identified during software development.
- With the above tracking of *sbufs*, we now separately count the total number of *sbufs* allocated and freed and validate that there are zero *sbufs* remaining when the main analysis is complete. Once again, this allows us to quickly identify memory leaks during development.
- We now define a clear allocation/deallocation policy for all objects in memory. Special attention has been made to implementation of C++ move operators, allowing the compiler to realize increased efficiency by using them instead of a copy and delete operator.
- Code that was `#ifdef`ed for Windows, macOS and Linux was replaced where possible with calls to the C++17 library. In particular we made extensive use of the `std::filesystem` class. The result of these changes made the code smaller and easier to validate.
- We likewise replaced many pre-processor `#define` statements with C++ inline static constants whenever possible. This makes the values available to the debugger, and makes the code easier to understand.
- We eliminated global variables used to track state. The only use of global variables that remain are static tables that are used for the precomputed value of CPU-intensive functions. The code that uses these variables now checks to verify that they have been initialized and throws an exception if they have not. Essentially, they are now singletons. It would be nice to change the memory protection of these variables to read-only, but that cannot be done in a portable manner and would require that the variables have their own memory pages.
- In many cases we have removed return codes that must be checked to detect errors. Instead, we use the C++ exception mechanism to signal and catch error conditions.
- BE1.6 used `gcc` compiler intrinsics for atomic increment in some locations, but made broad use of mutexes to protect variables shared between threads. In BE2 we have eliminated many explicit mutexes and
replaced them with the C++ `std::atomic<>` template.

- We removed the legacy POSIX `getopt` processing and replaced it with `cxxopts`[25], a command line option processing module that is reentrant and does not make use of global variables. This was necessary to allow unit tests that tested the option processing.
- We enabled all compiler warnings, not simply those enabled with `-Wall`.

The results of these changes:

- The BE2 configuration script now runs in 16 seconds on our reference Mac mini, instead of 25 seconds for the BE1.6 configuration script. This is not a significant improvement for users, but it is for BE developers. The compile time for both is 32 seconds using `make -j12` on the 6-core system.
- We were able to reduce the C++ code base by roughly ten thousand lines, or 17%, even accounting for the lines we added for the new unit tests. The program is now roughly 46 thousand lines of C++ and GNU flex code.

3.3. Dynamic Analysis with Unit Tests and Test Coverage

As hinted above, despite widespread use, BE lacked a modern approach to testing. Specifically, the BE codebase was devoid of systematic unit tests. Instead, there were test programs that were occasionally manually run from the command line for comparing the output with results of a previous run: if more features were extracted, the program was not obviously broken.

We implemented unit tests for all levels of the BE source code. We reviewed the list of C++ unit test frameworks on Wikipedia and chose Catch2[26], which has support for test scaffolds, implements a minimal CLI, can test for the presence (or absence) of thrown exceptions, and appeared to be well supported and maintained.

We also enabled AddressSanitizer [27] by default on our development system. (We enabled ThreadSanitizer[28] and found several thread sharing errors, but we also encountered a false positive due to a conflict between one of its heuristics and our multi-threading paradigm, preventing us from leaving it enabled by default.)

We started with unit tests for the `be2api` framework. We generally wrote unit tests as the new interfaces were designed and implemented, combining the creation of each new test with related refactoring. We decided to track and systematically increase the code coverage of the unit tests. We used the popular CodeCov.io website to display the code coverage of the unit tests.

Creating code coverage reports for C++ was straightforward: we re-ran `./configure` specifying additional compiler flags and libraries, then run a post-processing tool after the unit test runs, and finally run CodeCov’s script to upload the report to the website. After we got this working, we then integrated it with GitHub’s “Actions,” so that the unit tests would automatically be run and coverage reports uploaded after every commit to GitHub or pull request.

After all of the new and refactored code had unit tests, we examined the code coverage reports to determine which pieces of legacy code were not covered by the newly written unit tests. We established a target code coverage of 60%. In some cases, legacy code was covered by the new tests, because the new code called the old code. But for roughly two thirds of the code, there was no coverage by unit tests. For this legacy code, at first writing unit tests seemed largely like a compliance exercise—after all, BE had been in use for more than a decade, so we thought that all of the significant bugs, such a memory allocation errors, off-by-one errors, and so on, were gone from the code base. However, the act of writing the unit tests forced us to clarify internal documentation, simplify internal implementations, and in some cases we were able to eliminate legacy code that was no longer being used. To paraphrase the immortal Steve Jobs, the most reliable piece of code, the piece of code that you never need to test, is the line of code that you don’t write—or in this case, the line of code that you remove from your legacy programs. In total, more than ten thousand lines of C++ code was removed between BE1.6 and BE2.

3.4. Removing Functionality

In addition to removing experimental functionality, we improved performance of BE by disabling some functionality that would normally never be executed. In some cases the functionality can be re-enabled with command-line switches; in other cases it cannot.

Functionality that was disabled includes:

- We added flags to the description of scanners so that specific scanners that look for in-memory artifacts or disk-based artifacts will never be called to process the results of the majority of scanners that initiate a recursive reanalysis. For example, it makes little sense to look for NTFS directory entries in a decompressed gzip stream—acknowledging that this means we will not scan for filesystems on gzip-compressed disk images.
- By default, we now disable the hiberfile scanner (xpress decryption), because we lacked test vectors that could be used to demonstrate the correctness of our implementation, and because Windows may no longer be using the compression algorithm that we have implemented.
- We disabled (by default) scanning for 192-bit AES keys in memory, because in practice AES is rarely used in its 192-bit mode.
- We disabled (by default) xpress decompression, as other algorithms are now used to compress swap memory.

All of the features that are disabled by default can be re-enabled with a command-line switch.

We also removed key functionality from the tool that we had determined was not being used:
• We used internet search engines to see if some of the program’s more obscure command-line options are being referenced in open source programs, scripts, or even on blog entries that provided tutorials for using BE. Obscure options that were unused by the user community were eliminated.

• To the best of our knowledge, no one (other than the original developer) ever used BE’s shared library to let the program’s scanner system be called from C++ or from Python, so we dropped support for that. (It could be trivially added in the future.)

• The stand-alone BE test program that only scans a single file was dropped as additional code that did not need to be maintained. Instead, we now have the unit tests.

• The ability to load scanners as shared libraries at startup has not been updated for BE2, although this update is trivial and will be implemented if users request it.

Finally, we moved the BE2 Java user interface out of the BE repo and into its own that has the BE repo as a sub-module. While the Java GUI runs just fine with the BE2 engine, the build system has changed significantly. Moving the Java GUI into its own git repo allows us to better isolate the two build systems.

3.5. Incompatible Changes

Despite our efforts to retain full compatibility between BE1 and BE2, we needed to introduce a few minor incompatible changes were required in the interest of correctness and modernization:

• BE feature files are utf-8, but some of the information in them is binary and must be escaped. In BE1 non-Unicode characters were present and escaped in octal. In BE2 non-Unicode characters are escaped in hexadecimal.

• A persistent problem is how utf-16 features should be represented in the utf-8 feature files. BE1 presented UTF-16 as octal-escaped values, which was hard to read. BE2 converts utf-16 into utf-8 in the second (“feature”) column, but leaves the features as (escaped) utf-16 in the third (“context”) column.

• BE2 properly reports the start of features that are within ZIP-decoded data blocks, (see §4 for a detailed discussion).

• BE1 computed the MD5 hash code of forensic media that it processed; BE2 uses SHA-1.[29]

3.6. Performance Tuning

Despite the effort to eliminate all memory copies, an interim version of BE2 was dramatically slower than BE1.6. For example, scanning the 2009-domexusers[10] disk image on a 6-core Mac mini required approximately 10 minutes with BE1.6, but took 70 minutes with the development version.

BE has long had the ability to measure each scanner’s contribution to runtime. Specifically, it keeps counters (in std::atomic<> variables) of how many times each scanner is called and how many nanoseconds it spends executing. These counters became more accurate in BE2.0, with the decision to queue the recursive processing of sbuf’s longer than 4K to another thread. Looking at these counters we saw that just three scanners (rar, net, and aes) were responsible for the vast majority of the time spent scanning.

Each of these scanners has a hand-coded loop that scans through the memory image looking for a magic number. The loop had been implemented making a new sbuf for each location. Analysis of a 2GB disk image required creating over 3 billion sbufs! The first improvement we made was to implement the validator so that instead of validating the first position in the sbuf, it would take an offset. This eliminated the need to create a new sbuf for each offset. (Creating new sbufs is cheap, but not free!) Once the magic number was found, a new sbuf was created, so as to take advantage of the algorithmic simplification. Additional improvements were realized by moving the search for magic numbers into the sbuf implementation itself, so that it could be performed with memchr.

Once these changes were made, the rar scanner was no longer the slowest. Now the slowest scanners were net, aes, and the flex-based scanners email and accts (but not the other flex-based scanners, curiously enough). More than a month was spent going through these scanners line-by-line in an effort the determine the precise C++ statements responsible for the slow-down. The end results is that BE2 is now substantially faster than BE1 in all cases (see Table 1).

4. Validation

“A program that has not been specified cannot be incorrect; it can only be surprising.”[30]

We performed two kinds of validation on BE2: correctness and throughput. For correctness, we wanted to validate that BE2 produced results that were as good as the results of BE1. For throughput, we wanted BE2 to be at least as fast as BE1.

4.1. Correctness

When we found differences between the output of BE1 and BE2, some were cases in which BE2 was correct. In these cases, it appeared that the BE1 output had never been validated in detail. Most of these had to do with the location of recursively-analyzed features in the feature file.

For example, the BE forensic path 456536-ZIP-1255117 is read to mean that there is a feature that is located 1255117 bytes into an inflated ZIP stream that is itself located 456536 bytes from the beginning of the disk image. With the disk image nps-2010-emails[10], BE1 reported the ZIP stream beginning at 456536, but BE2 reports the same ZIP stream beginning at location 456596. The 60-byte difference is the result of the ZIP header. BE2 correctly reported that the ZIP stream began at 456596 because the address was tracked automatically by the revised
memory allocation routines that tracked the location of the sliced buffer that was handed to the decompressor. In BE1, the address was computed with explicit code, and that explicit code (rightly or wrongly) reported the location of the ZIP segment header, rather than the ZLIB-deflated stream. (See figure 1)

We discovered this specific error writing a unit test to test the forensic path printer—the part of BE that reads a forensic path and provides a hexdump of the contents of the evidence so indicated. Although this code had been in use for more than 10 years in the BE GUI, apparently it had never worked properly for the ZIP scanner, and none of BE’s users had ever reported it not working. (The GZIP scanner reported forensic paths correctly.)

Many of the code paths in the BE1 code base were painstakingly developed on specific test cases, but those test cases were not added to the code base as unit tests. For example, the net packet scanner[31] could carve IPv4 and IPv6 packets as well as recognize in-memory TCP header structures from Microsoft Windows memory dumps. The part of the scanners that accessed raw memory also received significant rewrites to go through the new sbuf API. We then wanted to validate that the rewritten scanners had the same functionality as the old ones. The only way to do this was by assembling specific test cases for each data type—and adding them to the code base. This is something that wasn’t done originally. Those test cases are now parts of the BE code base and the code is validated on every commit. This turned out to be invaluable for maintaining correctness during the performance tuning efforts described in the next section.

4.2. Throughput

It is straightforward to measure the speed with which BE processes a disk image or other form of electronic evidence. Explaining variations in speed is significantly harder. The time that BE spends processing evidence is highly dependent upon the contents. A disk that contains many compressed archives will take longer to process because each compressed run of bytes will be decompressed and recursively re-analyzed. A disk that is filled with JPEGs will analyze quickly, but if carving is enabled (the default), each JPEG will be copied off. (However, if carving mode is set to 2, only the JPEGs that had to be decompressed or otherwise decoded—the JPEGs typically missed by other carving tools—will be copied.)

BE also incorporates many techniques to discard data before applying the full recursive analysis. For example, duplicate data is typically not analyzed a second time. Likewise, pages that consist of a repeating n-gram (e.g. ABCABCABC...) will not be analyzed. Scanners contain flags in their metadata that determines if such analysis is desired.

Another factor in performance is the computer on which the program is run. The number of CPU cores, the amount of RAM, the speed of that RAM and the speed of the I/O system all impact throughput. And all of these factors interact with the evidence under examination: a disk image that has a lot of blank and repeated sectors will benefit more from a faster I/O system, while a disk image with a lot of complex data structures will benefit more from additional cores.

Therefore, throughput and benchmark results in general are best reported using evidence that is ecologically valid[32], such as an actual disk image. Although such media are commonly used in software development and in internal benchmarking, these media tend not to be publicly released due to privacy reasons.

In Table 1 we report the performance of BE1.6 and BE2.0 with three reference disk images from the DigitalCorpora collection, running on three different reference computers. The disk images are nps-2009-ubuntu, a 2.1GB disk image of a bootable USB drive running Ubuntu Linux; nps-2009-domexusers, a 42GB disk image of a Microsoft Windows system that was used by several individuals in a lab, and nps-2011-2tb, a 2.0TB disk image containing the entire GovDocs1 corpus and several other of the DigitalCorpora reference disk images. All were made at the Naval Postgraduate School between 2009 and 2011 and are hosted on the DigitalCorpora website.

We report performance using three Apple Macintosh computers. Both BE1.6 and BE2.0 were compiled on the computer on which the benchmark was run with the current LLVM compiler provided by Apple. All compilation was done with --3, with both AddressSanitizer and ThreadSanitizer disabled. We report BE1.6 and BE2 with the
default analysis. In this configuration 30 scanners are enabled for BE1.6 but BE2 disables hiberfile and AES192 key searching. For this reason, we also report BE2 with the BE1.6 configuration. As can be seen, BE2 is faster than BE1.6 in nearly every case, although the speedup is more pronounced on the faster, more modern hardware with more cores.

5. Recommendations and Future Work

This multi-year exercise shows the value of updating tools that appear to be working and bug-free to use current software engineering practices. We recommend a scrub of all modern digital forensics tools, as rewriting these tools will likely make them faster and more reliable.

Reading Stroustrup’s book was time consuming preparation for this project, but well worth the investment. We experienced a similar benefit from reading the entire Python reference manual prior to embarking on a large-scale Python project. We recommend detailed reading of all developer documentation for implementation languages and tools. Organizations investing in digital forensics research and tools should also be prepared to invest for the long-term, to provide for maintenance, adaptation, and growth of promising tools, as well as focused attention for developers.

We were stunned by the improvement in code quality that came from the pursuit of 60% unit test code coverage. We were also surprised by the power of AddressSanitizer in finding a wide variety of bugs. We recommend adopting test-driven development\[33\] and test-driven refactoring\[34\] as a primary tool, and always enabling AddressSanitizer during the development process.

The dramatic speed of C++ compared to Python is a clear incentive to use this language for speed-critical applications. However, given the lack of C++ programmers in the digital forensics community, it is clear that BE requires an interface to allow Python scanners to be called. Because Python is not thread-safe, a separate Python interpreter will be required for each analysis thread. We recommend using C++ with well-designed classes to provide memory safety, and providing Python-based APIs to access their functionality.

We achieved a 61% code coverage for the be2-api but only 47% for the BE2 code base (excluding the API). Clearly there is still room for improvement here.

Finally, the increased use of filesystem-level compression and encryption, combined with the use of the TRIM command on SSDs, means that the bulk data analysis of raw storage devices is likely to yield less data in the future than a systematic extraction of bulk data from resident files. That is, running BE2 with the -r (recursive) option on a mounted file system may one day yield more useful information than running it on the raw device. Ideally it would be possible to run BE2, keep track of the sectors that were scanned, and then process the remaining sectors raw. Another approach would be to perform two passes: one of the mounted files, and another of the raw device. Evaluation of these strategies is left as future work.

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