

# *Practical Testing of a C99 Compiler*

## *Using Output Comparison*

Access Systems Americas, Inc. (formerly PalmSource, Inc.)  
1188 East Arques Avenue  
Sunnyvale, CA 94305-4602  
Attn: Flash Sheridan  
Quality Lead for Compilers  
Tools Quality Assurance  
*flash@pobox.com*

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## Abstract

A simple technique is presented for testing a C99 compiler, by comparison of its output with output from preexisting tools. The advantage to this approach is that new test cases can be added in bulk from existing sources, reducing the need for in-depth investigation of correctness issues, and for creating new test code by hand. This technique was used in testing the PalmSource Palm OS® Cobalt ARM C/C++ cross-compiler for Palm-Powered® personal digital assistants, primarily for standards-compliance and correct execution of generated code. The technique described here found several hundred bugs, mostly in our in-house code, but also in longstanding high-quality front- and back-end code from Edison Design Group and Apogee Software. It also found eighteen bugs in the GNU C compiler, as well as a bug specific to the Apple version of GCC, a bug specific to the Suse version of GCC, and a dozen bugs in versions of GCC for the ARM processor, several of them critical.

Keywords: Compilers, program testing, correctness

## Introduction

The most time-consuming part of creating tests for a compiler is writing new code for new test cases, and deciding whether these cases should pass or fail, which requires detailed language-lawyer skills. This paper presents a simple technique for avoiding such effort in a large number of cases, provided that an existing tool or tools are available for comparison of output.

The basic insight is that different compilers are likely to have different bugs, and so bugs in one compiler are likely to result in output which differs from another compiler's for the same input. The preexisting tools do not need to accept exactly the same language as the tools under test, nor run on the same platform. Nor does their quality need to be perfect, though bugs in the preexisting tool are likely to look initially like bugs in the tool under test.<sup>1</sup> All that is required is a substantial overlap between

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<sup>1</sup> Indeed, the compiler under test incidentally found four bugs in GCC [1, GCC]. Testing of our assembler using these techniques found five bugs in the ARM assembler and/or its documentation.

the two tools, and a reasonable level of quality in the reference tools. Two forms of output need to be distinguished here: for simple tools (such as an assembler) comparison of the output of the tool itself with the output of the reference tool may suffice. For a more complex tool, such as a compiler, it is instead generally necessary to compare the output which results from executing the output of the tool.

The techniques presented here were developed for testing the PalmSource Cobalt ARM C/C++ embedded cross-compiler, part of the Palm OS Developer Suite for Windows [2, Palm OS Developer Suite], used to build applications for personal digital assistants running Palm OS® Cobalt [3, Palm OS® Cobalt]. (Very few devices running Cobalt were released; PalmSource switched to the Linux platform soon after testing of this compiler was completed.) The main goal of testing was ensuring the correct execution of the machine code generated by the compiler; the secondary goal was conformance to language standards and our own public documentation. The two reference tools used for output comparison with the PalmSource compiler chain were the Gnu C Compiler [4.5=1, GCC] in C99 [4, C99] mode (primarily version 3.3, with occasional reference to 3.4 later in the project), and the ARM ADS [5, ADS] 1.2 assembler. PalmSource's compiler used licensed code from Apogee Software [6, Apogee] for the back-end, which in turn used a front-end from the Edison Design Group [7, Edison Design Group]. A licensee of Apogee's code needs to provide additional target-specific compiler code, plus an assembler. The focus of PalmSource's testing was on our own new code.

The tests found three hundred and fifty-three bugs in our compiler, mostly in the code we had written in-house, but also found bugs in Apogee and Edison code. Both of the latter are long established and well respected, which suggests that compiler vendors could profitably use the simple techniques presented here. Of course, this technique presents some risk of missing bugs which occur in identical forms in both the reference compiler and the compiler under test. No testing strategy for a commonly-used language is likely to eliminate all bugs, and such bugs, at least, are unlikely to be very prominent, since corresponding bugs presumably shipped in a known product of reasonable quality.

During the course of this project, at the insistence of PalmSource's third-party developers, official support for C++98 [8, C++98 ISO/IEC] was added to the product. Additional testing for C++ was handled by a different tester, so this article largely focuses on C99 testing, though of course much of the test-

ing for C99 also applied to C++ code. Since the completion of this project and PalmSource's switch to Linux, we have been using the tools discussed in this paper in reverse, testing various versions of GCC by comparison of its output with our own compiler.

The techniques presented here are a supplement to existing test suites, not a replacement. GCC has its own test suite, which is discussed below; obviously making use of it, if practical, would provide valuable testing. But the simple techniques presented here found bugs missed by GCC's testing, in the Gnu [9, GCC Bug Database, bugs 15549, 15642, 21613, 21659, 22508, 22603, 22604, 23089, 23118, 23125, 23223, 23225, 23307, 24075, 24322, 26774, 26818, 26865, 27829, 27851, 27881], Apple [10, Apple Bug Database bug 666675], Suse Linux [11=9, GCC Bug 23472], and ARM [12=9, GCC bugs 24075, 24322, 27829; 13, CodeSourcery arm-gnu mailing list messages 346 and 381; CodeSourcery bug database bugs 401, 440, 444, 456, 458, 502, 726] versions. GCC's test suite is extensive and complicated; I believe that these results show that simpler testing for it would be worthwhile as well.

Commercial conformance suites are also available, and any organization undertaking to produce a compiler would be well advised to purchase one, but a nondisclosure agreement precludes discussing the limitations of the test suite which PalmSource used. Any new compiler will require validation well beyond mere conformance testing; the obvious temptation is to try to write all such cases oneself, deciding *a priori* what the results of each case should be. This cannot be avoided entirely, and writing some high-level language feature tests in-house is likely to be important, but this should be done only where writing new code is truly necessary, generally for features specific to the new compiler.

### General Considerations on Compiler Testing

Testing a compiler is, above all, a software testing endeavor; two of the standard works on testing are [14, Kaner et al] and (though much of it is from the mainframe era) [15, Beizer]. Given the complexity of the system of which a new compiler is likely to be a part, the conventional wisdom applies even more than usual: First, ensure that there is an adequate specification for the entire toolchain of which the compiler is a part, *before* testing starts. Second, ensure that the high-level specification matches real-

ity. Much more than user-level software, the quality of a developer tool is largely determined by the correspondence between the public specification and the actual behavior. There will be many compiler bugs which can be resolved just as well by changing the documentation as by changing the behavior. Such issues are surprisingly easy to miss, since they can be taken for granted by all of those familiar with the project from its early days.

Therefore, test breadth-first, not depth-first. It can be very tempting to test an interesting detail in depth, but in our experience, this sometimes led to missing much higher-level and more obvious bugs, which would have had a more severe impact on end users. More generally, it is woefully common in software testing to spend a great deal of time on difficult tests, finding obscure bugs, while missing more obvious and important ones. This phenomenon suggests an important law of quality assurance: *Nothing is ever too obvious not to need systematic testing.*

Three of the major compiler testing variables are optimization, debug information in the output code, and debug checking within the compiler itself. A good compiler will have a debugging version which double-checks itself as it compiles, terminating with an assertion failure if something goes wrong (GCC activates this when it is built with the `--enable-checking=all` option). Testing such a version can be extremely useful; especially for a cross-compiler, it is much easier to elicit bugs via a compile-time abnormal termination than through run-time incorrect execution. Note that this is distinct from debug *output* produced by the compiler; most compiler vendors ship a non-debug version of their compiler (though a preliminary limited release of a debug version is a good idea, and testing with it internally is crucial), but even the release version of the compiler must be tested for the production of debug output.

Rather unusually for quality assurance, crashes for a compiler are relatively benign, at least compared to execution-correctness bugs. A compiler crash or assertion failure affects only the programmer, and will be immediately obvious to him or her. The programmer may be able to work around the problem, and if the problem is reproducible, it will probably be straightforward to fix the compiler. In our experience, such crashes usually occurred, at least after the initial testing, when exercising relatively obscure compiler functionality, and hence were unlikely to affect a large number of programmers.

A code-correctness bug, on the other hand, may not be immediately apparent to the programmer. Ideally it will be noticed by testers, but it is possible (especially if the bug occurs only at high optimization) that it will only be noticed by end users after a product built with the compiler has shipped. This could require a recall of products built with the buggy compiler and sold to a large number of end-users.

As well as testing with both debug and release versions of a compiler, testing is required for the production and omission of debug output, and various levels of optimization in generated code. Any given compiler test could theoretically be run at all combinations of optimization level and debug output.<sup>2</sup> In our experience, when time was short, the most useful option was to test with full optimization, and either of the debug-output options. A better compromise was to test with all three debugging options, and with minimal and maximal optimization, making six combinations. Bugs specific to other cases were quite rare, though there were a few files which produced warnings only at intermediate optimizations. This was not a bug, though it initially looked like one: The compiler simply didn't notice the issue without optimization, and at the highest optimization, greater analysis revealed that what looked like a potential uninitialized reference could in fact never happen.

### *I: Compiler Acceptance/Rejection/Crash Testing*

The first, and simplest, technique is testing simply for correct compiler acceptance or rejection of individual source files. (A related issue was the issuance of warnings.) This had the side benefit of crash testing the compiler, especially at high optimizations, which turned out to be more valuable than the acceptance/rejection testing. The key observation was that, while GCC's C99 support was not perfect, any C file which it accepted in C99 mode, and which our compiler also accepted without optimization, was likely to be a valid test case. Any file which both compilers rejected was likely to be a valid rejection test case.

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<sup>2</sup> Our compiler had five levels of optimization and, in addition to the usual options to produce debug output, or to produce no debug output, a third option which produced debug output, while still allowing the inlining of functions.

A fortunate circumstance was that GCC also ships an extensive test suite, the GCC C-Torture Test Suite [16, GCC C-Torture], with a large number of test source files. Many of the C files were not valid C99; the most common problem was failure to prototype a function or to include the header for it, most frequently `printf`. However, there were over a thousand files (slightly more than half of the total) which were valid C99, and accepted both by GCC in C99 mode and by our compiler.

It was straightforward to write a Perl script which recursed the entire C-Torture source hierarchy, recording which files were accepted by each compiler, and which were rejected. An *ad-hoc* script indicated which files were supposed to be rejected (or to generate warnings), by moving them into appropriately-named subdirectories. The files on which GCC/C99 and our compiler (without optimization) agreed, were checked into our source repository. A second Perl script then recursed over the checked-in files, calling our compiler at every optimization and debug level, on each supported platform, for each build.<sup>3</sup> This found a few unexpected acceptances (or rejections) at higher optimizations, or on different platforms; normally acceptance should not be affected by optimization, and cases in which this happens deserve investigation. One such case turned out to be a genuine compiler bug; another case involved a linker error caused by an undefined reference, which was optimized out of existence at higher optimizations. A number of third-party source files showed such discrepancies without revealing bugs, most frequently because of invalid assembly code, and less frequently because of code explicitly conditionalized on optimization. (There is an additional possibility with some versions of GCC, which will reject some invalid code, e.g., taking the address of a cast expression, only at higher optimizations.) The greater benefit of this technique was compiler crashes or debug errors at higher optimizations. The GCC C-Torture files were very good at eliciting such bugs, but once the technique was set up, it was straightforward to add additional files from other sources, such as sample code available on the web, or the source files for Palm OS®. In one instance, we made a test case out of a complaint from a language purist in an internal chat room, who was annoyed that a rival compiler was willing to accept obviously non-standard code.

This machinery could also be applied for crash testing with arbitrary C/C++ code. This simply required pointing the recursive script at a directory of source code, and disregarding the accept/reject results, focusing solely on reported crashes or debug assertions. Open source projects were a good source of C/C++ source files for crash testing. We recursed over the source for Cygwin [17, Cygwin], Perl [18, Perl], Blitz++ [19, Blitz++], and GCC [20=1, GCC], as well as our internal source tree, but the most fruitful source of compiler crashes and errors were GCC C-Torture [21=16, GCC C-Torture] and the Boost C++ libraries [22, Boost]. Once a crash is found and reproduced, a tool such as Delta [23, Delta; 24, Zeller] should be used to reduce the code necessary to elicit the crash; this is especially important if the bug is to be reported publicly, but the code causing the crash is confidential. A Windows runtime check also found an uninitialized variable when the compiler was trying to compile itself; this is not a realistic test scenario for an embedded compiler, but turned out to be an interesting stress test.

Execution-correctness testing (covered in the next section) for such projects would have required getting them to execute under Palm OS, which would have been a significant engineering effort. Crash testing during the compilation phase is a cruder and easier technique than testing run-time execution, but given effective debugging checks in the compiler, can be surprisingly effective. One of the more interesting crashes found by this technique occurred only at optimization level 2 or higher, compiling the GCC C-Torture file 20010404-1.c, whose source code is below. Coincidentally, this file was added to the GCC test suite because it caused a crash in GCC at the same optimization level. The bug in our compiler was that constant-folding optimization asked the host processor to do arithmetic without checking the arguments for validity. This converted a run-time error (which is acceptable for invalid arguments) into a compile-time crash, which is not. More generally, dividing the most negative value of a signed integer type by -1 is a fruitful source of bugs, since it will overflow if integers are represented in twos-complement form.<sup>4</sup>

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<sup>3</sup> For non-milestone builds, the recursion was limited to the highest and lowest optimization, since we had very few bugs which happened only at intermediate levels of optimization, but many bugs which occurred only at the highest optimization levels.

<sup>4</sup> [25, Harbison & Steele], page 228.

```
#include <limits.h>

extern void bar (int);

void foo ()
{
    int a = INT_MIN;
    int b = -1;
    bar (a / b);
    bar (a % b);
}
```

Figure I: GCC C-Torture file 20010404-1.c

Note that the compile-time performance of arithmetic, which here elicited a bug, can also mask problems. When testing run-time operations, it is often necessary to mark variables as volatile, to prevent optimization from removing an operation from the generated code.

## II: Emulated-Execution Output Correctness Verification

Our principal technique for validating correct execution of generated-code used the output from a cross-platform desktop ARM emulator, based on an open source ARM emulator [26, ARMulator] but with significant in-house modifications. (Note that this is the second form of output correctness validation mentioned above: verifying the correctness of the output from the execution of the output of the compiler.) Some such emulator is useful for testing a cross-compiler targeted at an embedded device, though ours had significant limitations: Its runtime environment was fundamentally different from a real device's, which allowed the possibility of device-only compiler bugs. (It also lacked a graphical user interface, which precluded its use by application developers, but was less of a limitation for compiler testing.) If at all possible, anyone involved with a cross-compiler should insist on the importance of an emulator whose runtime environment (and, preferably, graphical user interface) matches the actual product closely. Even a limited emulator, however, was useful for broad coverage of basic code-correctness issues, using any available standards-compliant source code.

The method for taking a standards-compliant source code file, and converting it to a code-correctness test case, was simple but limited. Once a suitable source file was identified, a Perl script called GCC on the source file, and then ran the resultant desktop native executable. The script captured the output, and appended it to the source file, wrapped in comment markers. Once the file was supplemented with its expected output, and added to the test list, a different script would call our compiler on it (at some or all optimizations). This script would then run the executable under the desktop emulator, comparing the actual output to the expected, and reporting the first difference if the output was not as expected.

One advantage of the simplicity of this approach to compiler testing is that a wide variety of source files are suitable for execution comparison testing. Provided only that a file's main purpose was to write to the standard output, and it was careful about including the standard headers it required, and did not rely on anything outside the C99-mandated libraries, then it was a plausible candidate for addition to the test suite. Some source files' output depended on platform-specific details, such as the size of data types. This could be a serious difficulty for testing a multi-target compiler, but since our compiler had only a single target, it was usually straightforward to work around. Somewhat surprisingly, Macintosh

OSX [27, Macintosh OSX] turned out to be the most convenient desktop environment for generating output for comparison, as its run-time environment had much in common with the ARM Application Binary Interface [28, ARM ABI] which we were targeting.

A source file can even be useful if it only prints on failure, as long as its error reporting is reasonably specific. Specificity of failure reporting is even more important than usual for compiler correctness testing: At all but the earliest stages of development, a large majority of apparent test failures are likely to be bugs in the test rather than in the compiler.

A more advanced technique was to generate standard-compliant C99 or C++98 code automatically, using Perl. A script rotated through a list of constants of the principal arithmetic types, producing a source file for each of a list of operators, printing out the result of the operator for each pair of constants. The initial intent was to choose one number from each test case equivalence class,<sup>5</sup> but this quickly generated impractically large files for binary operators, so a somewhat arbitrary subset of numbers which seemed likely to elicit bugs was used instead. This found only a single bug in our compiler, which had already been found by test code generated from the documentation; the low bug count was probably because this code was primarily testing high-level code paths implemented by Edison and Apogee. It also found two bugs in Gnu GCC [30=9, GCC bugs #15549 and #24075], one bug in Suse Linux's version of GCC [31=9, GCC Bug 23472], and five bugs in CodeSourcery's version of GCC for the ARM processor [32=13, CodeSourcery; 33, CodeSourcery 2005Q3-2 Release announcement, issues 1 & 3]. This technique also elicited some unfortunate behavior on reasonable but out-of-spec code [34=9, GCC bug #16031], converting a floating-point number to a long long integer. The last issue showed the need to exclude out-of-spec code from being generated. Doing this in full generality would have required evaluating C expressions in Perl, but simple tweaking of the lists of constants, plus some special-case exclusion code, sufficed for our purposes.

This comparison technique also made it simple to validate manually-created expected output. A particularly fruitful approach was to take tables of constants from the public documentation, and massage them in a text processor into both print statements and expected output.

This technique provided reassurance that optimization, debug information, host platform, and endianness issues did not affect code correctness, at least under emulation. It found gratifyingly few code-correctness bugs, mostly in the desktop emulation environment. Given the criticality of any code correctness issue in a widely distributed compiler, testing like this is important even if it finds few of the bugs it targets. It found considerably more compiler crash or debug-assertion failures; as previously noted, these (though serious) were considerably less threatening than code-correctness bugs. One of the most interesting code-correctness bugs this technique found was the above-mentioned bug in GCC [35=9, GCC bug #15549], though our script initially reported it as a bug in our compiler. The symptom was that the (admittedly rather odd) arithmetic comparison “true < 'a'” returned false rather than true. This comparison was part of a large number of automatically generated operations, mentioned above. The underlying cause was that GCC used a simplified implementation of the “less than” operator when one of the arguments was a Boolean value, which was invalid unless both operands were Boolean.

The following were useful sources of standard-compliant code for emulated execution: C-Torture [36=16, GCC C-Torture] has been mentioned above; all of its files were useful for crash testing, and a subset were C99-clean and useful for execution testing using our framework.<sup>6</sup> Lindig’s Quest test system [37, Lindig] was a good source of clean code for argument-passing tests, though it fortunately failed to find any bugs in our compiler, presumably due to the quality of Apogee’s and EDG’s code; it has found a number of bugs in other compilers, and is recommended for new compiler testing. Tydeman’s mathematical tests [38, Tydeman] and the Paranoia floating point test suite [39, Kahan et al.] were useful for testing compiler correctness, though their focus is more on the mathematics library than on the compiler. The source code for the O’Reilly *C++ in a Nutshell* guide [40, Lischner] has a number of useful C++ tests. The STLPort [41, STLPort] self-test was a very good test of the compiler in general, without needing any of the machinery presented here; it tests run-time correctness as well as compile-time ac-

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<sup>5</sup> [29=14, Kaner et al.], page 125–132.

<sup>6</sup> Actual usage of the C-Torture suite framework itself was impractical for our compiler testing, not because of problems with the GCC suite itself, but because of problems with the underlying framework, DejaGnu. [52, DejaGnu bug mailing list message 2006-02/3 et al.]

ceptance of valid code. STLPort is an implementation of C++ standard libraries, but it exercised portions of the compiler which were relevant to both C and C++.

lcc [42, lcc; 43 Fraser & Hanson] ships with a test suite containing approximately seven thousand lines of new code, not counting the Paranoia suite, which the suite also includes. The most notable test is a file designed to have one test case for each section of the language specification in [44, Kernighan & Ritchie]. Unfortunately the test code relies on behavior deprecated in ANSI C, and will be rejected by a strict C99 or C++98 compiler; it can be useful, however, for testing a compiler which can accept old-fashioned C. SDCC [45, SDCC] includes approximately eight thousand lines of test code; the bulk of the source files are reasonably portable; but some crucial included code is highly non-portable, and would need to be adjusted to run on another compiler, and the error reporting is extremely terse.

#### Device Execution Correctness Testing

Code-correctness on an emulator is, of course, much less important than correctness on the device; but building for, and running on, the device was much more time consuming, and not subject to automation. Typically we ran the emulated execution script for each build on each supported platform, at the highest and lowest optimizations, with tests at all optimizations for major milestones. The latter took more time, though since it could run unattended, this was not a major concern.

Converting the test code to run on the device required another script and substantial manual intervention. The script iterated over the test list, skipping special cases and expected failures. For each test case, a series of commands was generated to copy the source file from our source control system to the directory for the device application. A second iteration of the script then searched the source file, conditionally changing the definition of "main()" to a unique name based on the source file name. Three other files were also generated: a header file with declarations of all the former mains, a source file which called all of the renamed mains in order, and a concatenation of all the files' expected output.

Considerable manual intervention was required, especially for C files, to avoid name collisions. C++ files could use namespaces to avoid these (name collisions for classes had been particularly difficult to diagnose), but C files often required the manual addition of "static" to function definitions to avoid

collisions. For C++ streams, additional care was necessary, since an I/O manipulator, whose effect was restricted to a single file in the desktop test scripts, would affect all subsequent C++ files in the combined executable. Once built, the application was run on the device, and its output compared to the expected output. As anticipated, the device's behavior largely matched the emulator's, and hence our compiler also matched GCC's code generation. This technique found several discrepancies in our compiler's output, fortunately relatively minor. A similar approach for testing PalmSource's version of the Freely Distributable Mathematics Library [46, FDLIBM] found forty-nine bugs in our modifications, but fortunately found no bugs in FDLIBM itself. The most interesting of these bugs was that the value of `hypotf` was incorrect, due to a confusion of two registers, in the comparatively rare case that its arguments differed greatly.

### Test Harness

PalmSource makes extensive use of an internal API (Application Program Interface) test harness, which runs at least one positive and negative test for each of our publicly-documented functions. Initially this seemed promising to apply to compiler testing, but it turned out to require a great deal of effort while finding no compiler bugs. Comparing the output from the harness's execution for the largest test suite (including failed test cases), with that from the same source code using the ADS compiler [47=5, ADS], turned up only a single discrepancy in nine hundred and ninety-five test cases. This turned out to be a bug in the source code rather than a compiler problem. The test suite was relying on the value of an uninitialized variable; the code was merely fortunate with the older compiler. This outcome may be common when using a large piece of existing code for compiler testing; compiler bugs are far less common than bugs in source code which haven't been noticed yet. This insight has been expressed from a different perspective as one of Mark Jason Dominus's Maxims for Programmers: "Looking for a compiler bug is the strategy of *last resort*." [48, Dominus]

### III: Assembler Output Comparison

The third technique to be presented found the greatest number of critical bugs, but is the least general in applicability. It involved comparing the machine code generated by PalmSource's ARM assembler, with that generated by ARM's own ADS assembler [49=5, ADS]. This required writing a translator to convert the dialect accepted by ADS, to that accepted by our assembler, which was slightly different. Instructions which had no simple conversion had to be skipped, which limited the scope of the testing.

When run on a Windows machine with a valid (and expensive) ADS license, the PalmSource assembly was translated to ARM assembly, and then assembled and the relevant machine code saved. This machine code was then checked into the source control system, so that it was available on other machines, either Windows machines without an ADS license, or non-Windows machines, which could not run ADS at all. Thus when the test was run on a machine without ADS, the output of the PalmSource assembler on the local machine could be compared with the output produced by ADS on a different machine. Even simple cases found a number of incorrect code generation bugs, which surprisingly were not detected by our commercial conformance test suite. Twenty-one correctness bugs were found; none of these was of general interest, and were predominantly transcription errors in the tables of operations and addressing modes. A non-macro assembler possesses none of the interesting complexity of a compiler, but even simple transcriptions are subject to error and need to be tested.

An additional complexity was ignoring the targets of branch instructions, since ARM's assembler and ours use different relocation types. This required complicated pattern matching within Perl, run on the output of Unix or Cygwin diff. (Cygwin [50=17, Cygwin] contains, among other things, Windows implementations of some standard Unix tools, and is extremely helpful for testing on Windows, especially if cross-platform testing is useful.)

The following sources of assembly were used for comparison. The first tests were run on each of the examples in the ARM Assembler Guide [51=5, ADS]. A second round of testing contained one instance for each opcode supported by both ARM and PalmSource. A third round of testing was based on a partial list of opcodes and addressing modes provided by the software engineer working on the assembler.

A fourth round of test generation was based on the ARM Assembler Guide's language syntax definition. In retrospect, an off-the-shelf expression generator should have been used to generate random ARM assembly instructions for comparison. Instead a Perl script was built incrementally, taking each ARM instruction definition and generating instances. An advantage, however, of the incremental in-house approach was that simple substitutions detected simple bugs, and bug hunting could proceed incrementally. Some tests were run using assembly generated from the C source files. Even using only a "Hello World" program turned out to be surprisingly difficult, so testing was largely restricted to artificially-created assembly code.

### Conclusion

The techniques presented here are neither universal nor comprehensive: Some of them would need to be altered substantially for use on a different compiler; and other techniques—commercial or Open Source—would still be needed to supplement them. Variations on these techniques may be useful for other compilers, especially early on, when finding simple and easily reproduced bugs is more important than breadth of test coverage. It is worth getting simple sanity checks up and running early, long before more complicated tests are ready to run.

The technique of recursive crash testing over the complete GCC C-Torture suite is straightforward to implement, and was a surprisingly rich source of optimization bugs; it is probably worth trying for any C/C++ compiler. Acceptance/rejection testing over C-Torture requires significantly more attention, but should be practical for any compiler accepting a language close to one of the GCC options. Comparison of the output from execution of generated code with that from GCC's generated code requires substantially more machinery, and considerable harmony between the runtime of the compiler under test and that used by GCC. It may not be practical for all compilers, but it supplies a great deal of assurance about code-correctness. Assembler output comparison is useful only if there is a preexisting assembler to compare with, with a language easily translatable to the new assembler's, at least in part. It is an extremely rigorous test, however; so if any component of a tool chain can be tested in a similar manner, it should be.

Below are four tables summarizing the origins of our test cases and bugs; the numbers are necessarily approximate and somewhat subjective, since our bug and source-code databases are designed to help ship a product, not to record historical information. The test code table is skewed by the required omission of the confidential commercial conformance suite we used, as well as by the inclusion of pre-processed files, which tend to be disproportionately large, but do not necessarily provide a proportionate degree of test coverage. The absolute numbers of bugs found are not comparable between tables: The table for our compiler includes bugs found at all stages of development; the GCC tables include only bugs found in publicly-released versions.

Table I: Origins of Test Code (lines of code)

<b>Automatically Generated</b>	1,119,302
<b>Gnu Code</b>	51,660
<b>Boost</b>	302,039
<b>Other (Non-Confidential)</b>	1,170,235
<b>Total (Non-Confidential)</b>	2,643,236

Table II: Origins of PalmSource Compiler Bugs

	<b>Assembler</b>	<b>C Com- piler</b>	<b>C++ Compiler</b>	<b>Optimizer</b>	<b>Linker</b>	<b>Runtime Libraries</b>	<b>Other</b>	<b>Total</b>
<b>Compile- Time Error</b>	25	58	32	13	6	6	5	145
<b>Primary Output</b>	21	3	1		0	1	0	26

<b>Comparison</b>								
<b>Run-Time</b>	0	14	12	11	3	9	1	50
<b>Other</b>	1	53	24	6	31	4	13	132
<b>Total</b>	47	128	69	30	40	20	19	353

Table III: Origins of x86 and Cross-Platform GCC Bugs

	<b>C Com- piler</b>	<b>C++ Compiler</b>	<b>Optimizer</b>	<b>Runtime Libraries</b>	<b>Other</b>	<b>Total</b>
<b>Compile- Time Error</b>	4	7	3		1	15
<b>Run-Time</b>	1		1			2
<b>Other</b>			1			1
<b>Total</b>	5	7	5		1	18

Table IV: Origins of ARM GCC Compiler Bugs

	<b>C Com- piler</b>	<b>C++ Compiler</b>	<b>Optimizer</b>	<b>Runtime Libraries</b>	<b>Other</b>	<b>Total</b>
<b>Compile- Time Error</b>	1	1	3		2	7
<b>Run-Time</b>	3		1	1		5
<b>Other</b>						
<b>Total</b>	4	1	4	1	2	12

The most striking contrast in the above table is the relative scarcity of run-time bugs in GCC, especially cross-platform or x86-specific ones. This is not surprising, given the large number of Open Source projects which use GCC; every user of one of these projects is implicitly testing the correctness of the compiler's generated code every time he runs an executable. The relative scarcity of such bugs does not excuse not testing for them, however. As noted above, run-time correctness bugs are the most important sort of compiler bug, and it is striking that the simple techniques presented here found any at all.

It is unlikely that other compiler developers will be in our exact situation; but the more general point is to find relevant special cases for the compiler under test. Don't use only difficult techniques with general applicability; our most surprising lesson was how much useful testing could be done with simple, high-level, but implementation-specific techniques.

Anyone contemplating the release of a compiler should investigate thoroughly both the GCC test suite and commercial test suites. If an organization considers the cost of a commercial test suite prohibitive, it is probably not serious about the resources required to ship a compiler, and it would be well advised to consider re-using existing technology instead. A compiler is a vastly complicated piece of code, with a testing space far larger than normal software, and correctness standards far higher than end-user applications. There are existing high-quality compilers, as well as existing compiler frameworks. If at all possible, an organization should reuse one of them, rather than doing its own work from scratch: It is hazardous as well as inefficient to reinvent the wheel.

### *Acknowledgments*

I would like to thank the GNU community for a high-quality compiler to use for comparison, and a great deal of useful test code. This article is a small attempt to pay back some of the many benefits PalmSource has received from the Open Source community. Now that PalmSource has announced that it will be developing for Linux, we have begun applying these techniques to testing the GNU C Com-

piler itself by using the techniques presented here in reverse, comparing its results to that of our in-house compiler.

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The literature on compiler testing is surprisingly scant. There is substantial literature on the theoretical design of compilers which would provably not need testing, but the audience for such work is largely disjoint from that for the testing of compilers for widely-used languages which will have a substantial user base. There are also a number of articles on the automated generation of test code, but given that there is now a substantial base of real Open Source software, this is less useful than formerly.

This article, and our testing, was firmly directed towards shipping a high-quality, but imperfect, compiler which would be of practical use to the developer community. Producing an inherently bug-free compiler for a theoretically desirable language was not an option. The goal was to catch as high a proportion of serious bugs as possible in a useful compiler for two widely-used languages, C99 and C++98.

The best available bibliography is over a decade old, by Dr. C.J. Burgess of the University of Bristol; it was a posting to the comp.compilers Usenet newsgroups, below [53, Burgess]. Bailey & Davidson [54, Bailey & Davidson] is an academic article on the testing of function calls, somewhat similar to Lin-

dig's Quest [55=37, Lindig]; it contains the interesting observations that "the state-of-the-art in compiler testing is inadequate" (p. 1040), and that in their experience, the ratio of failed tests to bugs was approximately one thousand to one (p. 1041). The standard work on compiler theory is *Compilers: Principles, Techniques and Tools* [56, Aho et al], commonly known as the Dragon book. It is a good general introduction, but had little direct relevance to our testing, except for some extra caution in including examples of spaghetti code; other standard compiler texts which were consulted, but did not have significant sections on testing, are omitted from the bibliography. *A Retargetable C compiler: Design and Implementation* [57=43, Fraser & Hanson] contains a brief section on the authors' experience with testing their compiler, with some practical advice on the importance of regression test cases; difficulties in using lcc's regression tests for other compilers are discussed above, in the section on emulated-execution output correctness testing. An updated and alphabetized version of this bibliography will be made available at [http://pobox.com/~flash/compiler\\_testing\\_bibliography.html](http://pobox.com/~flash/compiler_testing_bibliography.html).

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