1 Abstract

This paper presents Warrior1, a tool that detects performance anti-patterns in C++ libraries. Many programs are slowed down by many small inefficiencies. Large-scale C++ applications are large, complex, and developed by large groups of engineers over a long period of time, which makes the task of identifying inefficiencies difficult. Warrior1 was designed to detect the numerous small performance issues that are the result of inefficient use of C++ libraries. The tool detects performance anti-patterns such as map double-lookup, vector reallocation, short lived objects, and lambda object capture by value. Warrior1 is implemented as an instrumented C++ standard library and an off-line diagnostics tool. The tool is very effective in detecting issues. We demonstrate that the tool is able to find a wide range of performance anti-patterns in a number of popular performance sensitive open source projects.

2 Introduction

One of the challenges of modern C++ is the ability to write performance-predictable code using high-level abstractions. The C++ Standard Template Library (STL) provides data structures such as string, vector, map, list and smart pointers. These data structures are frequently used in C++ programs. These high-level data structures abstract away the low-level details, and in many cases hide performance issues. It is often difficult to reason about the performance of C++ programs without testing the code on real inputs. It’s hard to know when the code might allocate or copy large chunks of memory. Consider the code below.

```cpp
std::vector<int> v;
for (int i = 0; i < n; i++)
  v.push_back(i);
```

The standard C++ vector represents a sequence of elements that can grow dynamically. The amortized growth cost of vector is constant. Every time the vector underlying storage grows the standard library allocates a new buffer, copies the data and deletes the old buffer. As the vector grows the buffer size expands in a geometric sequence. Constructing a vector of 10 elements in a loop results in 5 calls to ‘malloc’ and 4 calls to ‘free’. These operations are relatively expensive. Moreover, the 4 different buffers pollute the cache and make the program run slower.

One way to optimize the performance of this code is to call the ‘reserve’ method of vector. This method will grow the underlying storage of the vector just once and allow non-allocating growth of the vector up to the specified size. The vector growth reallocation is a well known problem, and there are many other patterns of inefficiency, some of which are described in section 3.4.

```cpp
std::vector<int> v;
v.reserve(n);
for (int i = 0; i < n; i++)
  v.push_back(i);
```

2.1 The long tail of performance issues

In many programs, a small number of issues have a significant impact on the slowness of the program, but there are also many issues that slow down the program each by a small amount. It is easy to identify and fix the egregiously slow parts of the code. However, it’s often difficult to identify the long list of program inefficiencies. But these issues add up and make the system slow.

Software engineers often use profilers to identify hot spots, which are areas of the code in which the program spends a lot of time. This method is very effective in finding the major performance issues. However, profilers are not good at detecting the long tail of issues. A long list of small issues produce a flat profile, where the time is spent in many different places in the program. Programmers refer to the long tail of issues as "Death by a thousand cuts". Slowness is difficult to measure because one part of the code may evict the cache, and another unrelated procedure in a different part of the code may pay the price and run more slowly. Another issue is that programmers lack an a priori expectation for how fast a function should be. If a program spends 0.3% in some parts of the code, is that a lot?
Warrior1 was designed to catch the long tail of inefficient operations that only together add-up to a meaningful performance gain. The Warrior1 tool generates detailed reports that point out the exact location in the source code where the performance issues are located. The performance report is sorted by the severity of the issue. Figure 2 brings a section of the report that was generated for the Redex project.

2.2 How Warrior1 works

Warrior1 is built like a logger that records some of the methods in the C++ standard library. A good analogy would be the description of adding a call to ‘printf’ inside every method that reallocates a vector, string or a map. Analysis of the generated log, sorted by the instance pointer, can reveal inefficiencies. Any vector instance has enough information to know that it was resized several times. Of course that this is only an analogy and the actual implementation that takes into consideration the accuracy of the report and the performance of the system is more involved.

Warrior1 has several parts. First, a compiler toolchain that contains an instrumented standard library that contains calls to one specific log function. Every constructor and destructor and some methods contain a call to the log function. The second part in the system is the logger. The logger is called from different source files in the standard library. It records the current time, a stack trace and other relevant pieces of information. The logger compresses the events, coalesces them into large packets and writes them to disk. The third piece is a reporting tool that loads the log files, analyzes them and reports a list of warnings and suggestions.

3 Implementation

This section describes the implementation of the system. Figure 3 depicts a log of a single vector instance. The numbers that follow the method names are the parameters that are passed to the logger. The logger records the size and capacity of std::vector. The last number in the listing is the stack-trace id. The timestamp is omitted from the example. It’s easy to figure out from the log that the user calls the push_back API, and increases the size of the vector and that the vector re-allocates several times in the calls to the ‘slow-path’ method.

In order to generate efficient diagnostics the logger needs to records many different pieces of information: A full stack trace that reports the caller information. Stack traces typically have dozens of entries, each one is a 64-bit pointer. The logger also needs to record a 64-bit timestamp for each method. The logger records a 64-bit ‘this’ pointer that points to the address of the instance. The logger records the name of the class (such as "vector") and a string that contains the name of the method (such as "push_back"). The logger also records three 32-bit integers with additional information about the instance. For example, the std::string destructor reports the size, capacity and hash of the string content. In addition to the per-method information the logger records the names and addresses of all of the loaded shared objects in memory to allow off-line symbolication.

3.1 Log Compression

The methods in the C++ standard library are invoked millions of times in a short period of time. A naive implementation that writes uncompressed logs on each and every event would be very slow and generate huge log files. The Warrior1 logger implements several optimizations that make the approach practical. On average method events are compressed and encoded as three 64-bit words using techniques as side tables and path compression. When writing data into a file, the program has to make several system calls to open the file, append data at the end, and close the file. System calls and file IO are very slow and the system needs to minimize the number of operations. Warrior1 reduces the number of file-system operations by writing into a local memory buffer of several megabytes. The buffer is flushed to disk when enough data was accumulated.

The logger maintains a protocol that sends commands that the analysis tool can interpret. The commands help to compress the log file and the messages that are sent. For example, one of the basic commands that the logger sends is the command ‘register string’, that contains a string literal and a key integer value. Following packets can send textual information by using the integer that was previ-
Repeatedly growing a vector (total 177,723 reallocations) in 85,571 instances. Consider reserving space when the vector is constructed.

0) 0x9bbd4b void std::vector<cfg::Block*, std::allocator<cfg::Block*> >::_M_realloc_insert/<toolchain/include/c++/10.2.1/bits/vector.tcc:441
1) 0x9fbbdd std::_Function_handler<std::vector<cfg::Block*, std::allocator<cfg::Block*> >/<redex/redex/sparta/include/MonotonicFixpointIterator.h:530
 /toolchain/include/c++/10.2.1/bits/std_function.h:292
2) 0x9c1dfd sparta::wpo_impl::WpoBuilder<cfg::Block*, std::hash<cfg::Block*> >::construct/<toolchain/include/c++/10.2.1/bits/stl_vector.h:882
 /redex/redex/sparta/include/WeakPartialOrdering.h:357
3) 0x9c2f89 sparta::WeakPartialOrdering<cfg::Block*, std::hash<cfg::Block*> >::WeakPartial/<redex/redex/sparta/include/WeakPartialOrdering.h:194

Map instance is not used as an ordered containers (in 472 instances). Consider using std::unordered_map instead.

0) 0x9ad460 IRTypeChecker::run() /redex/redex/libredex/IRTypeChecker.cpp:393
 /redex/redex/libredex/IRTypeChecker.cpp:565
1) 0xa0e67f CheckerConfig::run_verifier(std::vector<DexClass*, std::allocator<DexClass*> >, <redex/redex/libredex/PassManager.cpp:186
2) 0xa0f305 std::thread::_State_impl<std::thread::_Invoker<std::function<
 /redex/redex/libredex/Trace.h:174
 /redex/redex/libredex/WorkQueue.h:439
 /toolchain/include/c++/10.2.1/thread:264

Figure 2: Sample report for the Redex program

Ousely specified. This allows the logger to send the string 'shared_ptr’ only once in a session, and use a 16-bit integer to refer to this string in every log entry. The logger sends the following commands:

- Register a new string.
- Register a new stack trace.
- Register a new shared-object section.
- A new stack-trace event.
- A new compact stack-trace event.

Stack traces are a list of pointers that point to executable code and describe the call-stack, which is the execution context of the current function. Every entry in the call stack is a 64-bit pointer, and there are usually dozens of entries in the stack trace. The main function is usually one of the first entries in the stack trace. Saving the full call stack is important for providing readable location information to the user, but saving around 16 64-bit numbers on each method invocation is unrealistic because so much data is written. Instead Warrior1 takes a different approach to saving stack traces. The logger maintains a Trie data structure. Stack traces are inserted into the Trie, where each node represents a frame address. Each leaf node is assigned with a unique 32-bit id. The logger sends the integer that identifies the stack trace. The logger also sends a new-node registration command on the first occurrence, but these commands are sent at a much lower frequency.

The logger can send two kinds of event commands: regular and compact. The regular event command lists the relevant log fields: timestamp, stack-trace id, this pointer, etc. In some cases the logger is able to fit all of the fields into a compact command. This happens when the parameters to the logger are small values that fit in fewer bits. The STL methods often log information such as the number of elements in the container, and zero and other small values can be encoded efficiently. Over 90% of the event commands are compact event commands that are encoded in only 3 64-bit numbers. These 3 64-bit numbers represent a complete entry that describes an event such as "a shared_ptr object of address X, with stack trace Y was destroyed and the reference count was 1."

3.2 Symbolication

Symbolication is the procedure of assigning source locations to a stack trace. The Warrior1 logger records the list of loaded ELF sections and the addresses of their text sections. Addresses in the stack traces should fall within the regions of memory that represent the code section of the loaded shared objects (the actual name of the code section is "text"). The logger does not save the actual shared
objects, so Symbolication needs to happen on the same file-system on which the recording was done.

There are two methods for symbolicating addresses. Non-stripped executables and shared objects contain a list of symbols with their addresses. Tools such as "addr2line" find the symbol closest to the searched address. They return strings that represent the mangled name plus some byte offsets into the function. The second method, which is more accurate, is the use of DW ARF debug information. The debug information in the binary records more information that includes things like functions that were inlined and source code information. Warrior1 uses the LLVM infrastructure to symbolicate stack traces and present accurate stack traces with detailed source information.

### 3.3 Report Tool

The report tool is an executable that loads the log file and prints diagnostic reports. The tool is built as a simple processing pipeline with several stages. The processing pipeline starts by loading the log file from disk and reconstructing the state that was saved by the logger. The report tool builds the stack trace Trie, expands strings and builds the memory map of remote ELF sections. Next, the report tool sorts the class instances into separate buckets. This is done by creating lists of command events that are indexed by the address of the instance (the 'this' pointer). Notice that the memory allocator may reallocate new instances on previously freed addresses. In order to create an accurate picture, the log parser breaks instances into different buckets by detecting destructors. The parser uses names like 'basic_string' to figure out that the instance has been destructed and any future method calls are a part of a new instance that was allocated at the same address. The output of this phase creates data structures similar to the example in figure 3. Next, the tool detects performance issues for all of the object instances in the program. And finally the tool sorts the warnings according to their severity before printing them to the user.

### 3.4 Diagnostics Rules

The report tools implements several rules that expose inefficient patterns:

- **Short-lifetime**: the report tool detects instances that are alive for a very short period of time. This rule exposes temporary objects and objects that are created as part of temporary expressions.

- **Vector and String growth-reallocation**: this rule detects strings and vectors that grow multiple times and recommends to reserve space when the object is created.

- **Data shift**: this rule detects cases where elements are inserted into the low parts of containers and many elements are shifted.

- **Push_back of non-copyable elements**: this rule detects cases where emplace_back should be used instead of the push_back method.

- **Shrink vectors to save memory**: this rule detects cases where a vector can be shrunk in order to free the unused remaining capacity (by calling shrink_to_fit).

- **Object and Value copy detection**: a set of rules that detect passing of objects by value, and copy of heap-allocated instances that contain object members.

- **A set of rules that detect vectors that remain small and can fit in small vectors.**

- **Unique shared pointer**: a rule that detects shared_ptr that has a reference-count of 1, and can be converted to a unique_ptr.

- **Duplicate string instance**: this rule compares the hash of the string content and compares it to previously-hashed strings. This rule detects string contents that are saved many times in memory in different places.

- **Unnecessarily ordered map**: this rule detects standard maps that are not traversed in a specific order. The recommendation is to convert the instance to unordered maps that are more efficient.

- **Double-map lookup**: this rule detects the pattern of 'operator[]' after 'count', which is a common map anti-pattern.
Figure 4: Number of instances in different size-buckets in Clang-11.

Figure 5: Lifetime of object instances (log2 of number of cpu cycles) in Clang-11.

- Unused instance: this rule detects instances that are constructed and never used. We pay the cost of constructing the object but never use it.
- Shared pointers with a very high reference count.

3.5 Visualization

The information that is collected during the execution of the program allows the tool to visualize different aspects of the program. In this section we bring a few reports from open source programs.

Figure 4 presents a histogram that categorizes instances of string and vector into different size buckets. Each size bucket represents the number of elements when the destructor is called. This figure shows that most strings and vectors are relatively small (below 64 elements), and that strings are more frequently used than vectors.

Figure 5 presents a histogram that categorizes the lifetime of object instances from the C++ standard library (vector, string, shared_ptr, map, etc). The data for figures 4 and 5 was collected by tracing an execution of the Clang compiler on two large C input file (oggenc.c and sqlite.c). The X-axis represents the number of cycles between the construction and destruction of the object, in log2 representation. The chart presents both stack-allocated instances and heap-allocated instances. It’s important to remember that stack-allocated instances of containers, such as vector and string, can allocate memory dynamically.

The large number of instances that live for a short period of time present an opportunity because perhaps some of these instances could be optimized away. Some of the rules in the Warrior1 report tool were designed to detect these short-lived objects and report them to the user.

Figure 6 presents a histogram that categorizes instances of shared_ptr by the highest reference count that was observed for each instance while tracing a program from the libtorrent library.

Figure 7 presents a histogram that categorizes instances of string by the number of times the string content appeared in previous strings. When a string instance is passed by value it is copied and the content is duplicated. This example was extracted from the Fish-shell program. In this program, most string containers hold almost-unique string values, but some non-empty string values are held by thousands of string instances. Perhaps some of these values could be eliminated.

4 Related work

C++ is a high-level programming language that was designed as an extension to C. Over the years C++ gained many features that interact in complex ways. The complexity of the language makes it difficult to write high-performance, correct, maintainable and secure programs. The C++ community overcame some of the problems by introducing tools. Valgrind and later the fam-
family of sanitizers, and especially the address-sanitizer[9], allowed users to catch memory-corruption bugs. Better compiler analysis and diagnostics exposed some classes of bugs. Clang-format and clang-tidy made the code more readable and maintainable.

High-level abstractions in C++ come with a performance cost. Compilers usually can't recover the performance loss that are introduced with high-level abstractions[2]. In this paper we highlighted the example of costly calls to 'malloc', but there are also other examples of atomic operations or just more instructions that are executed. BOLT[8] removes some of the C++ abstraction overhead by reordering the code according to the execution frequency. Moving the slow-path out of the way helps to make better use of the instruction cache.

Another effective approach to improving the performance of C++ programs is making memory allocations faster. JEMalloc[3] is an efficient memory allocator that is tuned for C++ programs.

Another approach to improving the performance of C++ programs is the use of linters[1] that pattern match the AST and apply a set of rules. Linters could catch patterns such as passing a vector by value instead of by reference. However, in practice, inefficient code patterns are complex and often span different parts of the code and in different compilation units. Moreover, some performance issues depend on the runtime behavior of the program. For example, if a vector remains small we may prefer to replace it with a non-allocating vector that has internal storage (such as Abseil’s InlinedVector, Folly’s small_vector or LLVM’s SmallVector).

Perflint[5] is similar to Warrior1. It is an analysis tool that identifies suboptimal use patterns of C++ containers. Both are implemented as instrumentation of the standard library and as diagnostics tool that analyzes the recorded traces. There are a few differences between their approach and ours. Perflint performs more of the analysis inside the host program, while our approach relies more on an external diagnostics tool. Perflint is focused on identifying the optimal data-structure, while our work enables the detection of a wider set of patterns, such as the map count-operator pair, or short-lived heap allocated objects.

Toddler[7] detects opportunities for loop invariant code motion in Java programs by inspecting traces of computation and memory access patterns.

5 Examples

This section brings a number of interesting examples from performance anti-patterns that the Warrior1 tool discovered in popular open source programs.

The code below, in LLVM (LiveVariables.cpp + 93), uses a vector as a stack for a worklist. However, the tool found that the typical stack size is relatively small. We replaced the code below with LLVM’s SmallVector data structure that contains on-stack inline storage and saved a large number of memory allocations. We found and fixed additional performance issues in LLVM: D83849, D83788, D83797, D84620, D85538.

```cpp
void LiveVariables::MarkVirtRegAliveInBlock(...) {
    std::vector<MachineBasicBlock*> WorkList;
    while (!WorkList.empty()) {
        // Fixed in D83920
    }
}
```

In the code below, from the CMake project (cmListFileCache.cxx + 372), a shared_ptr is passed by value instead of by reference. Shared pointers should be passed by reference because copying them is an expensive operation.

```cpp
cmlListFileBacktrace:: cmListFileBacktrace(
    std::shared_ptr<Entry const> top) {
    ...
}
```

In the code below, from the Ninja-build project (manifest_parser.cc + 300), a new instance of EvalString is created on each iteration of the loop. This data-structure contains a vector member that allocates and deallocates memory on each iteration of the loop. It is advised to move the EvalString instance outside of the loop and clear the vector before entering the loop.
In the code below, from the Z3 project (theory_lra.cpp + 1564), a map is searched twice. The first line searches the internal tree data-structure of the map in search of the key, and after finding the key, the second line searches the map again to return the key value.

```cpp
lp::impq get_ivalue(theory_var v) const {
    auto t = get_tv(v);
    if (m_variable_values.count(t.index()) > 0)
        return m_variable_values[t.index()];
```

In the code below from the Bitcoin project (bloom.cpp + 247), the vector ‘data’ saves the temporary value from the variable hash. This code pattern is inefficient because the vector allocates memory, and copies the content of ‘hash’ before passing it to the non-mutating insert method (that accepts a const vector). One possible fix would be to add a new method to the class that accepts iterators or a data structure that is similar to LLVM’s ArrayRef or Abseil’s Span.

```cpp
void CBloomFilter::insert(const uint256& hash) {
    std::vector<unsigned char> data(hash.begin(), hash.end());
    insert(data);
}
```

In the code below, from the ProtocolBuffers project (cpp_message.cc + 698), a map is constructed in some helper function. Later, each one of the keys and values, which are strings that are individually allocated, are copied into another map inside the AddMap method.

```cpp
void MessageGenerator::GenerateFieldAccessorDeclarations(...) {
    std::map<std::string, std::string> vars;
    SetCommonFieldVariables(field, &vars, options_);
    format.AddMap(vars);
    ...
}
```

In the code below, from the Redex project (ControlFlow.cpp + 1047), is written using a modern C++ style, where a loop is replaced by a for_each and a lambda method that constructs a temporary vector. The tool detected this issue because of the high number of memory allocations. The code below was replaced by a simple loop that counted the number of values and saved a large number of memory allocations. We found and fixed additional performance issues in Redex: D22828350, D22832242, D22832839.

```cpp
// Fixed in 8cdlee9
void ControlFlowGraph::sanity_check() const {
    auto num_succs =
        get_succ_edges_if(b, [](const Edge* e) {
            return e->type() != EDGE_GHOST;
        }).size();
}
```

In the code below, from the ethereum/solidity project (Scanner.cpp + 973), the struct CharStream is passed by value. This struct contains large strings that are re-allocated when the struct is copied when passed by value.

```cpp
void Scanner::reset(CharStream _source) {
    In the code below, from the libtorrent project (piece_picker.cpp + 350), a vector is returned by value. The vector is immediately destroyed and the memory is deallocated. Returning the iterator over the internal member could be a more efficient design. The average number of elements in the returned vector is 48, so passing a small-vector as a parameter to the function is also a possible design.

```cpp
std::vector<piece_picker::downloading_piece>
piece_picker::get_download_queue() const {
    std::vector<downloading_piece> ret;
    for (auto const& c : m_downloads)
        ret.insert(ret.end(), c.begin(), c.end());
    return ret;
}
```

In the code below, from the nlohmann-json project (json.hpp + 12734), a member of type output_adapter_t is returned by value. This type is an alias to a shared_ptr. This operation is expensive because passing a smart pointer by value updates the reference count multiple times, and this is done with atomic operations.

```cpp
class output_adapter {
    ...
    operator output_adapter_t<CharType>()
    {
        return oa;
    }
}...
output_adapter_t<CharType> oa = nullptr;
```

In the code below, from the Folly project (json.cpp + 192), the code constructs two temporary string instances before appending the result into a third string. These two string instances allocate memory if the size of the string exceeds the internal storage. A faster (and more readable
code) would just append the new line and the spaces in a loop.

```cpp
void newline() const {
    if (indentLevel_) {
        out_ += to<std::string>('\n',
                             std::string(*indentLevel_ * 2, ' '));
    }
}
```

In the code below, from the Mcrouter project (FailoverErrorsSettingsBase.cpp + 56), the code passes a vector of strings by value, instead of by reference. Passing the vector by value forces a memory-allocating copy of the vector and of each one of the strings in the vector.

```cpp
void FailoverErrorsSettingsBase::
List::init(std::vector<std::string> errors) {
    ...
}
```

In the code below, from the PyTorch project (function_schema_parser.cpp + 297), a function returns a union of two types, by value. The type FunctionSchema is a complex struct that contains multiple strings, shared pointers and vectors of structs that contain strings. The function returns the struct by value and copies the whole data structure.

```cpp
C10_EXPORT either<OperatorName, FunctionSchema>
    parseSchemaOrName(...) {
        auto parsed = parseSchemaOrName(schema);
    }
```

In the code below, from the GCC/libstdc++ project (regex.h + 2982), a function uses a standard vector to store the input and transform it. The typical input size is very small and could fit in a small vector and avoid a malloc. This code is found inside the C++ standard library itself.

```cpp
/**
 * @brief Gets a sort key for a character ...
 */
template<typename _Fwd_iter>
string_type
    transform_primary(...) const {
    ...
    std::vector<char_type> __s(__first, __last);
    __fctyp.tolower(..);
    return this->transform(...);
}
```

6 Challenges

Warrior1 is effective in detecting inefficient code sequences, but there are a few challenges that prevent the tool from being helpful in some environments.

One challenge is that in many cases the inefficiency in the program is built into some widely used API, and this makes it difficult to fix the program. For example, in LLVM’s table-gen tool a commonly used class declares a virtual method with the name "getName" that returns a string. This API is inefficient because returning a string forces memory allocation. The method is overridden by dozens of other methods that implement the same API. The tool detects a huge number of short-lived strings that allocate memory, but it is very difficult to fix the issues because of the large number of overriding methods and call sites.

Another limitation of the tool is that some large-scale C++ projects often implement their own data structures instead of using the standard library. One of the reasons is that older C++ projects started before the standard library was mature and reliable. Another reason is that many projects implement their own high-performance data structures (such as Folly, Absail). These data structures can’t be
analyzed by the tool without adding the logging methods and special diagnostics code in the reporting tool. Another challenge in applying the tool is that some software projects are already well optimized. For example, the inefficiencies that we found in Webkit’s JavaScript engine were not significant because engineers spent a lot of time optimizing the code. There are not that many opportunities to remove inefficient code in projects that are regularly inspected using a profiler by many people.

7 Acknowledgements

We’d like to thank Evgeny Fiksman and Maged Michael for their help in running the tool on Facebook workloads and in detecting and fixing issues in production services.

8 Conclusion

The C++ community is very familiar with the problem of inefficient code that’s caused by the design of the language and the implementation of complex abstractions. This paper presents Warrior 1, a tool for detecting inefficient code patterns in C++. Warrior 1 was designed to detect the long tail of small performance issues that are difficult to detect with a profiler, and that are the result of inefficient use of C++ libraries. We instrument the standard library to log operations and stack traces in a compressed binary format. We show that the tool is effective in detecting inefficient code patterns in a number of open source software projects. We fixed some of the issues that the tool detected in open source programs. We demonstrate that C++ containers are frequently misused in real programs (including in already relatively well-optimized ones, written by well-regarded C++ programmers, like LLVM). The techniques that we presented in this paper could be applicable to other programming languages, such as Rust, Swift and Java.

References

[1] Al Bessey, Ken Block, Ben Chelf, Andy Chou, Bryan Fulton, Seth Hallem, Charles Henri-Gros, Asya Kamsky, Scott McPeak, and Dawson Engler. A few billion lines of code later: Using static analysis to find bugs in the real world. Commun. ACM, 53(2):66–75, February 2010.

[2] Chandler Carruth. There Are No Zero-cost Abstractions, 2009 (CppCon 2019).

[3] Jason Evans. JEMalloc, 2005. http://jemalloc.net/

[4] Chris Lattner and Vikram Adve. Llvm: A compilation framework for lifelong program analysis & transformation. In Proceedings of the International Symposium on Code Generation and Optimization: Feedback-Directed and Runtime Optimization, CGO ’04, page 75, USA, 2004. IEEE Computer Society.

[5] L. Liu and S. Rus. Perflint: A context sensitive performance advisor for c++ programs. In 2009 International Symposium on Code Generation and Optimization, pages 265–274, 2009.

[6] Nicholas Nethercote and Julian Seward. Valgrind: A framework for heavyweight dynamic binary instrumentation. In Proceedings of ACM SIGPLAN 2007 Conference on Programming Language Design and Implementation (PLDI 2007), pages 89–100, San Diego, California, USA, June 2007.

[7] Adrian Nistor, Linhai Song, Darko Marinov, and Shan Lu. Toddler: Detecting performance problems via similar memory-access patterns. In Proceedings of the 2013 International Conference on Software Engineering, ICSE ’13, page 562–571. IEEE Press, 2013.

[8] Maksim Panchenko, Rafael Auler, Bill Nell, and Guilherme Ottoni. BOLT: A practical binary optimizer for data centers and beyond. CoRR, abs/1807.06735, 2018.

[9] Konstantin Serebryany, Derek Bruening, Alexander Potapenko, and Dmitriy Vyukov. Addresssanitizer: A fast address sanity checker. In 2012 USENIX Annual Technical Conference (USENIX ATC 12), pages 309–318, Boston, MA, June 2012. USENIX Association.

[10] Bjarne Stroustrup. Evolving a language in and for the real world: C++ 1991-2006. In Proceedings of the Third ACM SIGPLAN Conference on History of Programming Languages, HOPL III, page 4–1–4–59. New York, NY, USA, 2007. Association for Computing Machinery.