Low-cost Deterministic C++ Exceptions for Embedded Systems

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ABSTRACT

The C++ programming language offers a strong exception mechanism for error handling at the language level, improving code readability, safety, and maintainability. However, current C++ implementations are targeted at general-purpose systems, often sacrificing code size, memory usage, and resource determinism for the sake of performance. This makes C++ exceptions a particularly undesirable choice for embedded applications where code size and resource determinism are often paramount. Consequently, embedded coding guidelines either forbid the use of C++ exceptions, or embedded C++ tool chains omit exception handling altogether. In this paper, we develop a novel implementation of C++ exceptions that eliminates these issues, and enables their use for embedded systems. We combine existing stack unwinding techniques with a new approach to memory management and run-time type information (RTTI). In doing so we create a compliant C++ exception handling implementation, providing bounded runtime and memory usage, while reducing code size requirements by up to 82%, and incurring only a minimal runtime overhead for the common case of no exceptions.

CCS CONCEPTS

• **Software and its engineering → Error handling and recovery**; *Software performance*; *Language features*;

KEYWORDS

C++, exceptions, error handling

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1 INTRODUCTION

One of the major benefits of C++ is its promise of zero-cost abstractions and its rule of "you don't pay for what you don't use". This allows the use of various safer and more productive modern programming idioms, without the performance drawbacks with which their use is often associated. However, C++'s wide usage has not been without issues. For many of the different domains within industry the use of exceptions in C++, a core part of the language, has been disallowed. For example, the Google C++ Style Guide [7], the Joint Strike Fighter Air Vehicle C++ Coding Standards and the Mars Rover flight software [14] do not allow the use of exceptions at all, while MISRA C++ specifies detailed rules for their use [1].

While there are many advantages to the use of exceptions in C++, perhaps their greatest disadvantage lies in their implementation. The current exception implementations were designed to prioritise performance in the case where exceptions do not occur, motivated primarily by the idea that exceptions are exceptional, and thus should rarely happen. This prioritisation may suit applications for which errors are rare and execution time is paramount, but it comes at the cost of other factors – notably increased binary sizes, up to 15% in some cases [4], memory usage and a loss of determinism, in both execution time and memory, when exceptions do occur. These drawbacks make exceptions unsuitable for use in embedded systems, where binary size and determinism are often as, if not more, important than overall execution time [12, 18]. However, the C++ language, its standard library and many prominent 3rd party libraries, such as ZMQ [10] and Boost [2], rely on exceptions. As a result, embedded software developed in C++ generally disables exceptions [8], at the cost of reduced disciplined error handling through C++ exceptions and the exclusion of available libraries. The Arm C++ compiler tool chain, for example, and in contrast to most other compilers, disables exceptions by default [5].

In this paper we develop a novel C++ exception implementation, which reduces memory and run-time costs and provides determinism. The **key idea** is to apply and extend a recently developed low-cost stack unwinding mechanism [19] for C++ exceptions. In our novel C++ exception implementation we make use of a stack-allocated object that records the necessary run-time information for throwing an exception, such as the type and size of the exception object. This state is allocated in a single place and is passed between functions via an implicit function parameter injected into functions which support exceptions. The state is initialised by `throw` expressions, and is re-used to enable re-throwing. `catch` statements use the state in order to determine whether they can handle the exception. After a call to a function which *may* throw exceptions, a run-time check is inserted to test whether the state contains an active exception. We have implemented our new C++ exception implementation in the LLVM compiler Clang and evaluated it on both an embedded Arm as well as a general-purpose x86-64 platform. Using targeted micro-benchmarks and full applications we demonstrate binary size decreases up to 82% over existing implementations, and substantial performance improvements when handling and propagating exceptions. We demonstrate that our

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```
void C() {
  Bar bar;
  throw 0;
}
void B() {
  Foo foo;
  C();
}
void A() {
  try {
    B();
  } catch (int& p) {
    // Catch exception
  }
}
```

Figure 1: Example code showing a possible scenario in which exceptions are used. Function `A` has a `try/catch` block, that encompasses the call to `B`. `B` allocates a local object, and calls `C`, which also allocates a local object, and throws an exception.

novel C++ exception implementation achieves memory and execution time determinism, thus making it better suited for embedded applications with specified worst-case execution time requirements.

1.1 Motivating Example

Consider the motivating example in Figure 1, where function `A` has a `try/catch` block, that encompasses a call to `B`. `B` allocates a local object, and calls `C`, which also allocates a local object, and throws an exception. During exception handling stack unwinding is performed, i.e. stack frames for functions `C` and `B` must be removed from the call stack and local objects destroyed. Finally, the catch handler (found in `A`) is invoked. Figure 3 shows this operation in action for both the standard implementation, and our proposed implementation. In each case, the stack must be unwound from the *throw* site in function `C`, back to the catch handler in function `A`. This involves three steps:

(1) Local objects in `C` are destroyed, and callee saved registers are restored.
(2) Local objetcs in `B` are destroyed, and called saved registers are restored.
(3) Control is transferred to the catch handler in `A`.

The most common implementation of C++ exception handling, in use by both e.g. GCC and Clang, makes use of *table-based* stack unwinding. It seeks to eliminate *any runtime overhead* in the case where no exceptions are thrown. This is achieved by storing abstract instruction sequences required for identifying the catch handler, restoring the call stack and machine state, and invoking object destructors in *Unwind Tables*, which are generated at compile-time and embedded in the final program binary. When an exception is thrown, the *exception object* is allocated on the heap, and a 2-stage process for stack unwinding is started: The first stage, shown in

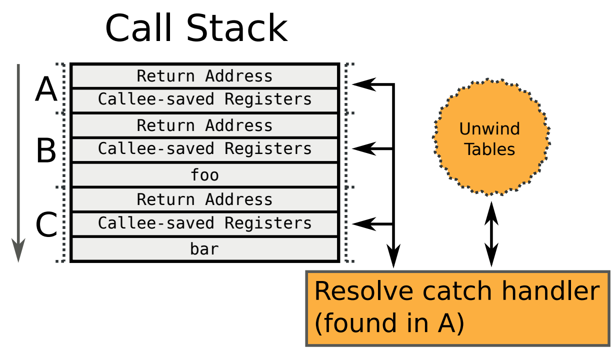


Figure 2: The standard exception handling implementation requires an initial phase to scan over the call stack, looking for a *catch handler*. This phase does not unwind the stack, it identifies how far back the stack should be unwound.

Figure 2, is concerned with finding a suitable catch handler. Using the unwind tables an embedded abstract machine executes the prepackaged instruction sequence to identify the catch handler by scanning over the call stack to determine how far back the stack should be unwound. The second stage, shown in the top half of Figure 3, then performs the actual stack unwinding. Again, an abstract machine implements a so-called *personality routine* which uses instruction sequences stored in the unwind tables to destroy local objects, remove stack frames from the call stack, update and commit the machine state and eventually invoke the catch handler.

The unwind tables used by the conventional C++ exception implementations can grow large and become complex. Furthermore, these tables typically encode operations to perform during stack unwinding (such as restoring registers, running object destructors, etc), which must be executed by an integrated software abstract machine. While this approach eliminates runtime overhead when no exceptions occur, it increases the memory footprint of the application and introduces non-determinism due to the abstract machine used at runtime for exception handling.

Our novel C++ exception implementation, shown in the bottom half of Figure 3, eliminates the need for *unwind tables*, and the associated abstract machine. Instead, we introduce a stack-allocated exception state object, which is allocated at the outermost *exception propagation barrier* (function `A`, in our example), and is populated at throw time (function `C`). This state object contains bookkeeping information for propagating the exception between the throw and catch sites. We pass this object into any invoked function via an implicit function parameter and use it to initiate and orchestrate exception handling. After each return from a function call the compiler inserts an additional check of the exception state to determine if an exception is in progress and, if so, uses a standard function return mechanism for step-by-step stack unwinding until we reach the matching catch statement (stages 1, 2, and 3 in Figure 3).

1.2 Contributions

In this paper we contribute to the development of a novel C++ exception implementation particularly suitable for use in embedded systems. We address following issues:

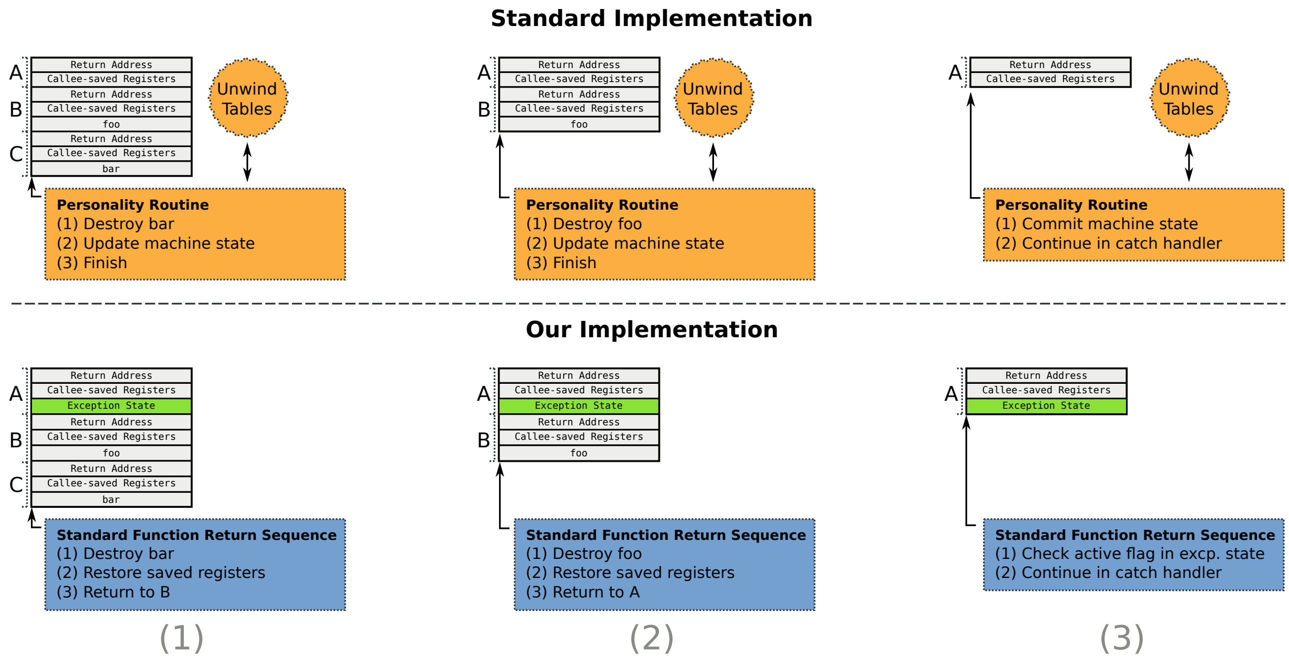


Figure 3: Stages involved in stack unwinding for the standard exception implementation (top), and our novel scheme (bottom).

(1) Reducing the binary size increase caused by exceptions.
(2) Permitting the bounding of memory usage and execution time when using exceptions, i.e. supporting determinism.
(3) Maintaining or improving the performance of exceptions.

Although we focus on embedded systems, we will ensure that these goals also apply to general-purpose applications.

2 DETERMINISTIC C++ EXCEPTIONS

Stack unwinding forms a core part of the mechanisms underpinning exceptions. It is also responsible for its poor execution times and increased binary sizes, and is part of the reason for exceptions being non-deterministic.

Sutter [19] has only very recently proposed re-using the existing function return mechanism in place of the traditional stack unwinding approaches, requiring no additional data or instructions to be stored, and little to no overhead in unwinding the stack. Furthermore, by removing stack unwinding’s runtime reliance on tables encoded in the program binary itself, the issue of time and spatial determinism is solved. As it is possible to determine the worst-case execution times for programs *not* using exceptions, it follows that exception implementations making use of the same return mechanism must also be deterministic in stack unwinding.

Given these clear advantages, we have based our implementation on this design, with a core difference being the replacement of their use of registers with function parameters, allowing for much easier interoperability with C code, which can simply provide the parameter as necessary.

A limitation with [19] is that they require all exceptions be of the same type, leaving much of the standard exception-handling functionality up to the user. Our novel approach includes a method of throwing and catching exceptions of arbitrary types (as with

```
1  void foo(__exception_t* __exception) throws {
2    // Exception state '__exception' assigned to by throw
3    throw SomeError();
4  }
5  int main() {
6    // State automatically allocated in 'main'
7    __exception_t __exception_state;
8    foo(&__exception_state);
9    // check for exception
10   if (__exception_state.active) goto catch;
11 }
```

Figure 4: Pseudocode showing injected exception state object (line 7) and parameter (line 1)

existing exception handling), without imposing any meaningful execution-time penalties when exceptions do not occur. We also reduce the size of run-time type information (RTTI), and maintain determinism over existing implementations.

Our scheme makes use of a stack-allocated object that records the necessary run-time information for throwing an exception, such as the type and size of the exception object. This state is allocated in a single place and is passed between functions via an implicit function parameter injected into functions which support exceptions. The state is initialised by `throw` expressions, and is re-used to enable re-throwing. `catch` statements use the state in order to determine whether they can handle the exception. After a call to a function which *may* throw exceptions, a run-time check is inserted to test whether the state contains an active exception.

```
1 auto safe_divide(float dividend, float divisor) throws {
2   if (divisor == 0)
3     throw std::invalid_argument("Divide by zero");
4   else
5     return dividend / divisor;
6 }
```

Figure 5: Example function marked with our proposed `throws` exception specifier (line 1) allowing exception propagation

Figure 4 gives an example of the variables the compiler will automatically inject during code generation. Line 1 shows the normally hidden implicit exception state parameter `__exception`. Line 3 assigns values corresponding to the `SomeError` type to the exception state parameter. Line 7 shows the automatically allocated `__exception_state` variable, emitted by all `noexcept` functions. Line 8 shows the exception state object being automatically passed to the `throws` function `foo`. Line 10 shows the check inserted after each call to a throwing function to test for an active exception.

The design of this implementation performs almost all of the exception handling directly within the functions being executed, allowing the optimiser to work most effectively, and by implementing exceptions on top of normal execution flow; code used in returning from functions is re-used when unwinding the stack following exceptions. This helps to reduce code size and unpredictability, and overcomes the largest roadblock in achieving deterministic execution time. This approach combines the exception-handling mechanism of C++ with the inter-mixed error-checking and non-error-handling code integral to the design of [9].

2.1 Throws Exception Specifier

A fundamental issue is to decide which functions should take the implicit exception parameter that our design requires (i.e. which functions could throw exceptions). The natural choice would be to apply it to all functions with C++ linkage, except for those marked `noexcept`, in keeping with the current exception implementation. However, the issue with this approach would be that C++ and C functions would then have different calling conventions. Whilst C++ functions can in general be called without special handling from C, this is only due to the coincidence that the two calling conventions are identical.

With our proposed scheme, the decision to have C++ functions support exceptions by default is impractical, as C++ has certain language holes when it comes to specifying linkage. Specifically, neither classes, structs nor their members, such as function pointers, can have a specified linkage. Therefore, we propose to have functions be declared `noexcept` by default. This change in default exception specification preserves compatibility with C at the cost of a language change in C++.

Like `noexcept`, we require functions that *might* throw encode this into their signature (similar to [19]), as this impacts on how they are called. Thus, to indicate that functions can throw exceptions, we introduce an exception specifier (that is part of the function prototype), as shown in Figure 5.

Name	Description
`type`	The "type id" variable address identifying the exception object's type
`base_types`	Pointer to an array of "type id"s identifying the exception object's base class types
`ptr`	Whether the exception object is a pointer to a non-pointer type
`size`	The size, in bytes, of the exception object
`align`	The alignment, in bytes, of the exception object
`ctor`	The address of the object's move or copy constructor
`dtor`	The address of the object's destructor
`buffer`	The address of the exception object
`active`	Whether the exception is currently active

Table 1: Exception State Fields

2.2 Throwing Exceptions and Exception State

The *exception state object* exists to hold run-time information on the exception currently in progress. Every function marked `noexcept`, including the program `main` function, and functions used as thread entry-points, allocates and initialises its own exception state object, effectively making `noexcept` functions boundaries beyond which exceptions cannot propagate.

The address of this object is passed to any of the *called* functions that are marked `throws`, allowing the exception to propagate down the call chain as far as the first `noexcept` function, where, if not handled, the program is terminated.

Following a `throw` expression, the fields in the exception state object are populated at the throw-site with values known at compile-time corresponding to the exception object given in the expression. The `active` flag is set to `true`, the exception object is moved into a buffer, and its address assigned to the `buffer` field of the exception state.

If the `throw` expression is directly within a `try` statement, the code jumps to the first `catch` block for handling. Otherwise, provided the current function is marked as `throws`, the exception is propagated; execution is transferred to the function epilogue as if returning normally, but the return value for the function, if any, is not initialised.

During the return sequence, local objects have their destructors executed as if a standard function return had occurred, efficiently unwinding the stack. The exception being marked active is not made visible to destructors, as destructors are necessarily `noexcept` in this context ("If a destructor called during stack unwinding exits with an exception, `std::terminate` is called (15.5.1)"[17]). In this way, the exception state is untouched until entering the initial `catch` block. If the current function is not marked as `throws`, propagation is replaced by an immediate call to `std::terminate` to terminate the program.

After each function call to a function marked as `throws`, a check is automatically inserted by the compiler to test whether the `active` flag has been set, and thus whether the exception has been propagated. This is the largest overhead as a result of our changes - requiring a test for each function called regardless of whether an exception was thrown or not. There is perhaps a good case to be made for its necessity, however. By indicating that a function can throw, via `throws`, the developer is encoding into the function signature the fact that an error may occur during its execution. Thus regardless of performance requirements, some test must be made for that error in a correct program.

2.3 Handling Exceptions

Once an exception has been thrown, and if it does not result in a call to `std::terminate`, control is transferred to the first available catch block.

Before each catch block executes, it first compares for value equality the "type id" of the exception type it handles, and the type marked in the `type` field of the exception state. If they are equal, or if the type the catch block handles is a base type of the type in the `type` field, then the catch block is entered. Otherwise, execution jumps to the next catch block, and repeats this process until the catch block is a catch-all, or all blocks have been exhausted. If no blocks remain, the exception continues propagation as described previously.

Once a catch block is executed, the `active` flag of the exception state is cleared, memory is allocated on the stack for the exception object, and the move or copy constructor is invoked to transfer ownership of the exception object into the current block.

If an exception was to occur during the move or copy operation, `std::terminate` is called to satisfy the C++ specification, which states "If the exception handling mechanism, after completing evaluation of the expression to be thrown but before the exception is caught, calls a function that exits via an exception, `std::terminate` is called (15.5.1)."

Catch filters can take two forms: (1) by value, where the catch variable represents an object allocated within the catch block, or (2) by reference, where the catch variable is a reference to the exception object allocated elsewhere.

In the latter case, an additional unnamed variable is introduced in which to store the exception object, and its allocation and initialisation is performed as described above using the equivalent non-reference type. The catch variable reference is then bound to this unnamed variable. In this way, even when the exception object is caught by reference, it is still owned by the catch block.

Following a successful move/copy of the exception object, the destructor is called on the original exception object instance within the buffer. Naturally, as destructors are necessarily `noexcept`, were the destructor to exit with an exception, again `std::terminate` would be called.

With the catch variable successfully initialised, the `catch` block then commences execution. Once complete, execution moves to a point past the final catch block in the current scope and the catch variable is destroyed as usual.

2.4 Re-Throwing

One of the issues with maintaining and passing references to a single instance of exception state via the exception state parameter is that more than one exception may be active at a time, and crucially the initial exception may require to be re-thrown following the intermediary exception.

```
try { throw 1; }
catch (int i) {
  try { throw 2; }
  catch (...) { }
  throw;
}
```

Figure 6: Re-throwing following a nested exception. The first exception's state must be persisted and not overwritten by the second exception to allow the re-throw.

Figure 6 gives an example. The first exception is thrown on line 1, caught on line 2, then a second exception is thrown on line 3 and caught by the catch-all on line 4. The first exception is then re-thrown on line 5, which requires the first exception's state to have persisted across the second inner throw/catch.

To allow for this, a local copy of the exception state is allocated when entering a `try` block, and if an exception occurs within the `try` block, the exception modifies the local copy. If the same exception is not handled by the `try` block's corresponding `catch` block or blocks, the local state is copied back to either the outer state, or to the function's exception state, as passed in the parameter, for exception propagation.

If the inner exception is handled correctly, only its local exception state is modified, thus the outer exception state is maintained and can be used, for example, to successfully re-throw the outer exception. As we only initialise the `active` field of the local copy, its cost is a simple stack allocation, plus zero-initialisation of a boolean flag.

C++ already has a mechanism for obtaining and re-throwing exceptions by making and passing around an explicit copy of (or reference to) the exception state via the use of `std::current_exception()`, which when called returns an instance of `std::exception_ptr`. To provide similar functionality in our implementation, we propose an equivalent mechanism, namely: `std::get_exception_obj`. This function returns a reference to a `std::exception_obj` instance stored on the stack.

What makes `std::exception_obj` novel is that its type is templated such that developers can specify a custom allocator, giving them control over where the exception object is to be allocated when being transferred to a new instance. However, we restrict the use of `std::get_exception_obj` such that it can only be called from directly within a `catch` block. This makes sense from a value-oriented perspective - functions can only inspect and access their own variables and not their callers' unless shared explicitly via parameters. Since in our implementation, the exception object is directly owned by `catch` block, functions called from within that `catch` block would not normally have access to the object.

Re-throwing in our implementation is achieved by calling the `std::rethrow` function, and passing a `std::exception_obj` instance. This is intuitive, arguably more so than the bare `throw;` expression, and crucially makes clear the cost of re-throwing, as `std::exception_obj` instances must be explicitly moved around.

Figure 7 shows a complete example. On lines 1 and 2, a function is declared taking a `std::exception_obj` instance using the default

```
1  void store_exception(
2    std::exception_obj<std::allocator<const char*>> obj)
3    throws {
4    // Move the exception object into a global
5    result.exception = std::move(obj);
6  }
7  // --------------------------------
8  try {
9    // ...
10 } catch (...) {
11   // Move the exception object out of the catch block
12   store_exception(std::move(std::get_exception_obj()));
13 }
14 // The exception can be re-thrown from a global
15 std::rethrow(std::move(result.exception));
```

Figure 7: Example of re-throwing the exception object using our proposed `std::rethrow` function and `std::exception_obj` type.

allocator. This object is move-constructed from the corresponding `std::exception_obj` instance, representing the exception object within the `catch` block on line 12, allocating the exception object as instructed. The object is then moved and stored in a global variable, `result.exception` on line 5, which is then re-thrown on line 15.

To enable re-throwing, the `std::exception_obj` instance also contains the exception state object, which is already populated with the details of the exception. Thus, all that is required to re-throw that exception is to copy those fields to the current exception state, restore the exception object to the buffer, to set the `active` flag and then to attempt to propagate the exception as if throwing normally.

2.5 Throwing Destructors

Although generally advised against by the C++ specification, destructors can throw, and can be explicitly marked as `throws`. Were such destructors to be called during stack unwinding, they would incorrectly share the same exception state as the uncaught exception. In particular, the `active` flag would be set, leading to incorrect execution flow when function calls from within the destructor performed their exception check.

To avoid this, we modify the compiler such that when throwing destructors are entered, they allocate and initialise their own local exception state, as if they were a `noexcept` function. This local state will be used within the destructor. If at any point an exception is unhandled within the destructor, such that it would exit with that exception, it first checks the exception state parameter to see if it is marked as `active`. If so, two unhandled exceptions are in progress, and thus the program must be terminated with `std::terminate` per the C++ standard (15.5.1, as quoted above).

As throwing destructors may be called when an exception is not active as part of normal logic, these additional measures constitute overhead on the in the case where exceptions are not thrown. However, throwing destructors are rare, and are conceptually odd - exceptions exist to indicate the failure of the operation, but in C++ destruction always succeeds.

2.6 Exception Object Type Identification

One of the disadvantages of current exception implementations is their use of RTTI in matching the types of thrown exception objects to a corresponding catch handler. Current approaches make use of complete RTTI objects in exception binaries, emitting a full `std::type_info` instance for each type, which includes a unique string identifying it. Either the address of these `std::type_info` instances, or the string identifier is used to compare against the corresponding `std::type_info` instance for the catch handler. Inheritance adds an additional layer of complexity, as each candidate type must also enumerate and compare its public base classes when matching against the catch block type.

Seeking to reduce binary sizes, we introduce an optimisation that both reduces the space required to represent types, and addresses concerns with execution time determinism. This solution is predicated upon the fact that each type requires solely some unique identifier, and not the full `std::type_info` instance.

For each unique type of exception object thrown, the compiler will automatically emit a `char`-sized variable with minimum alignment, whose identifier is composed of the name of the type prefixed with `__typeid_for_`. Pointer types will have an integer prefix corresponding to the number of levels of indirection. Type qualifiers such as `const` and `volatile` are ignored.

This "type id" variable will use its address to represent a unique type identifier with which types might be compared for equality. In a `throw` expression, the `type` field of the exception state will be assigned the address of the "type id" matching the thrown type.

To handle polymorphic types, for each unique type of exception thrown, an additional array of addresses will be emitted, containing the addresses of the "type id" variables for the base types. In similar fashion to the "type id" variables, its identifier is prefixed with `__typeid_bases_for_`, followed by the name of the type. For those types which do not have base classes, a single shared array with the identifier `__typeid_empty_bases` will be emitted, containing only a null entry.

Testing whether a given type is a base class of another type is then a matter of getting the pointer to the base class array (which is known at compile-time), and iterating through its fixed-size list of bases. When an exception is thrown, its corresponding base class array will be assigned to the `base_types` field of the exception state.

This same iteration of base classes applies when throwing and catching pointer types. While the `type` field will contain a "type id" identifying the pointer, the `base_types` field will correspond to the base type array of the pointee type.

In both the "type id" and base-array cases, to ensure both emission and uniqueness, these variables will be marked as being weak symbols, an indication given to the linker that only one instance of each variable will be preserved in the final binary.

2.7 Exception Object Allocation

When throwing an exception, the exception object must be allocated such that it is constructed in the scope where it was thrown, but is also accessible to the scope where it is caught. It is not enough to simply allocate the object on the stack, despite the fact that the

```
bool type_is_base(void* type, const char** bases) noexcept {
  for (; bases[0] != nullptr; bases++) {
    if (static_cast<const void*>(bases[0]) == type)
      return true;
  }
  return false;
}
```

Figure 8: Example iteration over base entries, the candidate base is passed to the type parameter and the array of base "type id"s to the bases parameter.

exception will cause the stack to be unwound, as local object destructors will run as the stack is unwound, potentially overwriting the exception object. Allocating the exception object on the heap is a solution, but the allocation may result in system calls, which (a) potentially have unbounded execution time, and (b) may fail if memory is exhausted. As our target is to support deterministic exceptions, standard heap allocation is not an option.

We propose a statically sized buffer using a simple constant-time stack allocator for our exception object, with a heap-backed fall-back upon buffer exhaustion for those applications who cannot compute or do not require run-time determinism. The size of this buffer will be given a default value by the ABI in use, but will be optionally application-overridden at link-time via a linker command-line parameter, to optimise or prevent any and all heap allocation.

In the worst-case scenario, our solution matches the performance of current exception implementations, as at least that of g++ uses a similar buffer. However, as we free our exception objects as early as possible, we expect usage of this buffer to be less than other implementations, and with our novel ability to customise its size (and in combination with earlier improvements), we uniquely offer deterministic allocation.

3 STANDARDS COMPLIANCE

In this section we consider the compliance of our exception implementation against the ABI specification, and the C++ standards document.

3.1 ABI Compliance

Existing ABI specifications mandate the use of tables and manual stack unwinding. However, since using the existing function return mechanism is a superior method of achieving stack unwinding, our implementation deviates entirely from their design. Therefore, we will not evaluate our solution against any existing ABI specifications. A side effect of this is that our own ABI is significantly easier to implement, as the stack unwinding and exception handling code is generated in a platform-independent way by the compiler.

3.2 C++ Standard Compliance

In general, our implementation conforms to the C++ standard's requirements for exceptions. However, we have observed four clauses where there are deviations:

Clause 18.1.4. describes the interaction between the exception object and `std::exception_ptr`, which is designed for exception objects allocated on the heap. This is therefore not suited to our stack-based implementation, however our replacement provides similar functionality.

Clause 18.2.2. requires local temporaries, such as return values, to have their destructors called when unwinding. However, clang's existing exception implementation does not conform to this part of the specification, and as a result our implementation also does not conform. This is a bug in the clang compiler (on which our implementation is based), and if this is repaired, our implementation will also be repaired.

Clauses 18.2.3 and 18.2.4. require the destruction of base class instances and sub-objects already constructed when an exception occurs during a constructor. This feature is not yet implemented, and will be addressed in future work, however it does not require any conceptual changes, as following from its simplicity and similarity to local object destruction, we foresee no issues that might occur in its implementation.

4 EVALUATION

We have implemented our novel scheme in the clang compiler, and present results showing the performance of our implementation, compared to the existing implementation.

4.1 Experimental Set-up

For our experiments, we used two different machines with two different platforms:

- **x86-64 Machine** Desktop computer running Ubuntu 18.04, Intel 8700k @ 3.7-4.7GHz, 32GB 3200MHz DRAM, Samsung 980 Evo NVMe storage.
- **Arm Machine** Raspberry Pi 1 Model B running Raspian Stretch Lite, ARM1176JZFS ARMv6 @ 700MHz, 512 MB DRAM, 16GB SD storage.

All binaries were built with identical flags, other than those determining the type of exceptions to use. Run-time type information is disabled (`-fno-rtti`), the symbol table is removed (`-s`), and `-O3` optimisation with link-time optimisation (`-flto`) is employed. Clang-7.0 was used as the compiler, along with `libstdc++` and `libgcc` on Arm, and `libc++` and `libunwind` on x86.

4.1.1 Benchmark Application. Lacking an obvious existing realistic benchmark with which to test exceptions, we instead developed our own microbenchmark. `xmlbench` is a simple XML parser, targeting ease of use and functionality as a real XML parser. It organically includes a good mixture of functions that can and can not throw exceptions, and also those which do throw exceptions and those which are "exception neutral", i.e. allowing exception propagation. By supplying different XML files as input to the parser, we can precisely control the rate of exceptions. Errors in input XML syntax, and external conditions (such as the input file missing, or an out-of-memory condition) can be influenced in a realistic way. This approach to benchmarking is similar to [15], who also use an XML parser as a representative application.

Platform	Implementation	Size
Arm	Standard	59,188 bytes
Arm	Deterministic	22,068 bytes
x86-64	Standard	105,312 bytes
x86-64	Deterministic	18,600 bytes

Table 2: Final binary sizes for `xmlbench` benchmark, with the standard and deterministic exception implementations.

4.2 Results

The following sections detail the results of our observations on various facets of the exception handling infrastructure.

4.2.1 Unwind Library Overhead. Statically-linked binaries participate in whole-program optimisation, and as such have the exception handling and unwind functions removed when using our implementation. This allows for a direct comparison against binaries that use the standard implementation.

Table 2 shows the results of the binary built with both the standard and the deterministic exception implementations. The results for both x86-64 and Arm show substantial decreases in binary size, when using our deterministic implementation. This measurement indicates how large the unwinding code is. Arm's unwinding code is smaller, but by removing it we see a decrease in binary size of 36.3 Kilobytes, a 62.7% reduction for our program. x86-64 has a much larger unwind library, with our implementation saving 84.7 Kilobytes, an 82.3% reduction in size for identical functionality.

On both platforms, the code section (`.text`) grows due to the inclusion of additional instructions for checking the exception state. On x86-64, the removal of the unwind tables compensates for this growth, with a reduction of 0.3%. However, on Arm missed optimization opportunities by the compiler leads to an net increase of roughly 8%.

4.2.2 Application Benchmark Performance. We generated two sets of XML files one with syntax errors, and one without, and parsed them with `xmlbench`. The syntax error is contained within the deepest element, resulting in an exception thrown with the stack at its largest number of function calls. For each run, we measured the total run-time of the `xmlbench` program, including the start-up time.

Figure 9 shows the average execution time in microseconds per XML element parsed by our benchmark, for both the Arm (Figure 9a) and x86-64 (Figure 9b) platforms. On the Arm platform, the results show there is little difference between execution times, except for the standard exception implementation generally performing the worst of the four, when faced with an exception. As was expected, the standard implementation performs better when no exception is raised with only 156 elements, as our implementation must check for active exceptions. This difference disappears as more elements are processed.

On the x86-64 platform, our deterministic implementation takes slightly longer per element than the standard implementation for larger numbers of nodes. This is primarily due to the overhead of checking whether an exception has occurred. As is expected, the difference in time for our implementation depending on whether an exception was thrown or not is very small, particularly in comparison to the same for the standard implementation, which at its peak has a 2.3% overhead.

	# Elems.	Throw?	Time (σ) Standard Impl.	Time (σ) Determ. Impl.
Arm	156	✗	42.7ms (0.6ms)	41.7ms (0.6ms)
	156	✓	43.7ms (0.6ms)	43.0ms (0.0ms)
	3,906	✗	158.7ms (2.1ms)	162.7ms (1.5ms)
	3,906	✓	160.7ms (1.5ms)	162.0ms (2.0ms)
x86-64	3,905	✗	3.3ms (0.6ms)	3.3ms (0.6ms)
	3,905	✓	3.3ms (0.6ms)	3.3ms (0.6ms)
	97,655	✗	68.0ms (1.0ms)	70.7ms (0.6ms)
	97,655	✓	69.0ms (1.0ms)	70.3ms (0.6ms)

Table 3: Overall execution time summary for `xmlbench` on the Arm and x86-64 platforms.

The benchmark clearly shows how throwing a single exception increases execution time for the standard exception implementation, given the lengthy unwind procedure. However, with our implementation, the improvements to exception handling speed are not quite enough to compensate for the overhead in the absence of exceptions. With more than a single exception, and particularly given the results for 488,281 elements, where the trend suggests that our implementation scales better than the existing one, it should be enough for our solution to out-perform the current one.

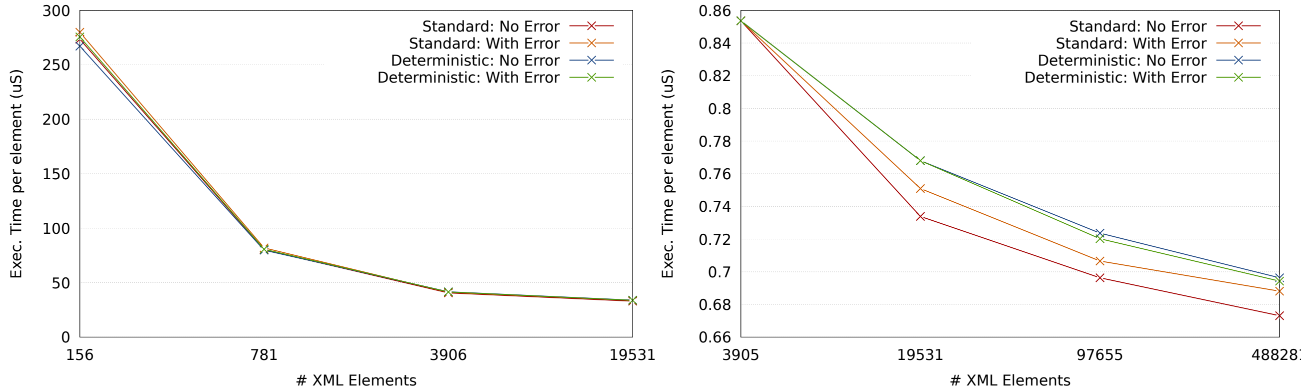
As shown in Table 3, our implementation creates a small additional execution time overhead in comparison to the standard implementation, however, the difference is negligible and within the standard deviation.

4.2.3 Exception Propagation. To test exception propagation, we used a different benchmark, which simply called the same function recursively as many times as indicated by *Stack Frames*, with a local object having a simple custom destructor within each frame. After *Stack Frames* calls, an exception is thrown, and caught by reference from the first invocation. The benchmark was compiled with the same flags as `xmlbench`.

The CPU time was measured between the first function call, and arrival in the catch handler. The experiment was run multiple times for each configuration, and the mean and standard deviation of the results are tabulated in Table 4.

The results show a significant difference in execution time between the two exception implementations. Our implementation is on average 98× faster at performing exception propagation on x86-64. The factor of improvement increases from 68× to 138× as the number of stack frames increases, indicating that the performance penalty seen in the current implementation increases as the number of frames increases. Our implementation performs best on x86-64 with deep call stacks.

On Arm, the improvement in execution time remains almost constant, at 32× to 33× for 100 and 1000 frames, and 35× speedup for 10,000 frames. This suggests that our implementation will consistently offer improved performance independent of the number of frames.



(a) Arm **(b) x86-64**

Figure 9: Execution times in μs per XML element for different element counts with our `xmlbench` benchmark on Arm (a) and x86-64 (b). Lower is better.

	Stack Frames	Implementation	Time	σ
Arm	100	Standard	1351.3μs	74.3μs
	100	Deterministic	41.7μs	0.6μs
	1,000	Standard	9.6ms	0.2ms
	1,000	Deterministic	0.3ms	0.0ms
	10,000	Standard	94.8ms	1.0ms
	10,000	Deterministic	2.7ms	0.1ms
x86-64	100	Standard	114.7μs	21.6μs
	100	Deterministic	1.7μs	0.8μs
	1,000	Standard	2572.0 μs	231.2μs
	1,000	Deterministic	29.0 μs	0.0μs
	10,000	Standard	8823.8μs	960.0μs
	10,000	Deterministic	64.0μs	6.4μs

Table 4: Execution times for the exception propagation benchmark.

	Stack Frames	Implementation	Time	σ
Arm	100	Standard	4.1ms	0.1ms
	100	Deterministic	0.2ms	0.0ms
	1,000	Standard	33.5ms	0.4ms
	1,000	Deterministic	1.8ms	0.0ms
	10,000	Standard	318.4ms	6.3ms
	10,000	Deterministic	18.2ms	0.1ms
x86-64	100	Standard	1071.7μs	363.3μs
	100	Deterministic	22.7μs	13.8μs
	1,000	Standard	3.8ms	0.1ms
	1,000	Deterministic	0.2ms	0.0ms
	10,000	Standard	22.0ms	0.3ms
	10,000	Deterministic	2.4ms	0.1ms

Table 5: Execution times for the exception re-throwing benchmark.

The improvements in execution time are a result of not having to resolve the encoded unwind information, and walk the stack twice to locate the catch handler before unwinding.

4.2.4 Re-Throwing. To measure exception re-throwing, we used another benchmark, which called the same function recursively as many times as indicated by *Stack Frames*, with a local object having a custom destructor within each frame. After *Stack Frames* calls, an exception is thrown, but unlike before, caught and re-thrown by each function. The benchmark was compiled with the same flags as `xmlbench`.

The CPU time was measured between the first function call, and arrival in the catch handler. The experiment was run multiple times for each configuration and the mean and standard deviation of the results are tabulated in Table 5.

These results show a similar pattern to those for straight propagation. On x86-64 for 10,000 stack frames, the current implementation takes almost 3× longer to catch and re-throw than simply propagating, while our implementation is 38× slower than when simply propagating. This factor of slowdown is to be expected given how fast our implementation is when not re-throwing, but also due to the multiple steps required to move the exception object into and then out of each stack frame. This is clearly a good target for optimisation, as such transfer is unnecessary. Despite this, our implementation yielded a 9× speedup over the standard implementation.

For 1000 stack frames on x86-64, the difference between execution times is larger, with our implementation executing 19× faster. With 100 frames, the results have a very high standard deviation, but there is a clear order of magnitude between the two times, indicating that the difference in performance remains largely independent of the number of frames.

On Arm, the additional time taken to initialise the exception state in our implementation is evident, as it takes roughly five times longer than in the propagation benchmark. The standard implementation also suffers a performance hit, but one which decreases as the number of frames increases, suggesting that a large part of it is constant. This matches the fact that in the standard implementation the exception object is allocated on the heap, creating a large up-front cost, but one which is amortised across many re-throwings.

In reality, however, re-throwing at every frame is highly unusual behaviour, making both this amortisation and our worsening performance unlikely to be noticed.

4.3 Timing and Memory Determinism

We base our understanding of the language and algorithmic requirements for determinism on Verber and Colnaric [20]. In general, the requirements for deterministic execution fall into two categories: *deterministic memory usage*, and *deterministic execution time*.

For *memory usage*, we can further subdivide the requirement into *stack* usage, and *heap* usage. When no exception occurs, our stack usage is static. A fixed-size allocation for the exception state occurs per `noexcept` function invocation, throwing destructor invocation, and `try` block entry.

When an exception is thrown, the object is either allocated with a fixed size determined by the catch block, or with a variable size that can be bounded by the maximum allocation size of all exception objects thrown. The functions called by our implementation have a well-defined order and number known at compile-time and are not recursive. While pointers are used to store this address, their addresses are fixed within the range of the exception object buffer, or the current stack frame.

Our implementation does not require heap allocation. However, it is possible for the program to allocate an arbitrary amount of memory, if local object destructors throw exceptions. For example, during stack unwinding, destructors may throw an exception, causing their own local objects to be destroyed, which in turn may throw additional exceptions.

However, since this potential execution flow is known at compile-time, and is akin to normal function calls made directly via their function definition, rather than via function pointer, static analysis tools are able to give a bound for the number and type of exceptions thrown, and thus the maximum size of allocation. Furthermore, due to the nature of stack unwinding, recursion is not possible, except where introduced explicitly by the developer's code, and thus the number of stack frames is known.

Deterministic *execution time* generally refers to the ability to calculate the worst-case execution time (WCET), as demanded by most real-time systems. For execution time, unlike with existing implementations, it is trivial to calculate the WCET of all of our operations. Aside from the allocation and initialisation of the local exception state, and the checking of the `active` flag (all of which have deterministic timing) we have three operations.

The first allocates the exception object in the exception buffer. In this case, the allocator is a stack allocator, which merely advances a pointer, except where the developer does not specify a correct maximum bound on exception allocation. The second frees the exception object, which again is trivially a pointer decrement. The final function resolves the base class "type id"s when matching polymorphic exception types against catch handlers. Our implementation's novel approach guarantees a fixed number of iterations through the list of base classes, again known at compile time and derived from the filter of the catch block.

Therefore, should a WCET analysis tool give correct predictions for programs not using exceptions, it would also give such predictions for our implementation, meeting the criteria for determinism.

5 RELATED WORK

Modern exception handling, including the semantics of *raising* (throwing) and *handling* (catching) exceptions, exception hierarchies, and control flow requirements were first introduced in [6].

In [11] inherent overheads, both in terms of execution time and memory usage, in the current C++ implementations of exceptions are identified. A further evaluation on how C++ features impact embedded systems software is presented in [16]. This report singles out exceptions and its prerequisite run-time type information (RTTI) as "the single most expensive feature an embedded design may consider".

Lang and Stuart [12] describe stack unwinding as it relates to exceptions in real-time systems and show how the worst-case execution time of the stack unwinding is unbounded. This has later been confirmed in [9]. For our own definition of determinism, we take insight from [20], which details many of the requirements necessary for languages to be susceptible to time analysis.

A new exception handling approach which is better suited to static analysis is presented in [13], but it requires substantial code rewriting. SetJmp/LongJmp and table-based exception handling are discussed in[3]. The results demonstrate large increases in binary size and an execution time overhead of 10-15%. Gylfason and Hjalmtysson [8] develop a variant of table-based exception handling for use within the Itanium port of the Linux kernel.

Most relevant to the work present in this paper is [19]. It focuses on propagating exceptions down the stack by duplexing the return value of functions so as to fit the exception object itself within the register or stack memory used for the return value, and, importantly, to re-use the existing function return mechanism to perform stack unwinding. This approach hinges on two complex changes to C++'s function calling convention, though. This kind of change would be significant, breaking compatibility with C code and all existing C++ libraries. Instead, our novel exception implementation maintains the existing exception model by finding a new way to store and match exceptions at run-time, with little to no additional performance impact when exceptions are not thrown.

6 SUMMARY & CONCLUSIONS

In this paper we have developed a novel implementation of C++ exceptions, which better suits the requirements of embedded systems, while still upholding the C++ core design tenets. Our implementation shows binary size decreases of up to 82.3% over existing implementations, performance improvements of up to 325% when handling exceptions, minimal execution time overhead on x86-64, and none on the Arm platform. We have shown that our implementation achieves memory and execution time determinism, making it significantly better-suited to calculating worst-case execution times, a major hurdle in the adoption of exceptions.

Our future work will investigate further code size improvements resulting from code optimizations and shrinking of the exception state object, while reducing execution time by allocating the `active` flag in the exception state to a register.

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