Exception Handling ABI for the Arm® Architecture

2021Q1

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arm

1 Preamble

1.1 Abstract

This document describes the exception handling component of the Application Binary Interface (ABI) for the Arm architecture. It covers the exception handling model, encoding in relocatable ELF files, language-independent unwinding, and C++-specific aspects.

1.2 Keywords

Stack unwinding, exception handling

1.3 Latest release and defects report

Please check Application Binary Interface for the Arm® Architecture for the latest release of this document.

Please report defects in this specification to the issue tracker page on GitHub.

1.4 Licence

1.5 About the license

As identified more fully in the Licence section, this project is licensed under CC-BY-SA-4.0 along with an additional patent license. The language in the additional patent license is largely identical to that in Apache-2.0 (specifically, Section 3 of Apache-2.0 as reflected at https://www.apache.org/licenses/LICENSE-2.0) with two exceptions.

First, several changes were made related to the defined terms so as to reflect the fact that such defined terms need to align with the terminology in CC-BY-SA-4.0 rather than Apache-2.0 (e.g., changing “Work” to “Licensed Material”).

Second, the defensive termination clause was changed such that the scope of defensive termination applies to “any licenses granted to You” (rather than “any patent licenses granted to You”). This change is intended to help maintain a healthy ecosystem by providing additional protection to the community against patent litigation claims.

1.6 Contributions

Contributions to this project are licensed under an inbound=outbound model such that any such contributions are licensed by the contributor under the same terms as those in the Licence section.

1.7 Trademark notice

1.8 Copyright

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2 About this document

2.1 Change control

2.1.1 *Current status and anticipated changes*

The following support level definitions are used by the Arm ABI specifications:

Release

Arm considers this specification to have enough implementations, which have received sufficient testing, to verify that it is correct. The details of these criteria are dependent on the scale and complexity of the change over previous versions: small, simple changes might only require one implementation, but more complex changes require multiple independent implementations, which have been rigorously tested for cross-compatibility. Arm anticipates that future changes to this specification will be limited to typographical corrections, clarifications and compatible extensions.

Beta

Arm considers this specification to be complete, but existing implementations do not meet the requirements for confidence in its release quality. Arm may need to make incompatible changes if issues emerge from its implementation.

Alpha

The content of this specification is a draft, and Arm considers the likelihood of future incompatible changes to be significant.

All content in this document is at the **Release** quality level.

2.1.2 *Change history*

If there is no entry in the change history table for a release, there are no changes to the content of the document for that release.

Issue	Date	Change
1.0		First public release.
2.0	24th March 2005	Second public release.
2.01	22nd August 2005	Minor typographical corrections in Exception-handling table entries.
2.02	5th October 2005	Add __cxa_get_exception_ptr, _Unwind_DeleteException, and VFP v3 support. Minor edits for clarity.
2.03	31st October 2006	Minor edits for clarity, particularly regarding use of the exception_cleanup field. Change to _Unwind_State type.
2.04	25th January 2007	Tiny clarification at end of paragraph 5 in Phase 2 unwinding.
A	25th October 2007	Document renumbered (formerly GENC-003536 v2.04).
B	24th November 2015	Use UAL instruction mnemonics where possible.
2018Q4	21st December 2018	Minor typographical fixes, updated links.

Issue	Date	Change
2020Q3	1st October 2020	• document released on Github • new Licence: CC-BY-SA-4.0 • new sections on Contributions, Trademark notice, and Copyright
2021Q1	12th April 2021	Added PACBTI-M unwinding information.

2.2 References

This document refers to, or is referred to by, the following documents.

Ref	URL or other external reference	Title
AAELF32		ELF for the Arm Architecture.
BSABI32		ABI for the Arm Architecture (Base Standard)
CPPABI32		C++ ABI for the Arm Architecture
EHABI32		Exception Handling ABI for the Arm Architecture. (*This document*)
ARMARM	Arm DDI 0100E, ISBN 0 201 737191 (Also from ARMv5 Architecture Reference Manual)	The Arm Architecture Reference Manual, 2nd edition, edited by David Seal, published by Addison-Wesley.
	Arm DDI 0406 (ARM Architecture Reference Manual ARMv7-A and ARMv7-R edition)	Arm Architecture Reference Manual Arm v7-A and Arm v7-R edition
HPIA64	IEEE Concurrency, October-December 2000, pp72-79	*C++ Exception Handling*, by Christophe de Dinechin.

2.3 Terms and abbreviations

The ABI for the Arm Architecture uses the following terms and abbreviations:

AAPCS

Procedure Call Standard for the Arm Architecture.

ABI

Application Binary Interface:

1. The specifications to which an executable must conform in order to execute in a specific execution environment. For example, the *Linux ABI for the Arm Architecture*.
2. A particular aspect of the specifications to which independently produced relocatable files must conform in order to be statically linkable and executable. For example, the AAELF32, RTABI32, ...

AEABI

(Embedded) ABI for the Arm architecture (this ABI...)

Arm-based

... based on the Arm architecture ...

Branch Target Identification

Security technique ensuring a degree of control flow integrity by marking valid targets of indirect branches.

core registers

The general purpose registers visible in the Arm architecture's programmer's model, typically r0-r12, SP, LR, PC, and CPSR.

EABI

An ABI suited to the needs of embedded, and deeply embedded (sometimes called *free standing*), applications.

Q-o-I

Quality of Implementation – a quality, behavior, functionality, or mechanism not required by this standard, but which might be provided by systems conforming to it. Q-o-I is often used to describe the tool-chain-specific means by which a standard requirement is met.

VFP

The Arm architecture's Floating Point architecture and instruction set. In this ABI, this abbreviation includes all floating point variants regardless of whether or not vector (V) mode is supported.

2.4 Acknowledgements

This specification has been developed with the active support of the following organizations. In alphabetical order: Arm, CodeSourcery, Intel, Metrowerks, Montavista, Nexus Electronics, PalmSource, Symbian, Texas Instruments, and Wind River.

3 Introduction And Scope

Catching an exception at run-time in languages such as C++ depends on run-time support code to:

- Unwind the stack of procedure activation records (or call frames) and call any clean-up code associated with each activation record.
- Check whether any handler associated with a frame matches the exception, and call it if it does.

There are several different implementation strategies for exception handling offering a trade off among:

- The impact of the catching exceptions on the size and performance of non-exceptional execution paths.

  For example, the implementation of exception handling that uses `setjmp` and `longjmp` adds to normal execution paths the cost of:

  - Registering object destructors in each function that creates objects that must be destroyed on passing or handling an exception.
  - Registering handlers in each function that catches exceptions.

- The performance of handling a thrown exception.

  For example, interpreting separate unwinding tables is probably 1,000 times slower than `longjmp`.

- The amount of auxiliary data that must be generated by an object producer, even for code that does not handle exceptions (which can be especially irksome for assembly language programmers).

  For example, producing separate unwinding tables is an overhead on all functions, whether they are intended to propagate exceptions or not. On the other hand, it may be possible to generate such tables from the debug (e.g. DWARF-2) call-frame description tables that object producers generate anyway.

In common with the IA-64 runtime architecture, the Arm Exception ABI specifies separate, per-function unwinding tables indexed by program counter. Each unwinding table entry specifies:

- How to unwind the stack frame associated with the function the program counter is in.
- How to perform language-specific actions associated with unwinding the stack frame such as destroying objects about to go out of scope.
- How to locate and transfer control to handlers associated with this function.

Some useful characteristics of this architecture are:

- Executables that promise not to throw exceptions (or for which throwing an exception is a catastrophic event) can discard their unwinding tables and any associated run-time support.
- Save in functions containing try {…} catch {…} blocks where additional, implicit flow-graph arcs inhibit code improvement, there are few code-generation concessions to propagating exceptions. In particular, exception-propagating code can still be optimized effectively (see [HPIA64] for a discussion of the issues).
- There is clean separation between local aspects of handling exceptions—managed by object producers—and the global aspects standardized by the EABI and the run-time system.

To minimize the impact on code generation, the scope of this architecture is limited to exceptions thrown within a thread of execution by calling the system-wide *throw* function, and caught within the same thread. Consequently:

- An exception can only appear to be thrown at the site of a function call, and leaf functions are exception-free.
- Function prologues and epilogues are exception-free, which simplifies unwinding, and exceptions create no additional barriers to code motion (function calls are significant barriers to code motion anyway).
- A hardware trap such as divide-by-zero or a floating-point exception cannot be caught directly. Rather, a function must wrap any operation likely to trap, catch the trap if it occurs, then throw an appropriate exception.

4 Design principles

Exception handling affects:

- The interface between relocatable object producers (such as compilers) and static linkers.
- The interface between object producers and run-time support code.
- The interface between static linkers and execution environments.

The encoding of exception tables in relocatable objects need not be the same as in executable files.

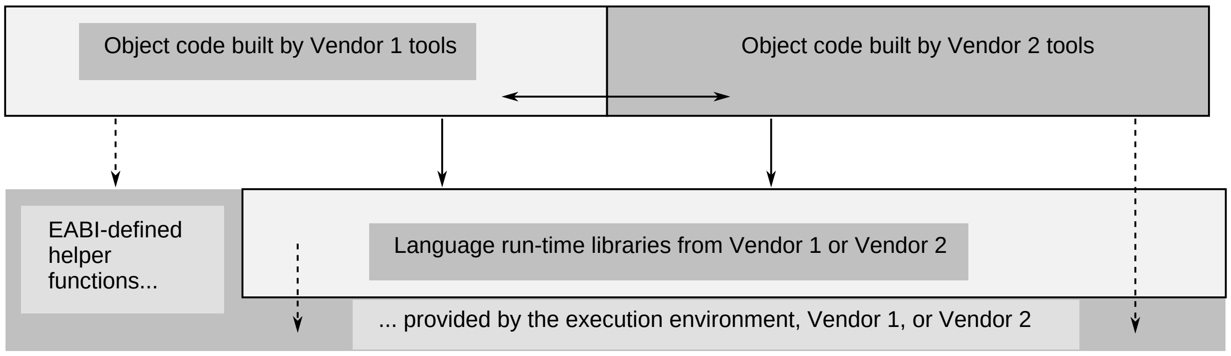
- The ABI for the Arm architecture controls the representation of exception-handling data in relocatable files.
- Separate supplements control the representation in executables for specific execution environments.

4.1 The execution-environment model

The ABI for the Arm architecture ([BSABI32]) specifies four generic execution environments, one “bare metal” and three OS-based.

- In each of the three OS-based environments, the encoding of exception tables in the execution environment is part of the program execution ABI for that environment.
- In the bare metal, or no OS, environment, there is no run-time agent to care about the format of exception tables other than the run-time support code. In this generic environment, a private agreement between the run-time support code and the static linker can determine the execution-time format of exception tables.

Hitherto, the ABI for the Arm architecture has permitted private agreement between a static linker and run-time support code. In practice, it is difficult to define an open interface between arbitrary run-time support functions. Realistically, there can only be one run-time system in a program, as depicted in the figure below.


Object code built by Vendor 1 tools
Object code built by Vendor 2 tools
EABI-defined helper functions...
Language run-time libraries from Vendor 1 or Vendor 2
... provided by the execution environment, Vendor 1, or Vendor 2

Run-time calls governed by the ABI for the Arm architecture (EABI)

The interface between functions built with different tool chains is, by definition, *exported*, so it is governed by the EABI. The interface to a run-time library defined by a programming language standard is also *exported*, and hence governed by the EABI. Solid arrows depict calls across such interfaces in the figure above.

Some helper functions are specified by the EABI. *All* run-time libraries must provide these (unless the execution environment provides them) even though no programming language standard specifies them. Some, such as, integer divide and software floating-point arithmetic functions, are universally needed, while others—for example, the functions described in The generic C++ exception handling ABI that implement generic C++ exception handling—allow code built by one tool chain to work with code built by another. Dashed arrows depict calls to such helper functions in the figure above.

Other helper functions are private to the language implementation. When an object built with that implementation is distributed for possible linking with objects built by other implementations, its private (implementation-specific) helper functions must be distributed with it.

4.1.1 The linker must match the run-time support code

All this suggests the following principle, which we adopt in relation to exception processing.

- In a static link step involving relocatable objects generated by different producers, the static linker and the run-time support code must be from the same tool chain.

Aside

This allows a static linker for a standalone execution environment to encode fully linked exception tables in any way acceptable to the matching run-time system.

4.2 The ELF model

4.2.1 Relocatable ELF

A design principle underlying ELF [AAELF32] can be caricatured as *smart format, dumb linker*. That's not to say that intelligent linking is precluded, or that the linking process is trivial, but to emphasize that the way a collection of relocatable objects should be processed should be explicit in those objects, with no hidden contract between object producers and the static linker.

4.2.2 Executable ELF

The execution environment determines the format of an executable or shared object. Historically, ELF as an execution format has been associated with Unix System V-based execution environments (such as Arm Linux).

4.2.3 Principles of usage

This suggests the following principles, which we adopt in relation to exception processing.

- At the interface between relocatable object producers and static linkers we give priority to ease of producing complete, precise exception table descriptions that can be processed straightforwardly by static linkers.
- At the interface between a fully linked executable (or shared object) and its execution environment, a post-processor should be able to generate the environment-specific encoding of the exception table from the generic form.

Aside

In practice, we expect such post-processing to be integrated into platform-specific linkers.

5 The top-level exception handling architecture

Except where stated otherwise, this section describes the execution architecture that would be created by a dumb linker. Object producers must emit object conformant with these descriptions. A dumb linker can take the objects and the matching runtime libraries and produce a working implementation by performing only standard linking operations. A smart linker might create a different execution architecture or simply a minor variant (for example it might change table index encoding to improve compaction), in which case compatible support code must be available in the associated environment runtime libraries.

5.1 Overview for executables, shared objects, and DLLs

This architecture applies to each independently loaded executable segment of a program. A program's executable segments comprise those of the root executable together with those from the shared objects or DLLs it links to dynamically.

Aside

A static link unit containing multiple executable segments destined for memory at disjoint addresses nonetheless has a single independently loaded executable segment for this purpose because the address relationships among such segments are either fixed or subject to load-time relocation. In any case, in all mainstream execution environments, each static link unit has precisely one executable segment.

With each independent executable segment we associate data structures that support unwinding:

- Exception handling tables for functions contained within the segment.
- A binary-searchable index table. Each entry associates a function with its exception-handling table.

The data structures are read-only at execution time and should be free of dynamic relocations, so that they are genuinely RO. To this end, references between them, and from them to code, are place-relative and hence position independent. References from them to writable or imported data are implemented in a platform-specific manner (possibly involving indirection through a dynamically relocatable location) which avoids the need to write into the structures at load-time.

5.2 The binary searched index table

Exception-handling table entries have a variable size. A handling table entry is found by searching a table of index entries. To support binary search, the index table must consist of contiguous fixed-size entries, each of which identifies a function start address, with the entries ordered by increasing function start address.

5.3 The exception-handling table

The exception-handling table (EHT) contains one entry for each non-leaf function that may need to be unwound. (By definition there are no entries for leaf functions because an exception can only be thrown from the site of a function call so a leaf function can never need unwinding).

A table entry has a variable size. It encodes, in a vendor- and language-specific way, the actions required to propagate an exception through the function. For C++ functions, this information is:

- How to unwind a stack frame associated with the function.

- How to perform any cleanup actions associated with the unwinding.
- How to locate handlers associated with the function.
- A description of exception types not blocked by this function.

Not all functions have cleanup actions or handlers and most functions simply pass all exceptions not handled.

In some usefully common cases, a handling table entry contains so little information that it's content can be packed directly into the index table entry (see Index table entries and Exception-handling table entries for details).

There are two table entry formats (again see Exception-handling table entries for details).

- **Generic**—a table entry consists of a place-relative offset to a function with an interface and run-time interaction protocol defined by this EHABI, followed by data in a format private to that function.
- **Compact**—a small number of bits encode the identity of the required function, facilitating the aforementioned packing.

This EHABI defines a number of compact formats, suitable for C++, C, and similar languages. We encourage language implementers to use these specific formats where possible (see Arm-defined personality routines and table formats for C and C++).

5.4 The object producer interface

5.4.1 Sections

An object producer must generate:

- One fragment of index table for each code section.
- One exception-handling table entry corresponding to each function that may need to be unwound.

Each fragment of index table (read-only data) must be generated in its own ELF section. It must contain an index entry for each non-leaf function in the associated code section, in the same order as that of the functions in the code section. The index table section name must be `.ARM.exidx` optionally followed by further characters. The section type must be SHT_ARM_EXIDX (see [AAELF32]). It must have the SHF_LINK_ORDER flag set in the sh_flags field of its section header and be linked to its associated code section via the sh_link field of its section header.

An object producer may generate exception-handling table entries (read-only data) in one ELF section, or one section per function. The name of a section containing an exception table fragment must be `.ARM.extab` optionally followed by further characters. The section type must be SHT_PROGBITS.

> ***Note***
>
> Tables are not required for ABI compliance at the C/Assembler level but are required for C++.

5.4.2 Relocations

A goal of the ABI is that it be possible to build object files that can be used on any target platform via appropriate platform-specific linking. This goal is supported by the provision of suitable relocations, whose use is mandated for some purposes in conformant object files. [AAELF32] and platform-ABI documents contain further details on this topic. This section describes the requirements placed on object producers so that RO exception tables are portable in this manner.

As stated earlier, exception tables should be free of dynamic relocations. A static relocation may be applied to an exception table for the following purposes:

- To reference an entity which, on all platforms, is within the same dynamic link unit as the exception table and is also RO. Such entities include exception tables and the code they are associated with.
- To reference other entities (potentially RW, or imported data). Such entities include C++ RTTI objects.
- To indicate a dependency, where this is not otherwise apparent to the linker. An example is a function that must be present in order to interpret a particular table format.

These uses are supported through the following means respectively (refer to [AAELF32] for additional details):

- A reference to RO in the same dynamic link unit is via an R_ARM_PREL31 relocation. Bit 31 of the relocated word does not participate in the relocation and may be used as data. The relocated 31 bits form a place-relative signed offset to the referenced entity. For brevity, this document will refer to the results of these relocations as “prel31 offsets”.
- Reference to other entities is via an R_ARM_TARGET2 relocation. This is a 32 bit relocation which on bare metal is equivalent to R_ABS32.
- Dependencies are indicated via an R_ARM_NONE relocation.

5.5 Tool chain quality of implementation issues

The collection of input objects passed to a static linker may be a mixture of objects with exception tables and objects lacking them. It must be possible to have the linker create an image from those objects. It is the user's responsibility to ensure functions that may participate in exception propagation have exception tables.

Smart linkers may support creation of exception tables under direction of the user. The information contained in a DWARF-2 or DWARF-3 call frame description can be translated into an unwinding description.

Some C compilers and assemblers may support creation of exception tables but this is not mandatory. For objects hand-written in assembly language it is more convenient where supported to rely on the assembler or linker to generate unwinding tables from the supplied frame information. If the tool chain cannot do this, any required tables must be defined explicitly in the assembly source.

5.6 Functional encapsulation

The exception propagation machinery is divided into:

- A language-independent component responsible for unwinding, that comprehends:
  - Platform-specific information, including representation of and manipulation of the machine state.
  - The content of exception index table entries and the language-independent first word of exception-handling table entries.
- Language-/implementation-specific components that implement the language-specific semantics of exception handling for each programming language in the image (one component per language).
- “Personality routines” which communicate with both of the above and which comprehend:
  - The programming language-specific semantics of exception handling.
  - The content of exception-handling table entries.

The interfaces and protocols for these are defined in detail later.

5.7 Restriction on implementation

It is mandatory that the machinery listed in Functional encapsulation is implemented using only the core (integer) registers as workspace, aside from when manipulating the real machine registers as part of a stack unwind. This permits demand-saving of non-core registers. In other words, when non-core registers need to be preserved over some operation (such as while searching the stack, see Language-independent unwinding library) they can be saved just before they are used, at the point when a reference to them in some stack frame is detected. They need not be saved on entry to the unwinder just in case the unwinder itself corrupts them. The usage restriction and demand-saving together confer two advantages that outweigh the costs:

- By using demand-saving, no additional mechanism is required to determine which registers are present in the execution environment – the mention of a register by the unwinding description of a live frame is sufficient guarantee of the register's existence. For example, on a platform without VFP there will be no attempt to use a VFP register at runtime and so no need to save or even consider saving the VFP registers.
- A single implementation can be compiled to execute on all hardware platforms regardless of which registers are present on a particular platform. This is important when mixing unwinding components from different vendors. Nevertheless it remains possible (for code size reasons, perhaps) to implement a restricted unwinder that only copes with a subset of possible execution environments (such as those without floating point).

6 Index table entries

An index table entry consists of 2 words.

- The first word contains a prel31 offset (see Relocations) to the start of a function, with bit 31 clear.
- The second word contains one of:
    - The prel31 offset of the start of the table entry for this function, with bit 31 clear.
    - The exception-handling table entry itself with bit 31 set, if it can be encoded in 31 bits (see The Arm-defined compact model).
    - The special bit pattern EXIDX_CANTUNWIND (0x1), indicating to run-time support code that associated frames cannot be unwound. On encountering this pattern the language-independent unwinding routines return a failure code to their caller, which should take an appropriate action such as calling terminate() or abort(). See Phase 1 unwinding and Phase 2 unwinding.

Note

- It is essential that link-time symbol vectoring (see [AAELF32]) does not break the index table's association between code and corresponding exception-handling tables. An index table entry first word must therefore not be constructed using a relocation (of 0) relative to *function symbol* since vectoring may attach *function symbol* to different code. A possible way for object producers to construct the first word is to use the section-relative offset of *function symbol*, or-d with 1 for a Thumb function, relocated by the place-relative offset to the *section symbol* for the section containing the function, since *section symbol* is not global and hence not vectorable.
- A table entry offset to be stored in the second word can be generated as 0 relocated by the *table entry symbol*, or as the offset of the table entry in the table section relocated by the *table section symbol*.
- EXIDX_CANTUNWIND is language-independent, so a smart linker may be able to group such entries (for smaller runtime table size) without needing to understand language-specific table encodings.

7 Exception-handling table entries

7.1 Overview

The unwinding of a function’s stack frame is performed by a *personality routine* capable of interpreting the exception-handling table (EHT) entry and unwinding the associated frame.

The language-independent unwinding library described in Language-independent unwinding library calls the personality routine to unwind a single stack frame. The arguments passed to the personality routine contain pointers to the function being unwound and its exception-handling table entry (see Language-independent unwinding types and functions).

The personality routine calls back to the language-independent unwinding library for various services, and calls a language-semantics library to maintain the particular language semantics.

Conceptually, an exception-handling table entry begins with the address of the personality routine:

```
/* See `Language-independent unwinding types and functions`_ for details of the various _Unwind types */
typedef _Unwind_Reason_Code (*PersonalityRoutine)(_Unwind_State,
                                                   _Unwind_Control_Block *,
                                                   _Unwind_Context *);
struct _Unwind_EHT_Entry {
  PersonalityRoutine pr;
  /*  then other data understood only by the personality routine */
};
```

Concretely, there are two possible encodings: the generic model, and the Arm-defined compact model. Bit 31 of the first entry word discriminates between them.

7.2 The generic model

An exception-handling table entry for the generic model is laid out as in the conceptual illustration above.

31	30 … 0
0	Offset of the personality routine
Data for the personality routine ...	

The address of the personality routine is encoded as a prel31 offset.

7.3 The Arm-defined compact model

Arm run-time systems additionally support a simple, compact model.

An exception-handling table entry for the compact model looks like:

31	30-28	27-24	23 … 0
1	0	index	Data for personalityRoutine[index]
More data for the personality routine ...			

Bits 24-27 select one of 16 personality routines defined by the run-time support code. Remaining bytes are data for that personality routine.

If the entire handling table entry fits in 4 bytes, the entry can be emitted inline in the index table instead (as described in Index table entries). Bit 31 then discriminates between such an inline entry and a prel31 offset to an entry in the handling table (for which bit 31 is 0).

Arm has allocated index numbers 0, 1 and 2 for use by C and C++. Arm-defined personality routines and table formats for C and C++ details the mapping from index numbers to personality routines and explains how to use them. Index numbers 3-15 are reserved for future use.

Object producers must emit an R_ARM_NONE relocation from an exception-handling table section to the required personality routine to indicate the dependency to the linker.

8 Language-independent unwinding library

8.1 Overview of operation

The language-independent component responsible for unwinding comprehends:

- Platform-specific information, including representation of and manipulation of the machine state.
- The content of exception index table entries (Index table entries) and the language-independent first word of exception-handling table entries (Exception-handling table entries).

This section describes the interfaces and behaviours of that component, and the protocol by which it interfaces to personality routines. The target environment runtime library must provide the language-independent *unwind library* routines specified in this section.

8.1.1 Terminology

When a function F calls some other function G, and G or one of its callees initiates a throw, the *apparently throwing call* in F is the call to G. The return address into F from G (ignoring any Thumb instruction set indicator in bit 0) denotes the *apparently throwing call site* in F.

From a language-independent unwinding viewpoint, a *propagation barrier* is a point at which a particular stack unwinding must cease. The code associated with a propagation barrier, a *handler*, retains control at the end of an exception propagation (and, indeed, returns it to the application).

A *cleanup* denotes some kind of frame-specific activity to be performed on a frame during unwinding (and also denotes the code that performs the activity) which on completion returns control to the unwinder. For example, C++ cleanups may destroy objects of automatic storage class.

A block of code associated with a parent function and entered for some purpose during exception propagation, such as to perform cleanup or to catch a thrown object, is called a *landing pad*. Sometime this phrase refers particularly to the initial part of such a code sequence.

A client language will implement handlers either as code reached via landing pads (for handlers specific to a particular parent function) or as independent functions (for handlers not tied to particular parent functions – an example is the C++ std::terminate() function).

8.1.2 Language-independent exception propagation

Stack unwinding happens in 2 phases:

- In phase 1 the stack is searched for a propagation barrier that will stop the eventual real unwinding.

  Such a barrier could be (in C++) a catch clause that will accept the exception object, or a function exception specification that will not allow the exception type to pass. C++ uses the general term ‘handler’ to refer to both a barrier and the code entered as a result of it.

Clearly, the recognition of a propagation barrier is language-/implementation-specific.

- In phase 2, the stack is unwound to the designated propagation barrier, performing cleanups on the way.

  The appropriate action (enter landing pad, call special routine...) is performed when the barrier is reached.

  Clearly, the action performed is language-/implementation-specific.

From a language-independent unwinding viewpoint, an exception propagation begins at the start of phase 1 and ends shortly after phase 2, when the handler notifies the unwinder that it has extracted any data it needs from the exception object. Particular languages may have a broader notion and may allow an exception object to be reused (re-thrown) from an exception handler. This is treated as a new exception propagation by the language-independent unwinder.

During phase 1, the language-independent unwinder calls the personality routine of a frame to discover whether a barrier exists within the frame. During phase 2 the personality routine is again called, this time to initialize internal state so that real unwinding may be performed. The language-independent unwinder transfers this internal state to the real machine so that execution is transferred to the designated code. After a cleanup, the personality routine will eventually be re-entered to decide what to do next; it is allowed to go round several cleanup cycles per frame. After dealing with all the cleanups it must use the frame unwinding information to load the internal state in a way that causes the frame to be removed from the stack. It then indicates this to the language-independent unwinder, which will locate the personality routine for the next frame and invoke it, and so on. This protocol is described in detail in Phase 1 unwinding and Phase 2 unwinding.

As stated, a cleanup should exit by returning control to the unwinder (possibly via an intermediate language-specific routine). Throwing out of a cleanup would violate this and is thus normally forbidden (C++ cleanups forbid exit by throw and the exception table covering their range should enforce this). Languages (if any) which need to permit throw out of a cleanup must take the necessary steps to explicitly terminate the previously active exception propagation. Also their cleanup may need its own cleanup. Infinite regression is avoided because eventually there must be a simple cleanup that does not end by throwing.

8.1.3 Exception propagation state

When propagating an exception through a particular function during unwinding phase 2, it is guaranteed that the first landing pad entered is entered in the machine state prevailing at the point of the apparently throwing call within that function, aside from any registers used to pass arguments to the landing pad. If the landing pad is a cleanup (so it returns control to the unwinder on exit) it is possible that further pads may be entered for the same function. The entry state for such pads is the exit state from the previous pad, again possibly modified by any arguments passed to the pad.

In particular when a pad is entered, the stack pointer has the value it had immediately before the call to the apparently throwing function (assuming stack-moves-once). It follows that no unwinding function stack frame can persist over a landing pad invocation. Therefore, all data needed to track the exception propagation state must be held in the thrown object itself, or be reachable from it, or be in thread-safe global store.

State information may be categorized according to its ownership and its duration. State may be conceptually owned by:

- The application.
- The language originating the propagation.
- The language owning the handler frame located for the propagation.
- The language owning a frame currently being unwound.
- The language-independent unwinder.

The most long-lived state is valid (not necessarily constant) over the lifetime of an object. Other state is valid for a shorter duration, such as over a single exception propagation, or across a cleanup.

The thrown object is divided into three parts to hold the long-lived state:

- The state in the throwing application's view.
  When a language initiates a throw, it throws a particular object that we call the *exception object* or EO. In C++, the EO is constructed from the object arising as the result of the *throw* expression.

- The state in the throwing language's view.

  The throwing language may need to maintain extra housekeeping information to ensure correct propagation semantics. It will hold this in the *language exception object* or LEO associated with the EO, and may also maintain some (thread-safe) language-specific global storage.

- State which every object has.

  This includes an indication of the originating language and implementation. This is held in the *unwinding control block* or UCB.

The UCB is also used to hold ephemeral state required for all exception propagations.

The contents of the LEO are specific to an implementation of the semantics library for the throwing language; implementations need not publish their details, and other languages and/or implementations will only understand them by agreement beyond the scope of this specification. The semantics library will update the contents of the LEO in response to calls made to the library's interface routines. The contents of the EO are specific to an implementation of a language; nonetheless, the language-specific components of the EO are governed by the ABI for the language (in the case of C++, the ABI of which this specification is a part). Provided the LEO and any implementation-specific fields of the EO are constructed by calling a library function, inter-working between independent ABI-conforming implementations is guaranteed by the *one run-time library* rule of The execution-environment model.

The UCB is defined as part of this ABI - see Language-independent unwinding types and functions.

Collectively the LEO, UCB and EO form an *exception control object* or ECO. ECOs may therefore differ in length. Each ECO has its own originating language, responsible for allocating store for the ECO and for releasing it when it is no longer required.

A pseudo-declaration for the exception control object is:

```
typedef struct ECO {
  LEO leo;              // contents are language-/implementation-dependent
  UCB ucb;              // size and content defined by this specification - see
                        // `Language-independent unwinding types and functions`_
// ... the application's pointer to an exception points here...
  EO eo;                // contents and size may vary
} ECO;
```

As the UCB (which has a specified size) immediately precedes the EO, it is easy for any language implementation to recover the address of the UCB given the address of the EO. The LEO and UCB themselves can be opaque (indeed invisible) to the code of the application, which sees only the EO.

8.2 Language-independent unwinding types and functions

The language-independent unwind library routines give access to environment-specific functionality.

Unwinding the stack (whether a real unwinding affecting the actual machine registers, or a virtual unwinding in which the machine-state is tracked through successive frames) requires one or more buffer areas to hold copies of the real machine registers or other relevant machine state. Such a buffer area is called a *virtual register set* or VRS. Virtual register set access routines are described separately in Virtual register set manipulation; the runtime representation is opaque to users of the unwind library and hence implementation-defined.

The rest of this section describes the unwind control block and the language-independent routines used to control exception propagation. The following types and functions are used:

```
typedef enum {
  _URC_OK = 0,                /* operation completed successfully */
  _URC_FOREIGN_EXCEPTION_CAUGHT = 1,
  _URC_HANDLER_FOUND = 6,
  _URC_INSTALL_CONTEXT = 7,
  _URC_CONTINUE_UNWIND = 8,
  _URC_FAILURE = 9            /* unspecified failure of some kind */
} _Unwind_Reason_Code;

typedef uint32_t _Unwind_State;

static const _Unwind_State _US_VIRTUAL_UNWIND_FRAME  = 0;
static const _Unwind_State _US_UNWIND_FRAME_STARTING = 1;
static const _Unwind_State _US_UNWIND_FRAME_RESUME   = 2;

typedef struct _Unwind_Control_Block _Unwind_Control_Block;
typedef struct _Unwind_Context _Unwind_Context;
typedef uint32_t _Unwind_EHT_Header;

typedef struct _Unwind_Control_Block {
  char exception_class[8];
  void (*exception_cleanup)(_Unwind_Reason_Code, _Unwind_Control_Block *);
  /* Unwinder cache, private fields for the unwinder's use */
  struct {
    uint32_t reserved1;     /* init reserved1 to 0, then don't touch */
    uint32_t reserved2;
    uint32_t reserved3;
    uint32_t reserved4;
    uint32_t reserved5;
  } unwinder_cache;
  /* Propagation barrier cache (valid after phase 1): */
  struct {
    uint32_t sp;
    uint32_t bitpattern[5];
  } barrier_cache;
  /* Cleanup cache (preserved over cleanup): */
  struct {
    uint32_t bitpattern[4];
  } cleanup_cache;
  /* Pr cache (for pr's benefit): */
  struct {
    uint32_t fnstart;             /* function start address */
    _Unwind_EHT_Header *ehtp;     /* pointer to EHT entry header word */
    uint32_t additional;          /* additional data */
    uint32_t reserved1;
  } pr_cache;
  long long int :0;               /* Force alignment of next item to 8-byte boundary */
} _Unwind_Control_Block;

/* Unwinding functions */
_Unwind_Reason_Code _Unwind_RaiseException(_Unwind_Control_Block *ucbp);
void _Unwind_Resume(_Unwind_Control_Block *ucbp);
void _Unwind_Complete(_Unwind_Control_Block *ucbp);
void _Unwind_DeleteException(_Unwind_Control_Block *ucbp);
```

_Unwind_Reason_Code is a general return type used for several purposes.

_Unwind_State values are passed to a personality routine by the unwinder to indicate what the personality routine being asked to do:

- _US_VIRTUAL_UNWIND_FRAME Used in phase 1. See Phase 1 unwinding.
- _US_UNWIND_FRAME_STARTING Used in phase 2. See Phase 2 unwinding.
- _US_UNWIND_FRAME_RESUME Used in phase 2. See Phase 2 unwinding.

To support future or private extensions, it is recommended that the personality routine exits with a failure code if it is passed an unexpected value for its _Unwind_State argument.

_Unwind_Context is an opaque type used as a handle to access a virtual register set. The unwinder passes an (_Unwind_Context *) to the personality routine. See Virtual register set manipulation.

The **_Unwind_Control_Block** contains members and substructures as follows;

- Exception_class is an 8 character identifier recording the originating language and implementation. Personality routines can use this to determine whether their own language originated the exception (and, for known foreign languages whose exceptions this language can catch, how to extract the language-specific data). By convention the first 4 bytes indicate the implementation and the second 4 bytes indicate the language. The Arm C++ implementation uses `ARM\0C++\0`.
- Exception_cleanup is used to support multi-language environments and to delete objects that are no longer required. See Cross-language support, and object deletion.
- Unwinder_cache is reserved for use by the language-independent unwind library, with the proviso that users of the library must initialize the reserved1 field to zero before the language-independent unwind routines first see the object.
- Barrier_cache is reserved for use by the language semantics library and personality routine associated with the stack frame in which the propagation barrier is located. All use by the semantics library routines forms part of the documented interface to those routines (and consequently the personality routine is free to use any members not explicitly claimed by the semantics library routines). See Phase 1 unwinding and Phase 2 unwinding.
- Cleanup_cache is reserved for use by a personality routine to save internal state whilst a cleanup runs. When the cleanup has finished, the personality routine will eventually regain control and it can recover its state from the cleanup cache and resume processing of the frame. Typically the personality routine would save a representation of the current position within the exception handling table. See Phase 2 unwinding.
- Pr_cache is reserved for use by the unwinder for passing data to the personality routine. The data passed includes:
  - fnstart, the start address of the function containing the apparently throwing call site.
  - ehtp, the start address of the exception-handling table entry.
  - additional, a word which may be used to pass additional information. Currently only the least significant bit is defined:

    Bit 0: single_word_EHT, a flag set if and only if the exception-handling table entry is known to occupy precisely one word. (Language-independent unwinding code only inspects the first word of the EHT entry and doesn't comprehend anything beyond that.)

There are several routines concerned with unwinding:

_Unwind_RaiseException begins a new exception propagation. See Phase 1 unwinding.

_Unwind_Resume resumes an existing exception propagation after execution of a cleanup. See Phase 2 unwinding.

_Unwind_Complete is called to indicate that the current propagation is entirely finished, and that the unwinder may perform any appropriate housekeeping. The details are implementation-defined, but see unwinding library implications for implementations.

_Unwind_DeleteException is described in Cross-language support, and object deletion.

8.3 Phase 1 unwinding

In phase 1, the stack is virtually unwound looking for a propagation barrier.

The language raising the exception will have allocated and initialized an ECO, and will then (from C++ via __cxa_throw, see ABI routines) call the language-independent routine _Unwind_RaiseException with a pointer to the UCB. This begins the propagation.

_Unwind_RaiseException captures the machine register-state on entry and copies it to a VRS. It copies the return address from VRS[r14] to VRS[r15] for the initial index table lookup. This saved state will be used repeatedly later. _Unwind_RaiseException should also allocate any resources required by the implementation to perform the propagation (these can later be deallocated by _Unwind_Complete – see unwinding library implications for implementations for further remarks).

_Unwind_RaiseException copies the VRS to a “temporary VRS” to preserve it over the stack scan. Scanning then proceeds as follows:

1. The index table is searched for the entry E that matches the return address (in VRS[r15]). If no matching entry is found, or if the entry contains the special bitpattern EXIDX_CANTUNWIND (see Index table entries), the unwinder returns to its caller with _URC_FAILURE and the caller should take appropriate language-specific action (in C++, call terminate()). Otherwise the personality routine (PR) for the frame is obtained via E, and the unwinder initializes the UCB pr_cache substructure. Finally it calls the PR, passing state _US_VIRTUAL_UNWIND_FRAME, the UCB pointer, and an _Unwind_Context pointer for VRS access.
2. The PR must discover whether this frame contains a propagation barrier to the exception object, by examining the EHT entry, pointed to from the UCB pr_cache. It must also adjust the VRS as necessary by calling functions in the language-independent unwinding library. It returns to _Unwind_RaiseException with one of:
   - Barrier found (_URC_HANDLER_FOUND)
   - No barrier (_URC_CONTINUE_UNWIND)
   - Error (_URC_FAILURE)
3. _URC_FAILURE indicates that some error occurred that prevented further processing (this includes falling off the top of the stack, or any other detected error). _Unwind_RaiseException returns to its caller with _URC_FAILURE.
4. _URC_CONTINUE_UNWIND indicates that no applicable propagation barrier was found in the function. Before returning, the PR is required to have done a virtual unwind by updating the VRS to reflect the machine state at the call to the current function. In particular the virtual unwind should set VRS[r15] to the return address into that previous function. The EHT entry must contain sufficient information about the function’s frame to support this (possibly in the form of a language-dependent, encoded unwind description). Scanning then continues with the next frame. **Go to** step 1.
5. In the _URC_HANDLER_FOUND case, the PR is required to initialize the UCB barrier_cache substructure before returning. It must save the SP value for the current frame and also anything mandated by the language semantics library of the language owning the frame. Typically it will also save such other information as it need to recognise the propagation barrier easily and unambiguously in phase 2. Usually this will be the address of some point in the EHT entry, and it may cache additional information to avoid re-computing it.

When the PR returns _URC_HANDLER_FOUND, _Unwind_RaiseException copies its “temporary VRS” back to the primary VRS and calls a private routine, for exposition named _Unwind_Next_Frame, with the UCB pointer to start phase 2 unwinding.

8.4 Phase 2 unwinding

In phase 2, the stack is really unwound and cleanups are run.

The VRS content at the start of phase 2 is that which existed at the start of the call to _Unwind_RaiseException. Unwinding will proceed frame by frame until a personality routine indicates it should stop, or an uncontinuable error is encountered.

Note

Statically detectable errors should be found during phase 1, allowing the throwing language to make a language-dependent response.

The details are as follows:

1. At the start of each new frame, _Unwind_Next_Frame is entered with a pointer to the UCB. It searches the index table for the entry E that matches the return address (in VRS[r15]). If no matching entry is found, or if the

entry contains the special bitpattern EXIDX_CANTUNWIND (see Index table entries), the unwinder will call abort(). Otherwise the personality routine (PR) for the frame is obtained via E, and the unwinder initializes the UCB pr_cache substructure. The unwinder must then preserve VRS[r15] by some means, as the value may be needed again after performing any cleanup initiated by the PR. Finally it calls the PR, passing state _US_UNWIND_FRAME_STARTING, the UCB pointer, and an _Unwind_Context pointer for VRS access.

   At this point:

   - The PR has just been entered for the first time for this frame.
   - The UCB pr_cache and barrier_cache substructures are valid.

2. The PR should now examine the EHT entry and the barrier_cache to decide what to do. It should return one of:

   - _URC_FAILURE
   - _URC_CONTINUE_UNWIND
   - _URC_INSTALL_CONTEXT

3. _URC_FAILURE indicates that some error occurred that prevented further processing. The unwinder will call abort().
4. _URC_CONTINUE_UNWIND indicates that the current frame has been fully dealt with, and that the PR has virtually unwound the frame. The PR does this by updating the VRS to reflect the machine state at the call to the current function, using the frame-specific unwind description. In particular the virtual unwind should set VRS[r15] to the return address into that previous function. The unwinder will (re)enter _Unwind_Next_Frame to initiate unwinding of the parent frame. **Go to** step 1.
5. _URC_INSTALL_CONTEXT instructs the unwinder to save any state it needs and then to upload the virtual register set to the real machine registers. This causes the unwinder frames to vanish and whatever routine the PR installed in VRS[r15] to be entered. The PR will make this return when it wants to run a cleanup or when it wants to enter the handler that was located during phase 1. The PR must have set up the VRS with the required register-state to enter the designated code, including any arguments it knows it must pass. If the PR expects to eventually get control back (after running a cleanup) it must also save in the UCB cleanup_cache substructure whatever state-tracking information it requires so it can resume scanning the EHT entry at the correct place on re-entry.

   Note

   In general an unwinder must load *all* the machine registers listed in the VRS.

   If Branch Target Identification mechanism is enabled, the unwinder may transfer control to the routine installed in VRS[r15] using a BTI-setting instruction that requires a BTI-clearing instruction at the destination.

6. After a cleanup has finished, the unwind must be continued by passing the UCB pointer to _Unwind_Resume. A cleanup may exit via some language-specific ABI-defined routine (in C++, __cxa_end_cleanup) to do this. The cleanup may have made changes to the machine register state which must not be lost, for example updating the value of a variable held in a register. Thus _Unwind_Resume must copy the registers to the VRS. It must set VRS[r15] to the value saved in step (1) as this may be required for further scanning of the EHT entry (and it must again preserve that value across the next PR call). _Unwind_Resume then calls the PR with state _US_UNWIND_FRAME_RESUME, the UCB pointer and an _Unwind_Context pointer. The PR should recover data that it saved in the UCB cleanup_cache, so that it can continue scanning the EHT entry from where it left off. **Go to** step 2.

Note

- The language-specific cleanup exit routine must not corrupt any significant registers before calling _Unwind_Resume, and may therefore require a small assembly wrapper if it additionally performs language-specific housekeeping. The intent of these register rules is that the compiler should not be unduly constrained when code-generating a cleanup fragment, and that the fragment's register saving can be minimised.

- It is expected that the unwinder will use the UCB unwinder_cache to preserve the VRS[r15] value over a PR call and cleanup.

8.5 Virtual register set manipulation

The Arm architecture defines a number of optional extensions such as VFP. The registers associated with such extensions are not present on all platforms; only the core (integer) registers are guaranteed present.

Aside

In this context a register is 'present' if instructions using it appear to work - the register (and instruction) could be physically present on the system or transparently emulated.

The in-memory representation of saved registers is not necessarily identical to the bitpatterns notionally in the registers, and very specific instruction sequences may be required to undo a register save. For example, restoring VFP registers saved by an FSTMX instruction, without using knowledge of the particular implementation, requires execution of the precisely matching FLDMX instruction (however these specific instructions are deprecated from Armv6 onwards – see [ARMARM]). In the general case, the representation and target register together dictate the machine instruction sequence to be used to restore the register - there may be many suitable sequences, or use of a single particular machine instruction may be necessary.

Frame unwind descriptions therefore describe not only which registers were saved, they also encode information about the saved representation, and thus the restore instruction sequence. A personality routine will interpret the unwinding sequence and must update the virtual register representation accordingly. To make this simpler, and to encapsulate the platform-specific details of managing the registers, routines are provided to carry out the necessary data movements. These must be passed the _Unwind_Context handle that the language-independent unwinder passed to the personality routine.

The interfaces support the data movements required on current systems, allow for future extension, and permit particular implementations to support only a subset of the possible registers if they so choose.

8.5.1 Control types

```
typedef enum {
_UVRSC_CORE = 0,          /* integer register */
  _UVRSC_VFP = 1,         /* vfp */
  _UVRSC_WMMXD = 3,       /* Intel WMMX data register */
  _UVRSC_WMMXC = 4,       /* Intel WMMX control register */
  _UVRSC_PSEUDO = 5       /* Special purpose pseudo register */
} _Unwind_VRS_RegClass;

typedef enum {
  _UVRSD_UINT32 = 0,
  _UVRSD_VFPX = 1,
  _UVRSD_UINT64 = 3,
  _UVRSD_FLOAT = 4,
  _UVRSD_DOUBLE = 5
} _Unwind_VRS_DataRepresentation;

typedef enum {
  _UVRSR_OK = 0,
  _UVRSR_NOT_IMPLEMENTED = 1,
  _UVRSR_FAILED = 2
} _Unwind_VRS_Result;
```

8.5.2 Assignment to VRS registers

```
_Unwind_VRS_Result _Unwind_VRS_Set(_Unwind_Context *context,
                                   _Unwind_VRS_RegClass regclass,
                                   uint32_t regno,
                                   _Unwind_VRS_DataRepresentation representation,
                                   void *valuep);
```

Valuep must be a pointer to suitably aligned memory. The return code conveys a meaning as follows:

_UVRSR_OK: Operation succeeded.

_UVRSR_NOT_IMPLEMENTED: Operation not implemented. The contents of the VRS are guaranteed unchanged by the call.

_UVRSR_FAILED: Operation failed in some unspecified way. The contents of the VRS are undefined (but registers of a class unrelated to the call will have been preserved - thus a failed call to set a VFP register would not corrupt any core register).

The behaviour is determined by examining the regclass and representation and is explained in the table below.

Behaviour of _Unwind_VRS_Set

Regclass	Representation	Regno	Behaviour
_UVRSC_CORE	_UVRSD_UINT32	0-15	Internally casts valuep to (uint32_t *) and sets the value of core register regno to the pointed-to value.
_UVRSC_VFP	_UVRSD_VFPX	0-15	Performs an FLDMX from the pointed-to memory to VFP register D<regno>.
_UVRSC_VFP	_UVRSD_FLOAT	0-31	Internally casts valuep to (float *) and sets the value of VFP register S<regno> to the pointed-to value as if by FMSR.

Regclass	Representation	Regno	Behaviour
_UVRSC_VFP	_UVRSD_UINT32	0-31	Internally casts valuep to (uint32_t *) and sets the value of VFP register S<regno> to the pointed-to value as if by FMSR. (This operation has effects identical with (_UVRSC_VFP, _UVRSD_FLOAT))
_UVRSC_VFP	_UVRSD_DOUBLE	0-31	Internally casts valuep to (double *) and sets the value of VFP register D<regno> to the pointed-to value as if by FMDHR,FMDLR.
_UVRSC_WMMXD	_UVRSD_UINT64	0-15	Internally casts valuep to (uint64_t *) and sets the value of WMMX data register regno to the pointed-to value.
_UVRSC_WMMXC	_UVRSD_UINT32	0-3	Internally casts valuep to (uint32_t *) and sets the value of WMMX control register regno to the pointed-to value.
_UVRSC_PSEUDO	_UVRSD_UINT32	0	Internally casts valuep to (uint32_t *) and sets the value of Return Address Authentication Code pseudo-register to the pointed-to value.

If a call is made with a (regclass, representation) pair not in the above table, the behaviour and return code are undefined.

Note

A given implementation is not required to implement all the above pairs. Calls featuring an unimplemented pair should yield return code _UVRSR_NOT_IMPLEMENTED. The (_UVRSC_CORE, _UVRSD_UINT32) pair must always be implemented.

8.5.3 Reading from VRS registers

Only a subset of the assignment representations are supported because usually the content of floating point registers is unknown.

```
_Unwind_VRS_Result _Unwind_VRS_Get(_Unwind_Context *context,
                                   _Unwind_VRS_RegClass regclass,
                                   uint32_t regno,
                                   _Unwind_VRS_DataRepresentation representation,
                                   void *valuep);
```

Valuep must be a pointer to suitably aligned memory. The return code conveys a meaning as follows:

_UVRSR_OK: Operation succeeded.

_UVRSR_NOT_IMPLEMENTED: Operation not implemented.

_UVRSR_FAILED: Operation failed in some unspecified way.

The behaviour is determined by examining the regclass and representation and is explained in the table below.

Behaviour of _Unwind_VRS_Get

Regclass	Representation	Regno	Behaviour
_UVRSC_CORE	_UVRSD_UINT32	0-15	Internally casts valuep to (uint32_t *) and stores the value of core register regno to the pointed-to memory.

Regclass	Representation	Regno	Behaviour
_UVRSC_VFP	_UVRSD_VFPX	0-15	Performs an FSTMX to the pointed-to memory from VFP register D<regno>.
_UVRSC_VFP	_UVRSD_DOUBLE	0-31	Performs an VSTM to the pointed-to memory from VFP register D<regno>.
_UVRSC_WMMXD	_UVRSD_UINT64	0-15	Internally casts valuep to (uint64_t *) and stores the value of WMMX data register regno to the pointed-to memory.
_UVRSC_WMMXC	_UVRSD_UINT32	0-3	Internally casts valuep to (uint32_t *) and stores the value of WMMX control register regno to the pointed-to memory.
_UVRSC_PSEUDO	_UVRSD_UINT32	0	Internally casts valuep to (uint32_t *) and stores the value of Return Address Authentication Code pseudo-register to the pointed-to memory.

If a call is made with a (regclass, representation) pair not in the above table, the behaviour and return code are undefined.

Note

A given implementation is not required to implement all the above pairs. Calls featuring an unimplemented pair should yield return code _UVRSR_NOT_IMPLEMENTED. The (_UVRSC_CORE, _UVRSD_UINT32) pair must always be implemented.

8.5.4 Moving from stack to VRS

```
_Unwind_VRS_Result _Unwind_VRS_Pop(_Unwind_Context *context,
                                   _Unwind_VRS_RegClass regclass,
                                   uint32_t discriminator,
                                   _Unwind_VRS_DataRepresentation representation);
```

Let 'VRS[R_SP]' denote the vrs stack pointer.

Commencing at the stack address contained in VRS[R_SP], pop registers from the stack to the VRS and (unless otherwise stated) afterwards update VRS[R_SP] to point to the next valid stack location. Return codes have the following meanings:

_UVRSR_OK: Operation succeeded.

_UVRSR_NOT_IMPLEMENTED: Operation not implemented. The contents of the VRS are guaranteed unchanged by the call.

_UVRSR_FAILED: Operation failed in some unspecified way. The contents of the VRS are undefined (but registers of a 'kind' unrelated to the call will have been preserved - thus a failed call to pop VFP registers would not corrupt any core register aside from VRS[R_SP]).

The behaviour is determined by examining the regclass and representation and is explained in the table below.

Behaviour of _Unwind_VRS_Pop

Regclass	Representation	Behaviour
_UVRSC_CORE	_UVRSD_UINT32	Pop core registers, on the assumption the operation is undoing an STMFD. The discriminator is a mask specifying the registers to pop (register rn represented by or'ing in 2^n). If R_SP appears in the mask, the value of VRS[R_SP] after the operation will be that loaded from the stack, rather than the usual the writeback value computed based on the number of registers popped. [Example: 0x00000060 transfers r5 and r6]
_UVRSC_VFP	_UVRSD_VFPX	Pop VFP registers, on the assumption the operation is undoing an FSTMFDX. The discriminator specifies the registers to pop, starting from the base register specified in the most significant halfword and transferring N consecutive registers where N is specified in the least significant halfword. [Example: 0x00040002 transfers D4 and D5]
_UVRSC_VFP	_UVRSD_DOUBLE	Pop VFP registers, on the assumption the operation is undoing one or more VPUSH instructions. The discriminator specifies the registers to pop, starting from the base register specified in the most significant halfword and transferring N consecutive registers where N is specified in the least significant halfword. [Example: 0x00040002 transfers D4 and D5]
_UVRSC_WMMXD	_UVRSD_UINT64	Pop Intel WMMX data registers, on the assumption the operation is undoing a sequence of WSTRD instructions which saved a contiguous register range with the lowest numbered register at the lowest stack address. The discriminator specifies the registers to pop, starting from the base register specified in the most significant halfword and transferring N consecutive registers where N is specified in the least significant halfword. [Example: 0x00040002 transfers wR4 and wR5]
_UVRSC_WMMXC	_UVRSD_UINT32	Pop Intel WMMX control registers, on the assumption the operation is undoing a sequence of WSTRW instructions which saved registers with the lowest numbered register at the lowest stack address. The discriminator is a mask specifying the registers to pop (register wCGRn represented by or'ing in 2^n). [Example: 0x0000000e transfers wCGR1, wCGR2 and wCGR3]
_UVRSC_PSEUDO	_UVRSD_UINT32	Pop a special-purpose pseudo-register, on the assumption the operation is undoing an STMFD. The discriminator specifies the register to pop. The Return Address Authentication Code pseudo-register is denoted by discriminator 0.

If a call is made with a (regclass, representation) pair not in the above table, the behaviour and return code are undefined.

Note

A given implementation is not required to implement all the above pairs. Calls featuring an unimplemented pair should yield return code _UVRSR_NOT_IMPLEMENTED. The (_UVRSC_CORE, _UVRSD_UINT32) pair must always be implemented.

8.6 Cross-language support, and object deletion

Language implementations must specify the circumstances under which they will catch exceptions thrown by other language implementations.

So-called ‘foreign exceptions’ can be caught by a catch-all propagation barrier (in C++: `catch (...)`), or by cooperation between the languages involving examination of the UCB exception_class field for a known language or implementation, and knowledge of type matching against that language/implementation.

After handling a foreign exception, if the handler is exited other than by re-throwing the exception, the language owning the exception object’s memory must be notified. The UCB contains an exception_cleanup member to receive this notification:

```
void (*exception_cleanup)(_Unwind_Reason_Code, struct _Unwind_Control_Block *);
```

The language that allocates the exception object should initialize this.

At the point where the exception object is no longer required by the handling language (e.g. when a handler is being exited), the handling language must make an indirect call through the exception_cleanup pointer (if non-NULL) with an _Unwind_Reason_Code and a pointer to the UCB. Permitted _Unwind_Reason_Codes are _URC_FOREIGN_EXCEPTION_CAUGHT and _URC_FAILURE. The exception_cleanup function will perform whatever language-dependent operation is appropriate, normally deletion of the object if it is no longer required.

The function _Unwind_DeleteException may be invoked to call the exception_cleanup function (if non-NULL) with _URC_FOREIGN_EXCEPTION_CAUGHT:

```
void _Unwind_DeleteException(_Unwind_Control_Block *ucbp);
```

A language is permitted to call its own exception_cleanup function under other circumstances.

Note

For legacy reasons the exception_cleanup pointer is allowed to be NULL, though this is not recommended.

8.7 unwinding library implications for implementations

Before the first propagation of an ECO, the semantics library which allocated the object is required to initialize the UCB unwinder_cache.reserved1 field to 0; the unwinder can subsequently use this field to co-ordinate its operations.

Some languages support the possibility of an ECO participating in more than one propagation at once. This can happen if a cleanup is able to obtain the exception object and re-throw it. In such cases state recorded in the ECO by the first propagation must not be destroyed by the second propagation.

Whether such a second propagation is permitted at all is in part a quality of implementation issue; at any point for any propagation the semantics library or unwinder might fail to obtain some resource they need and then refuse to continue. Nevertheless some languages are expected to permit such propagations even though they are likely to be very uncommon. Supporting them carries some code overhead so some implementations may elect to be smaller but non-compliant.

The decision of whether to permit a second propagation is initially made by the language semantics library. It must arrange that the second propagation does not destroy state held in the LEO, before passing control to the unwinder.

From the unwinder perspective, a given propagation begins when _Unwind_RaiseException is called and ends when _Unwind_Complete is called. The unwinder can allocate and release resources at these points and can also arrange to preserve and restore the UCB state over a second propagation.

_Unwind_Complete is therefore permitted to modify UCB fields whose contents are specific to a particular propagation, such as the barrier_cache. It must not modify fields that are independent of a particular propagation, such as the exception_class and exception_cleanup.

In C++, exception propagations must be strictly nested (the C++ Standard phrases this by saying that if a destructor called during stack unwinding exits with an exception, terminate() is called). Consider a hypothetical language L in which exception propagations aren't required to nest, but can overlap. Presumably in such a case, where one propagation 'overtakes another', the 'overtaken' propagation must be disposed of. Some slightly delicate analysis suggests that it would suffice to add one further _Unwind function that did this. The function would be called (from a semantics library routine for L) only when an exception object participated in more than propagation, and it would tidy up (discard) state saved for the previous (i.e. second-most-recent) propagation, thus disposing of that propagation. Support for this possibility will be deferred until demand for it arises.

9 The generic C++ exception handling ABI

9.1 Section overview

The C++ language exception semantics are implemented via calls to Standard Library routines and a set of ABI routines. The routines may be collected together into a single "C++ exception semantics library".

All compliant C++ exception semantics libraries should implement the functionality described in this section and will therefore be interchangeable aside from their interactions with the exception support of other languages. Recall that the exception_class member of every exception object identifies both the originating language and library vendor - implementations may differ in the support they provide for dealing with particular foreign exceptions.

Correct runtime behavior is achieved through co-operation between the application code, personality routines and handling tables. Where there is flexibility, personality routine authors should document the circumstances under which they call the semantics library routines and it is the responsibility of the compiler writer to ensure that application code, including landing pads, interacts with the personality routine's behavior to produce the correct runtime semantics.

C++ landing pads divide into two categories:

- Entry points to code fragments which eventually exit by resuming the current unwind, and therefore purely perform cleanups such as destroying automatic variables. We call these *cleanup landing pads*.
- Entry points to code fragments which eventually re-enter application code (such as catch handlers). The code fragment may optionally perform cleanups before control enters the handler. We call these *handler landing pads*.

The C++ Standard uses the general term 'handler' to refer to both a propagation barrier and the code entered as a result of it. Two special functions defined by the Standard – std::terminate() and std::unexpected() – should also be regarded as handlers when entered as a consequence of throwing an exception (see Appendix A – C++ Uncaught Exception Semantics for a further discussion of this). Programs are also allowed to call these functions directly, outside of an exceptions context.

Conceptually there is a stack of exception objects which are being handled (i.e. which have resulted in entry to a handler which has not yet exited). The item at the top of this stack is the *currently handled exception object*.

9.2 Data structures

A complete C++ exception control object consists of the C++ object being thrown (the EO), local housekeeping state (the LEO) and the language-independent unwinding control block (the UCB) as described in Exception propagation state. The size and content of the LEO are private to the semantics library implementation.

The semantics library mandates the following usage of the UCB barrier_cache. All C++ personality routines must respect this:

- On entry to a catch handler, ucbp->barrier_cache.bitpattern[0] must be the address of the type-matched object.
- __cxa_call_unexpected must be able to traverse the set of types associated with the violated function exception specification. The traversal is made possible via data passed in ucbp->barrier_cache.bitpattern[1] through [4] as follows:
- [1] A count N of type_info object references.
- [2] Unused (should be 0). [This member was used in earlier versions of the EHABI]
- [3] The stride S (in bytes) between successive type_info object references.
- [4] A pointer P to the first 4-byte type_info object reference.
- This asserts there are N type_info object references available, at addresses P, P+S, …, P+S*(N-1). This representation permits a variety of exception-handling table implementations at little cost. Each reference must

be the platform-specific result of resolving an R_ARM_TARGET2 relocation to the required type_info object (see Relocations). __cxa_call_unexpected will know how to follow these to the type_info objects.

9.3 Routines from the C++ Standard Library

The C++ exception semantics library must define the following routines which are part of the C++ Standard Library but which require knowledge of the implementation:

```
bool std::uncaught_exception(void)
void std::terminate(void)
std::terminate_handler std::set_terminate(std::terminate_handler h)
void std::unexpected(void)
std::unexpected_handler std::set_unexpected(std::unexpected_handler h)
```

9.4 ABI routines

All routines are declared `extern` “C”.

9.4.1 Compiler helper functions

Compiled C++ application code calls the following generic routines to implement C++ exception handling semantics.

```
void *__cxa_allocate_exception(size_t size);
void __cxa_free_exception(void *p);
void __cxa_throw(void *, const std::type_info *, void (*dtor)(void *));
void __cxa_rethrow(void);
void *__cxa_begin_catch(_Unwind_Control_Block *);
void *__cxa_get_exception_ptr(_Unwind_Control_Block *);
void __cxa_end_catch(void);
void __cxa_end_cleanup(void);
```

The routines are described below.

`void *__cxa_allocate_exception(size_t size)`

Size is the size (in bytes) of the EO type to be thrown. The routine allocates an area of thread-safe persistent store for the exception control object (the LEO + UCB + EO). If it fails to allocate the required memory it must call terminate(). It may initialize UCB fields, and may initialize some of the LEO. It returns a pointer to the (suitably aligned) EO for initialization by the caller.

Note

As the language is C++, the final 4 bytes of exception_class should be initialized to `C++\0`.

`void __cxa_free_exception(void *p)`

Releases the object into which p points. P must be the result of a call to __cxa_allocate_exception. The application should not call this explicitly in a handler (see __cxa_end_catch). It should call it only if the object has never been thrown via __cxa_throw.

`void __cxa_throw(void *p, const std::type_info *t, void (*d)(void))`

Initiate a throw. P must be the result of a call to __cxa_allocate_exception, and this routine must be used at most once per EO. T is a pointer to the type_info object for the EO type, and d is the address of the destructor for this type, or NULL if the type has no destructor. The destructor will be run automatically on the EO when the EO eventually requires destruction. __cxa_throw must complete initialization of the UCB and LEO begun by __cxa_allocate_exception (specifically, between them they must initialize the exception_class, exception_cleanup and unwinder_cache.reserved1 fields), perform housekeeping as required to indicate that a propagation has started, then call _Unwind_RaiseException to begin unwinding. __cxa_throw does not return to its caller.

`void __cxa_rethrow(void)`

The currently handled exception object may be rethrown (`throw;`) at any time. __cxa_rethrow calls terminate() if there is no currently handled exception. Otherwise it performs whatever housekeeping is required and re-throws the exception by calling _Unwind_RaiseException. This routine does not return.

Do not use this routine to resume unwinding at the end of a cleanup fragment – use __cxa_end_cleanup.

Note

Collaboration between __cxa_rethrow and __cxa_end_catch is required so that the latter never destroys an EO which is being re-thrown. See Handlers and landing pads.

`void *__cxa_begin_catch(_Unwind_Control_Block *)`

On entry, a handler is passed a pointer to the UCB. It must call __cxa_begin_catch with this pointer. __cxa_begin_catch must do the housekeeping required by C++ exception handling semantics and then return the contents of the UCB barrier_cache.bitpattern[0] field which, in the context of a catch handler, must have been set by the personality routine. If __cxa_begin_catch is called from a non-catch handler (see later notes on __cxa_call_terminate and __cxa_call_unexpected) the return value is undefined.

Immediately before returning, __cxa_begin_catch must call _Unwind_Complete.

See Handlers and landing pads for remarks on use of this routine.

Note

_Unwind_Complete may overwrite certain UCB fields whose contents are specific to the exception propagation that has just completed, including the barrier_cache, so any required values must be extracted before making that call. See unwinding library implications for implementations for more details.

`void *__cxa_get_exception_ptr(_Unwind_Control_Block *);`

Return the contents of the UCB barrier_cache.bitpattern[0] field which, in the context of a catch handler, must have been set by the personality routine. If __cxa_get_exception_ptr is called from a non-catch handler the return value is undefined. See Handlers and landing pads for remarks on use of this routine.

`void __cxa_end_catch(void)`

During exit from a handler for any reason, even by re-throwing, __cxa_end_catch must be called to do the housekeeping on the currently handled exception. If the ECO belongs to C++, and it is no longer required (if it is not currently caught in any other handler and is not being re-thrown), __cxa_end_catch must cause a call of the EO destructor if it has one, and then a call to __cxa_free_exception to free its memory. If the ECO belongs to some other language, __cxa_end_catch must call the ECO's exception_cleanup function if it is non-NULL, and the recommended way of doing that is by calling _Unwind_DeleteException. See Cross-language support, and object deletion and Catching foreign exceptions.

Note

Earlier versions of this specification stated that '__cxa_end_catch must call' the destructor and __cxa_free_exception, implying direct calls were mandatory. The calls need not be direct, and in particular languages may choose to move the calls into the exception_cleanup function and call that.

`void __cxa_end_cleanup(void)`

A cleanup must return control to the unwinding code by tail calling __cxa_end_cleanup. The routine performs whatever housekeeping is required and resumes the exception propagation by calling _Unwind_Resume. This routine does not return.

> ***Note***
>
> The cleanup may have made changes to the machine register state which must not be lost, for example updating the value of a variable held in a register. __cxa_end_cleanup must not corrupt any significant registers before calling _Unwind_Resume, and may therefore require a small assembly wrapper.

9.4.2 Personality routine helper functions

There are additional functions primarily intended for use by personality routines, but also callable from compiler-generated code should the compiler so choose:

```
bool __cxa_begin_cleanup(_Unwind_Control_Block *ucbp)
__cxa_type_match_result __cxa_type_match(_Unwind_Control_Block *ucbp,
                                         const std::type_info *rttip,
                                         bool is_reference_type,
                                         void **matched_object)
void __cxa_call_terminate(_Unwind_Control_Block *ucbp)
void __cxa_call_unexpected(_Unwind_Control_Block *ucbp)
```

They are described below.

`bool __cxa_begin_cleanup(_Unwind_Control_Block *ucbp)`

This routine must be called before entry to or early on during a cleanup, to allow the semantics library to perform any required housekeeping and to arrange that a later call to __cxa_end_cleanup can recover the UCB to resume unwinding. The routine returns false if any error occurs, else true.

> ***Note***
>
> The Arm-defined personality routines call this routine before entering a cleanup landing pad, so the landing pad itself must not call it if using these personality routines.

```
typedef enum {
     ctm_failed = 0,
     ctm_succeeded = 1,
     ctm_succeeded_with_ptr_to_base = 2
} __cxa_type_match_result;
__cxa_type_match_result __cxa_type_match(_Unwind_Control_Block *ucbp,
                                         const std::type_info *rttip,
                                         bool is_reference_type,
                                         void **matched_object)
```

Check a C++ type, described by rttip and is_reference_type, for exceptions type-compatibility with the type of the exception object associated with ucbp. If the check fails, return ctm_failed. On a successful match of a pointer-to-base-class against a thrown pointer-to-derived-class, set *matched_objectpp to the address of the matched base class object and return ctm_succeeded_with_ptr_to_base. For other successful matches, set *matched_objectpp to the address of what matched (the exception object itself or a base class of the exception object) and return ctm_succeeded.

Note

The rules for matching are specified by section 15.3 of the C++ Standard. The C++ Standards Committee Defect Report 126 states that the rules for matching types in function exception specifications are intended to be the same as those for catch. Hence __cxa_type_match may be used for both purposes.

`void __cxa_call_terminate(_Unwind_Control_Block *ucbp)`

If ucbp is non-NULL and the exception object is not foreign, call terminate() in a manner which invokes the terminate handler that was in force when the exception object was created. Otherwise call terminate() in a manner which invokes the current global terminate handler. This routine never returns.

__cxa_call_terminate should not be called directly by a personality routine. Rather the personality routine should load the virtual register set to invoke it and then return _URC_INSTALL_CONTEXT to its caller. Alternatively the compiler may elect to call this routine from a landing pad.

Note

Entry to terminate() as a consequence of an exception constitutes "handling" the exception. __cxa_call_terminate() must carry out the handler obligations of terminate() by calling __cxa_begin_catch (or otherwise implementing the same effects) unless ucbp is NULL. If __cxa_call_terminate() is called from a landing pad, the pad must not itself make a call to __cxa_begin_catch.

`void __cxa_call_unexpected(_Unwind_Control_Block *ucbp)`

Call unexpected() in a manner which invokes the unexpected handler that was in force when the exception object was created, or the global handler in the case of a foreign object. This routine never returns normally. If unexpected() exits via a throw, the routine must check the thrown type against the permitted types and act in accordance with the C++ semantics, either rethrowing the new object, throwing std::bad_exception, or calling terminate(). On entry the UCB barrier_cache.bitpattern fields must contain data as described in Data structures to support this type checking.

__cxa_call_unexpected should not be called directly by a personality routine. Rather the personality routine should load the virtual register set to invoke it and then return _URC_INSTALL_CONTEXT to its caller. Alternatively the compiler may elect to call this routine from a landing pad.

Note

Entry to unexpected() as a consequence of an exception constitutes "handling" the exception. __cxa_call_unexpected() must carry out the handler obligations of unexpected() by calling __cxa_begin_catch (or otherwise implementing the same effects) and calling __cxa_end_catch (or otherwise implementing the same effects) when it exits. If __cxa_call_unexpected() is called from a landing pad, the pad must not itself make calls to __cxa_begin_catch and __cxa_end_catch.

9.4.3 Auxiliary functions

There are a number of additional routines that interface to the library, and which may be called from generated code, from other library functions, or explicitly from user code:

```
void __cxa_bad_cast(void)
void __cxa_bad_typeid(void)
struct __cxa_eh_globals *__cxa_get_globals(void)
const std::type_info *__cxa_current_exception_type(void)
```

They are described below.

`void __cxa_bad_cast(void)`

Raise a bad_cast exception (see C++ Standard, section 18.5.2). The routine does not return to its caller.

`void __cxa_bad_typeid(void)`

Raise a bad_typeid exception (see C++ Standard, section 18.5.3). The routine does not return to its caller.

`struct __cxa_eh_globals *__cxa_get_globals(void)`

Returns a pointer to the implementation-defined exception 'globals', which are per-thread. The first time this function called, it arranges that the structure is properly allocated and initialized. In some implementations the function may reserve additional memory for exceptions use, so calling it early increases the likelihood of being able to throw a std::bad_alloc exception when the heap is exhausted. The return value should be ignored when the function is called for this purpose. The function will never return an invalid pointer (such as NULL); the action it takes on any failure (such as failure to allocate the memory) is implementation-defined.

`const std::type_info *__cxa_current_exception_type(void)`

Returns the type of the exception currently being handled, or NULL if there are no handled exceptions or a foreign (non-C++) exception object is involved.

9.5 C++ exception handling implications for implementations

9.5.1 *Expected implementations of __cxa_allocate_exception and __cxa_throw*

The C++ semantics require that if the implementation ever calls terminate() as a consequence of propagating an exception, the terminate handler called must be the one in force immediately after evaluating the throw expression. Similar remarks apply to unexpected(). Compiler writers should assume behavior as if __cxa_allocate_exception caches the current global handlers.

__cxa_throw calls _Unwind_RaiseException. If the latter cannot find a matching handler or other propagation barrier, it will return and __cxa_throw should call terminate().

9.5.2 *Order of events during throwing*

A possible order of events while throwing is:

- Evaluate the throw expression (which might itself throw).
- Obtain store for the EO via __cxa_allocate_exception.
- Copy the throw expression result to the EO, possibly by copy-construction.
- Call __cxa_throw().
- Different sequences may be used so long as the semantics are correct; for example if the throw expression cannot throw, evaluating it may be deferred until after the __cxa_allocate_exception call.
- If the copy construction throws, terminate() must be called. A possible implementation is to describe the copy construction call site suitably in the exception-handling table.

9.5.3 *Violation of function exception specifications*

In the case of a throw terminating because it violates a function exception specification, the runtime must arrange that automatics in the function body are destroyed and that eventually __cxa_call_unexpected is entered. Possible implementation strategies include:

- The personality routine runs cleanups, virtually unwinds the frame, updates the virtual register set to call __cxa_call_unexpected, and then returns _URC_INSTALL_CONTEXT. In this mode of operation, function exception specifications probably have a table encoding distinct from that of catch descriptions.

- The function exception specification is implemented as if by catch and rethrow of permitted types, with a default catch-all whose landing pad calls __cxa_call_unexpected. In this mode of operation, function exception specifications may have an encoding similar to that of catch descriptions.
- Whichever strategy is used, any permitted throw out of unexpected() must behave as if unwinding resumes at the call site to the function whose exception specification was violated.

9.5.4 Handlers and landing pads

A handler must call __cxa_begin_catch with a pointer to the UCB of the caught ECO. As __cxa_call_terminate and __cxa_call_unexpected are ATEPCS-compliant functions, they will expect the UCB pointer in r0. A handler landing pad must receive the UCB pointer in some register, and the personality routine specification will state which register (expected to be r0), so the compiler knows what code to generate.

When called in a catch context, __cxa_begin_catch and __cxa_get_exception_ptr will return a pointer to the object that matched the catch parameter type (the pointer is to either the EO itself or a non-leftmost base class of it, as placed in the barrier_cache by the personality routine). This pointer should be used to initialize the catch parameter if there is one. The C++ Standard mandates that object initialization is as if by copy construction and that any throw out of the copy construction must result in a call to terminate(). The copy construction region must be protected against throws accordingly.

Calling __cxa_begin_catch completes entry to a handler, and so the housekeeping it performs will include updating the result to be returned by std::uncaught_exception. The C++ Standard requires that any catch parameter is constructed as if the construction takes place before handler entry completes. Therefore a construction operation whose behavior might depend on whether an exception propagation is in progress – a non-trivial copy construction that might call std::uncaught_exception – must be performed *before* the call to __cxa_begin_catch, and the handler code will then be of the form:

```
Save UCB pointer somewhere (and move it to r0 if not already there)
BL __cxa_get_exception_ptr
Initialize catch parameter
Recover UCB pointer to r0
BL __cxa_begin_catch
```

Constructions whose behavior is independent of whether an exception propagation is in progress can use the shorter sequence:

```
Move UCB pointer to r0 if it is not already there
BL __cxa_begin_catch
Initialize catch parameter if there is one
```

Any exit from a handler requires a call to __cxa_end_catch. Exit from the handler by a means other than throwing should include an explicit call to __cxa_end_catch. Exit by throw requires interrupting propagation to call __cxa_end_catch, probably by creating a cleanup which does this. When exiting a catch handler, the C++ Standard semantics imply __cxa_end_catch should be invoked after destroying body automatics and the catch parameter.

Collaboration between __cxa_rethrow and __cxa_end_catch is required so that the latter never destroys an EO which is being re-thrown. This may be managed by having the LEO track both active propagations and active handlers of the EO.

9.6 Catching foreign exceptions

The aspects of this facility common to all languages are described in Cross-language support, and object deletion.

For C++ as the originating language, the exception_cleanup function must adjust the C++ data structures as appropriate so that the exception is no longer active and, if required, must cause the destructor to be called and the memory released.

For C++ to support catching foreign exceptions, __cxa_begin_catch() and __cxa_end_catch() must correctly cope with catching them and __cxa_rethrow() must be able to re-throw them.

10 Arm-defined personality routines and table formats for C and C++

10.1 Constraints on use

The language-independent run-time support code for this scheme can be distributed freely in binary form, so 3rd parties are encouraged to generate tables compatible with it.

Aside

Every language-specific run-time library must provide this language-independent functionality.

This model is intended to be suitable for Arm's C and C++ implementations as they stand now and as they are expected to develop in the foreseeable future, and also for third party implementations which adopt a similar, but not necessarily identical code generation strategy.

The operations required to unwind a stack frame are encoded as a sequence of bytes:

- Unwinding operations that occur [statically] frequently are encoded relatively compactly.
- Unwinding operations that occur [statically] infrequently are catered for, but less compactly.
- Some operation codes are left unallocated, for future expansion.

A single unwind description applies to the whole function. Thus it is required that the object code implementing a function can be partitioned into:

- An entry sequence, in which all register saving occurs and which cannot throw.
- One or more exit sequences, which restore registers and which cannot throw.
- Fragments which might throw.

The encoding requires that at all points within a function body from which unwinding can start (that is, from each function call site), the addresses of saved registers are compile-time offsets from a fixed register chosen by the compiler. Often this will be sp, but it may be an alternative frame pointer register. In other words, compilers have two choices.

- Do not adjust the stack pointer in the function body (only during entry and exit).
- Allocate a frame pointer register whose value is not changed in the function body.

The choice can be made on a per-function basis.

10.2 Personality routine exception-handling table entries

An exception-handling table entry is a sequence of words and halfwords, beginning on a word boundary.

The first word is as described in The Arm-defined compact model. The most significant byte encodes the index of the personality routine (PR) used to interpret what follows.

0 Su16—Short frame unwinding description followed by descriptors with 16-bit scope.

1 Lu16—Long frame unwinding description followed by descriptors with 16-bit scope.

2 Lu32— Long frame unwinding description followed by descriptors with 32-bit scope.

The corresponding personality routines are declared as:

```
extern "C" {
  _Unwind_Reason_Code __aeabi_unwind_cpp_pr0(_Unwind_State state,
                                             _Unwind_Control_Block *ucbp,
                                             _Unwind_Context *context);
  _Unwind_Reason_Code __aeabi_unwind_cpp_pr1(_Unwind_State state,
                                             _Unwind_Control_Block *ucbp,
                                             _Unwind_Context *context);
  _Unwind_Reason_Code __aeabi_unwind_cpp_pr2(_Unwind_State state,
                                             _Unwind_Control_Block *ucbp,
                                             _Unwind_Context *context);
}
```

Aside

As stated in The Arm-defined compact model, object producers must emit an R_ARM_NONE relocation from an exception-handling table section to the required personality routine to indicate the dependency to the linker.

A frame unwinding description is a sequence of unwinding instructions (described in Frame unwinding instructions) that can be interpreted byte by byte. There are two formats.

Short 3 unwinding instructions in bits 16-23, 8-15, and 0-7 of the first word. Any of the instructions can be *Finish*.

Long Bits 16-23 contain a count N of the number of additional 4-byte words that contain unwinding instructions. The sequence of unwinding instructions is packed into bits 8-15, 0-7, and the following N words. Spare trailing bytes in the last word should be filled with *Finish* instructions.

Unwinding instruction bytes are executed in order of significance within their containing word (most significant byte first) and in increasing word address order. An implicit *Finish* instruction is assumed to be positioned after all the explicitly present instructions.

Descriptors describe regions of interest within the function. There are three kinds of descriptor, each of which consists of a scope entry followed by some other data that depends on the kind of descriptor. The list of descriptors is terminated by a zero word (the first word of a valid descriptor entry can never be zero).

A scope encoding consists of the length of the scope (in bytes) followed by the offset within the function at which the scope starts. Consequently, the start S and length L map to the half-open address interval [S, S+L).

Aside

For example, in a table for an Arm-code function, a length of 4 specifies a range containing just one Arm instruction.

The length and offset can be short (16 bits) or long (32 bits) dependent on the personality routine used.

Both length and offset must be multiples of 2 and length must be non-0.

The least significant bits of length and offset encode the kind of descriptor as follows:

0,0 A cleanup descriptor—The scope is followed by a prel31 offset (see Relocations) to a landing pad, with bit 31 clear.

1,0 A catch descriptor—The scope is followed by a landing pad word and a word describing the type to be caught. The landing pad word contains a prel31 offset to a landing pad, with bit 31 set if the catch handler catches a reference type and bit 31 clear otherwise. The type description word should be one of:

- **A reference to a type_info object (the type of the handler),**

  resulting from an R_ARM_TARGET2 relocation.

- **The special encoding 0xffffffff (-1), denoting the *any* type in**

  `catch(...)`.

- **The special encoding 0xfffffffe (-2) denoting the *any* type in**

  `catch(...)` and requiring the personality routine to immediately return _URC_FAILURE; in this case the landing pad offset should be set to 0. This idiom may be used to prevent exception propagation out of the code covered by the associated scope.

  0,1 A function exception specification descriptor—The scope is followed by a sequence of words

  N type_info^1 ... type_info^N

  or

  N|0x80000000 type_info^1 ... type_info^N landing_pad_offset

  where N is an unsigned integer count (up to 31 bits) and type_info^i is a reference to a type_info object for a type which may be passed and which results from an R_ARM_TARGET2 relocation. The N==0 case represents the situation in which no types may be passed, corresponding to the source syntax 'throw()'. If the high bit is set in the word containing N, then the type_info list is followed by a prel31 landing pad offset (with bit 31 clear) to be entered in the event that no type matches the thrown type. High bit clear in the N word signifies that implicitly the no match case should result in a call to __cxa_call_unexpected. When the high bit clear format is used, object producers must emit an R_ARM_NONE relocation to __cxa_call_unexpected to indicate the dependency to the linker.

Descriptors are listed in depth first block order so that all applicable descriptors can be processed in a single linear scan of the handling table entry. Interpreting the tables explains how the personality routine processes a table.

Note

Recall that when the personality routine returns _URC_FAILURE, the language-independent unwinder will (in phase 1) return to its caller for a language-dependent response or (in phase 2) will call abort immediately. If the caller is C++, the language-dependent response in phase 1 is to call terminate(). See Phase 1 unwinding and Phase 2 unwinding for more details.

10.3 Frame unwinding instructions

The encoding makes only general assumptions about compiler implementations. For example, we assume that: code generators will prefer to:

- Use a compact subset of the callee-saved registers starting with r4—{r4}, {r4, r5}, {r4-r6}, … {r4-r11}—rather than an arbitrary subset.
- Maintain 8-byte stack alignment by saving {r4-r11, ip, lr} when {r4-r11, lr} must be saved.

ehabi32-table4, below, describes the Arm-defined frame-unwinding instructions used by personality routines 0, 1, and 2. Each instruction modifies a virtual stack pointer (vsp).

The implicit value of vsp at the start of a sequence of unwinding instructions is the value of sp that identifies the frame being unwound.

Upon completion of the unwinding instructions, the return address into the previous function must be in VRS[r15].

The encoding has been designed to meet the following criteria.

- It should be possible to unwind almost all frames using 3 or fewer unwinding instructions (short format).
- The frame unwinding instructions should (in principle) be straightforward to generate from DWARF .debug_frame descriptions.
- The following remarks clarify the table:

a. Code 0x80 0x00, *Refuse to unwind*, causes the PR to return _URC_FAILURE and hence prevents throwing out of the current function. Its behaviour is thus similar to EXIDX_CANTUNWIND (see Index table entries) but it permits descriptors in the function body.

b. 'Pop' generally denotes removal from the stack commencing at current vsp, with subsequent increment of vsp to beyond the removed quantities. The sole exception to this rule is popping r13, when the writeback of the loaded value to vsp is delayed until after the whole instruction has completed. When multiple registers are popped by a single instruction they are taken as lowest numbered register at lowest stack address.

c. Code 0xb0, *Finish*, conditionally copies VRS[r14] to VRS[r15] and also indicates that no further instructions are to be processed for this frame. The copy is performed only if the personality routine has not already updated VRS[r15] while unwinding the frame.

d. When popping N VFP registers saved (as if) by FSTMX, vsp is incremented by 8N + 4 and valid registers are D0-D15. When popping N VFP registers saved (as if) by VSTM/VPUSH, vsp is incremented by 8N, valid registers are D0-D31, and more than 16 registers may be specified in a single unwind instruction.

e. Some instructions can encode a register range that would appear to specify registers that are not present in any defined Arm architecture; such encodings are Reserved.

f. If a Reserved or Spare code is encountered, the PR will return _URC_FAILURE.

g. Functions, compiled with Return Address Authentication, will need to keep a pointer authentication code used to validate integrity of the return address upon function exit. The Return Address Authentication Code is an unsigned integer with the same size as a general-purpose register. Upon completion of the unwinding instructions, the Return Address Authentication Code can be used to validate the content of VRS[r15], using vsp as a modifier.

Arm-defined frame-unwinding instructions

Instruction	Explanation
`00xxxxxx`	vsp = vsp + (xxxxxx << 2) + 4. Covers range 0x04-0x100 inclusive
`01xxxxxx`	vsp = vsp – (xxxxxx << 2) - 4. Covers range 0x04-0x100 inclusive
`10000000 00000000`	Refuse to unwind (for example, out of a cleanup) (see **remark a**)
`1000iiii iiiiiiii` `(i not all 0)`	Pop up to 12 integer registers under masks {r15-r12}, {r11-r4} (see **remark b**)
`1001nnnn` `(nnnn != 13,15)`	Set vsp = r[nnnn]
`10011101`	Reserved as prefix for Arm register to register moves
`10011111`	Reserved as prefix for Intel Wireless MMX register to register moves
`10100nnn`	Pop r4-r[4+nnn]
`10101nnn`	Pop r4-r[4+nnn], r14
`10110000`	Finish (see **remark c**)
`10110001 00000000`	Spare (see **remark f**)

Instruction	Explanation
`10110001 0000iiii` `(i not all 0)`	Pop integer registers under mask {r3, r2, r1, r0}
`10110001 xxxxyyyy`	Spare (xxxx != 0000)
`10110010 uleb128`	vsp = vsp + 0x204+ (uleb128 << 2) (for vsp increments of 0x104-0x200, use 00xxxxxx twice)
`10110011 sssscccc`	Pop VFP double-precision registers D[ssss]-D[ssss+cccc] saved (as if) by FSTMFDX (see **remark d**)
`10110100`	Pop Return Address Authentication Code pseudo-register (see **remark g**)
`101101nn`	Spare (nn != 00, was Pop FPA)
`10111nnn`	Pop VFP double-precision registers D[8]-D[8+nnn] saved (as if) by FSTMFDX (see **remark d**)
`11000nnn (nnn != 6,7)`	Intel Wireless MMX pop wR[10]-wR[10+nnn]
`11000110 sssscccc`	Intel Wireless MMX pop wR[ssss]-wR[ssss+cccc] (see **remark e**)
`11000111 00000000`	Spare
`11000111 0000iiii`	Intel Wireless MMX pop wCGR registers under mask {wCGR3,2,1,0}
`11000111 xxxxyyyy`	Spare (xxxx != 0000)
`11001000 sssscccc`	Pop VFP double precision registers D[16+ssss]-D[16+ssss+cccc] saved (as if) by VPUSH (see **remarks d,e**)
`11001001 sssscccc`	Pop VFP double precision registers D[ssss]-D[ssss+cccc] saved (as if) by VPUSH (see **remark d**)
`11001yyy`	Spare (yyy != 000, 001)
`11010nnn`	Pop VFP double-precision registers D[8]-D[8+nnn] saved (as if) by VPUSH (see **remark d**)
`11xxxyyy`	Spare (xxx != 000, 001, 010)

It may be possible for application code to save registers in a variety of data representations. When restoring registers the personality routine will assume that the application saved the registers using the following representations:

- An integer register is assumed to be on the stack as if transferred by a STR instruction.
- A sequence of VFP registers encoded in a single unwind instruction are assumed to have been saved as if by FSTMFDX or VPUSH, depending on the unwind instruction used.
- A WMMX data register is assumed to have been saved as if by WSTRD.
- A WMMX control register is assumed to have been saved as if by WSTRW.

10.4 Interpreting the tables

Recall that the return address into the current function is in VRS[r15] on entry to the personality routine. The personality routines interpret an exception-handling table entry as follows:

The descriptors are traversed linearly.

Cleanup descriptors are ignored in phase 1. In phase 2, if the return address is within the specified range, the PR must update the virtual register set for entry to the landing pad, call __cxa_begin_cleanup (see ABI routines), save whatever it needs in the UCB cleanup_cache (see Language-independent unwinding types and functions) then return _URC_INSTALL_CONTEXT.

Catch descriptors are examined in phase 1. If the return address is within the specified range, the type of the thrown exception is checked for a match against the catch type. __cxa_type_match (see ABI routines) may be used when offset encodes a type_info object. A match denotes a propagation barrier and the PR should fill in the barrier_cache and return _URC_HANDLER_FOUND. On re-encountering the barrier in phase 2, the PR should set the VRS for landing pad entry (passing the UCB address in r0) and return _URC_INSTALL_CONTEXT.

Function exception specification descriptors are examined in phase 1. If the return address is within the specified range, the type of the thrown exception is checked for a match against the specified types. __cxa_type_match (see ABI routines) may be used. No match against any of the types denotes a propagation barrier and the PR should fill in the barrier_cache and return _URC_HANDLER_FOUND. On re-encountering the barrier in phase 2, the behaviour depends on whether the descriptor has an explicitly specified landing pad (signified by high bit set in the type count word) or not:

- If it does, the PR should set the VRS for entry to that pad (passing the UCB address in r0), ensure the data required for __cxa_call_unexpected is in the barrier_cache (see Data structures), and then return _URC_INSTALL_CONTEXT. The pad will call __cxa_call_unexpected.
- If it does not, the PR should execute the unwind description to virtually unwind the frame, set the VRS for entry to __cxa_call_unexpected (see ABI routines), ensure the data required for __cxa_call_unexpected is in the barrier_cache (see Data structures), then return _URC_INSTALL_CONTEXT.

If the PR has retained control after processing the final descriptor, it must execute the unwind description to virtually unwind the frame. It must then return _URC_CONTINUE_UNWIND, causing the unwinder to locate and initiate processing of the next frame.

The PR is not allowed to change its mind about a barrier between phase 1 and phase 2.

In summary, the Arm personality routines always pass a pointer to the UCB in r0 when entering a handler or a handler landing pad.

10.5 Arm personality routines implications for implementations

The Arm personality routines call __cxa_begin_cleanup (see ABI routines) before entering a cleanup landing pad, so the landing pad itself should not do so.

When a function exception specification has been violated on a function F called from function G, the C++ Standard requires that F's automatics are cleaned up before unexpected() is entered. If a successful rethrow out of unexpected() occurs, these automatics must not be destroyed a second time and more generally any table descriptors previously encountered while processing F must be ignored on this occasion; the behaviour must be as if unwinding resumes in G at the call site to F. Thus if F contains such descriptors, it is essential to change the apparently throwing call site from its current location in F before __cxa_call_unexpected is entered. There are 2 supported ways of doing this:

a. Entering a landing pad in G which then explicitly calls __cxa_call_unexpected.

b. Removing F's entire frame and then causing a call to __cxa_call_unexpected as if the call to F in G instead calls __cxa_call_unexpected.

Case (a) has a user-code overhead but allows F to be inlined in G. __cxa_call_unexpected must be entered by branch-and-link (or equivalent) so that the apparently throwing call site and corresponding return address in r14 change. Case (b) avoids the code overhead but has the consequence that the function exception specification descriptor for F must be the outermost descriptor for the apparently throwing call site within F. This usually means the associated scope will cover the whole of F. Also it is likely to prevent inlining of F (but not necessarily; F may be still be inlined into G provided the constraint that the descriptor is outermost for the call site is maintained. Thus if G has no descriptors whose scopes contain the call to F, F may be inlined and the frame for G will be removed when F's exception specification is violated. This may lead to a reduction in debuggability). It falls to the compiler to select the most appropriate implementation strategy in any particular case.

11 Implementation details

11.1 Thread safety

The implementation described here is thread safe provided that new() and delete() are thread safe.

Environments that do not care about thread safety may replace the function that finds the working space by one that owns an equivalent amount of static storage.

11.2 Stack unwinding

The runtime environment must ensure a stack unwind cannot proceed beyond the valid stack region, possibly by marking the caller of main() as EXIDX_CANTUNWIND.

12 Appendix A – C++ Uncaught Exception Semantics

The C++ standard is unclear about whether uncaught_exception() can ever be true even when all exceptions have been *caught*. This is very complicated, in part because the Standard is poorly phrased.

C++ DR208 (http://www.open-std.org/jtc1/sc22/wg21/docs/cwg_defects.html - 208) is an attempt to deal with some of the defects that arises in the Standard in the context of nested throws (specifically the behavior of *throw*). The status of *DR* assigned to this item means it is expected to be in the next Technical Corrigendum (though it appears not to be in the unofficial list of revisions published 1 September 2002). Nonetheless, we conclude that we should expect it to make the Standard, and so should pay attention to it (especially if it makes possible an implementation that was not previously possible).

Ignoring DR208 for now, the Standard lists the circumstances under which terminate() is called.

15.5.1 The terminate() function [except.terminate]

1. In the following situations exception handling must be abandoned for less subtle error handling techniques:

   - When the exception handling mechanism, after completing evaluation of the expression to be thrown but before the exception is caught (15.1), calls a user function that exits via an uncaught exception, [**Footnote.** For example, if the object being thrown is of a class with a copy constructor, terminate() will be called if that copy constructor exits with an exception during a throw. **End footnote**]
   - When the exception handling mechanism cannot find a handler for a thrown exception (15.3), or
   - When construction or destruction of a non-local object with static storage duration exits using an exception (3.6.2), or
   - When execution of a function registered with atexit exits using an exception (18.3), or
   - When a throw-expression with no operand attempts to rethrow an exception and no exception is being handled (15.1), or
   - When unexpected throws an exception which is not allowed by the previously violated exception-specification, and std::bad_exception is not included in that exception-specification (15.5.2), or
   - When the implementation's default unexpected_handler is called (18.6.2.2)

2. In such cases, void terminate() is called (18.6.3). In the situation where no matching handler is found, it is implementation-defined whether or not the stack is unwound before terminate() is called. In all other situations, the stack shall not be unwound before terminate() is called. An implementation is not permitted to finish stack unwinding prematurely based on a determination that the unwind process will eventually cause a call to terminate().

In summary, terminate() is called by the implementation under several circumstances while a throw is in progress (where *in progress* means from the end of throw expression evaluation (before end of copy-construction, if such is required), until the exception is *caught*).

There is also this section:

> 18.6.3.3 terminate [lib.terminate]
>
> void terminate();
>
> 1. Called by the implementation when exception handling must be abandoned for any of several reasons (15.5.1). May also be called directly by the program.
> 2. Effects: Calls the terminate_handler function in effect immediately after evaluating the throw-expression (18.6.3.1), if called by the implementation, or calls the current terminate_handler function, if called by the program.

So terminate() can also be called by the user, and needs to discover which terminate_handler to call. The terminate_handler to call depends on who called terminate(), not on whether an exception is/was in progress.

The above extracts use the terms *handler* and *caught* in a technical sense (indicated by italics in the Standard). In the Standard's syntax diagram at the start of chapter 15, a <handler> is a catch statement. However, that section goes on to say:

> 15.1/1 Code that executes a throw-expression is said to *throw an exception*; code that subsequently gets control is called a *handler*.

And *handled* is defined as:

> 15.3/(8) An exception is considered handled upon entry to a handler. [Note: the stack will have been unwound at that point.]
>
> 15.3/(9) If no matching handler is found in a program, the function terminate() is called; ....

By this definition, terminate() may or may not be a *handler*, but the intention seems to be that it isn't.

Caught is defined in 15.1/7:

> 7 [...] An exception is considered *caught* when initialization is complete for the formal parameter of the corresponding catch clause, or when terminate() or unexpected() is entered due to a throw. An exception is considered finished when the corresponding catch clause exits or when unexpected() exits after being entered due to a throw.

This states clearly an exception is *caught* once terminate() is called by the implementation due to a throw.

Now, the function uncaught_exception() is supposed to give a hint as to whether it might be safe to throw. One might well think that uncaught_exception() would be true while there is an live exception which is not *caught*, and that consequently uncaught_exception() would be false after terminate() is entered due to a throw.

What the Standard actually says is:

> 15.5.3 The uncaught_exception() function [except.uncaught]
>
> 1. The function bool uncaught_exception() returns true after completing evaluation of the object to be thrown until completing the initialization of the exception-declaration in the matching handler (18.6.4). This includes stack unwinding. If the exception is rethrown (15.1), uncaught_exception() returns true from the point of rethrow until the rethrown exception is caught again.

This does not mention *caught* or terminate() at all. There is a second definition:

> 18.6.4 uncaught_exception [lib.uncaught]
>
> bool uncaught_exception();
>
> 1. Returns: true after completing evaluation of a throw-expression until either completing initialization of the exception-declaration in the matching handler or entering unexpected() due to the throw; or after entering terminate() for any reason other than an explicit call to terminate().
>
>   **Note**
>
>   This includes stack unwinding (15.2).
>
> 2. Notes: When uncaught_exception() is true, throwing an exception can result in a call of terminate() (15.5.1).

18.6.4/1 does not parse well. There are 2 possible parses for the involvement of terminate():

1. Uncaught_exception() is true after the implementation calls terminate().
2. Uncaught_exception() is true from evaluation of a throw-expression until after the implementation calls terminate() [and is false in terminate()].

EDG accept interpretation 1, and after reading it a lot of times we think we also prefer it to 2.

But 15.1/7 says an exception is *caught* once terminate() is called by the implementation, so we are forced to either reject interpretation 1 or to assume that *caught* and uncaught_exception() cover related but different concepts.

Now as a further complication we have to consider DR208. Actually this turns out to clarify some of the ambiguities. The DR makes changes as follows (here we ignore parts of the DR not relevant to this issue):

3. Delete 15.1 except.throw paragraph 7.
4. Add the following before 15.1 except.throw paragraph 6:

    An exception is considered caught when a handler for that exception becomes active (15.3 except.handle).

    > **Note**
    >
    > An exception can have active handlers and still be considered uncaught if it is rethrown.

5. Change 15.3 except.handle paragraph 8 from

    An exception is considered handled upon entry to a handler.

    > **Note**
    >
    > The stack will have been unwound at that point.

    to

    A handler is considered active when initialization is complete for the formal parameter (if any) of the catch clause. [Note: the stack will have been unwound at that point.] Also, an implicit handler is considered active when std::terminate() or std::unexpected() is entered due to a throw. A handler is no longer considered active when the catch clause exits or when std::unexpected() exits after being entered due to a throw.

    The exception with the most recently activated handler that is still active is called the currently handled exception.

So in the revised wording, by 15.3/8 terminate() is a handler. If we categorize handlers as *normal* (catch) and *implicit* (terminate, unexpected) then an implicit handler is *active* as soon as it is entered, and a normal handler is *active* once it's parameter is constructed. By 15.1/6 a propagating exception transitions from *uncaught* to *caught* once it gets an active handler.

This clarifies that an exception is *caught* if/when it causes terminate() to be entered [and is also *caught* under other circumstances].

So we arrive at the conclusions:

- If terminate() has not been called by the implementation, uncaught_exception() is true if and only if there is a propagating exception which has not been *caught*.
- If terminate() has been called by the implementation, uncaught_exception() is true. Presumably this is to discourage throwing after entry to terminate() [which may result in a recursive call to terminate()].
- uncaught_exception() can be true even if all live exceptions have been *caught*.

13 APPENDIX B: Example C++ language implementation

This section is for illustration only and the actual Arm implementation may deviate without notice from the details presented here.

13.1 Exception Control Object

At the time of writing, the following structure is used by the Arm C++ implementation.

```
struct __cxa_exception {
  const std::type_info *exceptionType;  // RTTI object describing the type of the exception
  void (*exceptionDestructor)(void *);  // Destructor for the exception object (may be NULL)
  unexpected_handler unexpectedHandler; // Handler in force after evaluating throw expr
  terminate_handler terminateHandler;   // Handler in force after evaluating throw expr
  __cxa_exception *nextCaughtException; // Chain of "currently caught" c++ exception objects
  uint32_t handlerCount;                // Count of how many handlers this EO is "caught" in
  __cxa_exception *nextPropagatingException; // Chain of objects saved over cleanup
  uint32_t propagationCount;            // Count of live propagations(throws) of this EO
  _Unwind_Control_Block ucb;            // Forces alignment of next item to 8-byte boundary
};
```

A complete C++ exception object consists of a __cxa_exception followed by the C++ exception object (EO) itself. Type __cxa_exception includes the LEO members required for housekeeping by the C++ implementation, and the unwinding control block (UCB—see Language-independent unwinding types and functions).

13.2 Per-thread global memory

The __cxa_eh_globals structure records the per-thread handlers set by std::set_terminate() and std::set_unexpected(), and contains other fields needed by the implementation.

```
typedef void (*handler)(void);
typedef void (*terminate_handler)(void);
typedef void (*unexpected_handler)(void);
struct __cxa_eh_globals {
  uint32_t uncaughtExceptions;               // counter
  unexpected_handler unexpectedHandler;      // per-thread handler
  terminate_handler terminateHandler;        // per-thread handler
  bool implementation_ever_called_terminate; // true if it ever did
  handler call_hook;                    // transient field for terminate/unexpected call hook
  __cxa_exception *caughtExceptions;         // chain of "caught" exceptions
  __cxa_exception *propagatingExceptions;    // chain of "propagating"(in cleanup) exceptions
  void *emergency_buffer;                    // for when rest of heap full
};
```

__cxa_eh_globals contains the following fields:

- *uncaughtExceptions* is a count of C++ exceptions which are active but not in the *caught* state (in the technical meaning of the C++ Standard).
- *UnexpectedHandler* and *terminateHandler* are the current (per-thread) handlers set by std::set_unexpected() and std::set_terminate() respectively.
- *implementation_ever_called_terminate* is true if the unwind mechanism ever called terminate(). We believe this is required for correct implementation of std::uncaught_exception(). See Appendix A – C++ Uncaught Exception Semantics for a lengthy discussion).
- *call_hook* is set by the implementation to the handler it wants std::terminate() or std::unexpected() to call.

If std::terminate() or std::unexpected() are entered and find this field non-NULL, they should set the field to NULL and call the provided function (it will be the hook which existed at the time the throw was initiated, if the throw was initiated by C++). Otherwise they should call the __cxa_eh_globals terminate or unexpected handler as appropriate. This machinery is required because std::terminate() and std::unexpected() have behavior that depends on whether they were called directly by the application, or by the implementation.

- *caughtExceptions* is required by re-throwing using *throw* with no argument. See immediately below for a brief explanation and Appendix A – C++ Uncaught Exception Semantics for a lengthy discussion.
- *propagatingExceptions* allows the current exception object to be recovered by __cxa_end_cleanup.
- *emergency_buffer* is a pointer to reserved memory which can be used when attempting to throw an exception when the heap is exhausted.

A C++ exception object (EO) can be caught in more than 1 catch clause, if re-throwing has occurred. C++ DR 208 has an example, and here is another.

```
void f() { try { throw 1; } catch(...) { A a; flag=1; throw; } }
A::~A() { try { if (flag) throw; } catch(...) { /* 1 */ } }
```

At the point /* 1 */, the EO for the thrown integer 1 is live in 2 handlers.

So, we need to determine the number of handlers an EO is active in, and an EO should only be destroyed when this count falls to 0. A uint32_t counter in the LEO suffices.

Also, it is necessary that *throw;* can retrieve the *currently handled exception* object in order to re-throw it. This requires the C++ run-time support to maintain, at least, a chain of currently handled exception objects, of which *throw* re-throws the top one. Thus a next exception pointer is required in the LEO. Foreign (not C++) exceptions can be put into the chain using a special marker block to indirect through.

14 Appendix C: Unwinding instruction encoding costs

In this analysis we assume the proportion of functions containing > 64KB of code is negligible. Such functions require 32 bit offsets in the handling table and use long unwinding descriptions.

Aside

We could introduce a fourth personality routine to handle the rare case of > 64KB functions that are nonetheless easy to unwind, but today this does not seem to be good use of the encoding space.

We are principally concerned with the cost of unwinding C functions, where the cost is pure overhead. In C++, additional functionality justifies the cost. Treating the Arm code-size database as C gives the following table.

Cost of unwinding only (C-style)

Arm code-size database build option	RO size (bytes)	Index table size (including short unwinding)	Extra cost of long unwinding
Arm-state, software floating-point, -O1	9,327,956	30033 * 8 (2.6%)	210 * 8 (0.02%)
Thumb-state, software floating-point, -O1	6,275,440	30208 * 8 (3.9%)	218 * 8 (.03%)
Arm-state, VFP, -O1	8,776,180	30035 * 8 (2.7%)	268 * 8 (0.02%)

Overheads –O2 are very similar (for example, 4% instead of 3.9% in Thumb-state).

In particular:

- Only about 200 frames of more than 30,000 need more than 3 unwinding instructions, whether the code is built to use software floating point (no floating-point unwinding) or built to use VFP.
- No frame requires more than 7 unwinding instructions (so the long format consumes at most 1 extra word).