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Automatic bridging of native code to Lua using existing debugging information

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Todo list

~~***Title:*** *Project Kind:* Classic engineering project. *Student: Director: Tribunal members: Resevere members: Reading date: Mark:*~~

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En A Coruña, a

Do it, or don't, but don't try.

Acknowledgements

To my wife, who supported unconditionally me during the long hours I have devoted to this project, and helped to proof-read the final iterations of the present document.

To my parents, whom have not thought that I would ever get this piece of work done.

Also, I would like to thank my Finnish "adoptive" family, who have kindly accepted me as one more of them, and that have been of invaluable support. Their appreciation of knowledge is something I am willing to pass down to upcoming generations.

Summary

The objective of this project is ~~implementing~~ to implement an automated mechanism that, using the DWARF debugging information from ELF shared objects, allows the Lua virtual machine to call native functions from ~~the shared object~~ shared objects implemented in the C programming language. The process ~~has to be~~ is automatic, in the sense that the user ~~will~~ does not need to write code to convert values passed between Lua and the invoked C functions, and ~~a~~ the C functions will behave essentially like Lua from the user point of view. The ultimate goal is to allow transparent usage of existing C libraries from Lua.

Lua has been chosen because it provides a clean C interface to its Virtual Machine (VM), which has been designed from the ground up to be embedded in larger projects. The implementation is also compact (under 16.000 lines of code), which makes it feasible to gain in-depth knowledge of its innerworkings in a relatively short time. Lua has also grown in popularity in the last years as its adoption has skyrocketed in the ~~games~~ game industry.

The reason to focus on the combination of debugging information in DWARF format contained in ELF shared objects is that they are a widespread, standard configuration used by the majority of contemporary Unix-like operating systems. The target system during development ~~will be~~ has been a GNU/Linux system running on the Intel x86_64 architecture, which also uses the aforementioned configuration, though provisions are to be included in the design to ease future porting efforts for other platforms.

In order to validate the correctness of the implementation, an automated test suite ~~is also provided. The unit tests will be also used~~ was also developed. Unit tests were used also as regression tests, to ensure that modifications to the system ~~do not affect the correctness of the implementation.~~

did not introduce programming errors in the implementation.

Keywords

- Automatic binding generation.
- ELF.
- DWARF.
- Debugging information.
- Lua programming language.
- Virtual machines.
- FFI.

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Chapter 1

Introduction

1.1 Description & Motivation

Most programming languages provide some mechanism to use libraries —sometimes called *modules*— implemented in some other language. Most of the time, this other language belongs ~~to the members of the "C family"~~ family of the C language, which can be compiled into *native object code*. The reasons are twofold: ~~this~~ it allows to reuse functionality provided by the system that otherwise would not be available, and in the other hand it opens the ~~possibility of~~ door to implementing performance–critical pieces of a system using native code.

Despite the advantages, using native code from a dynamic programming language requires creating a layer of software often called *bridge*, or *binding* from now on, which wraps the native library to provide an interface compatible with the run-time environment of the dynamic programming language. Those bindings, created either manually or with the help of code generation tools, need to be compiled before they can be used.

~~However, when~~ When building native code, compilers are capable of adding *debugging information* to their output, which can be used to gain additional insight into a program using a *symbolic debugger*. As a matter of fact, any other tool capable of understanding the format in which the compiler writes the debugging information can make use of it for its own purposes. Among plenty other details about the source program, debugging information includes descriptions of the ~~function~~ functions compiled as part of each compilation unit, parameters and their corresponding data types,

~~the return type~~return types, and the memory layout of the involved user-defined types; which is a superset of the information needed to invoke those functions. ~~The~~ In other words, the debugging information contains all the details needed to make library bindings automatically, potentially allowing dynamic programming languages to invoke native code directly without any kind of human intervention.

1.2 Project Goals

The main goal of this project ~~is developing~~ to develop an automatic binding system for the Lua programming language which allows seamless usage of libraries written in C at runtime. To achieve this, it will use the debugging information generated by the C compiler. ~~In particular~~Additionally:

- Modifications to the Lua virtual machine, or its core libraries ~~is~~ are to be avoided, if possible. The less the changes, the lower the maintenance cost of the system when Lua is updated. An implementation which does not modify Lua itself would be usable with Lua packages provided by the operating system, thus easing the setup process.

- The implementation will ~~be able to~~ load Executable and Linkable Format (ELF) shared objects into the Lua virtual machine, and use the debugging information in Debugging With Attributed Record Formats (DWARF) format present in them.

- Values of C types, including user defined ones, ~~should~~ will be readable and modifiable from Lua. It will also be possible to create new values of C types from Lua.

- Invocation of functions from loaded shared objects will ~~work for function~~ be supported for functions of arbitrary return types, ~~for functions of~~ and any number of parameters of any supported type. Lua values passed to functions will be automatically converted to C types whenever possible. Values of C types created from Lua will also be accepted as valid function parameters.

- The implementation will target the GNU/Linux operating system running on the x86_64 architecture~~,~~.

- The design of the system ~~should~~ will be extensible, allowing to add support for more shared object formats, debugging information formats, operating systems,

and architectures.

1.3 Planning & Methodologies

During the planification phase, the following tasks and subtasks have been identified:

1. Initial study, including:

   - Understanding how different kinds of data are stored in ELF object files.

   - Identifying the parts of the DWARF specification which apply to the scope of the project.

   - ~~Investigation of~~ Investigating existing tools which share similar goals.

2. Analysis, including:

   - Understanding the relevant parts of the DWARF debugging information format.

   - Getting acquainted with Lua and the implementation of its VM.

3. ~~Setting-up the work environment and getting acquainted with the tools used during the development of the system.~~

   ~~Design of the~~ Designing the automatic binding system.

4. ~~Implement~~ Implementing the automatic binding mechanism.

5. ~~Test and validate~~ Testing and validating the system, including:

   - ~~Investigate existing unit testing frameworks with Lua support and determine whether they are usable in the context of this project. Design~~ Designing a set of unit and regressions tests.

   - ~~Implement the~~ Implementing unit and regression tests.

6. ~~Develop~~ Developing example Lua programs which demonstrate the capabilities of the system, and ~~will serve to validate the system with real-world programs~~ rewriting at least one previously existing program to validate usage of the system in a real–world scenario.

7. Writing of the final report.

	#	Task	Estimation (days)
	1.	Initial study	5
	2.	Analysis	15
~~Environment setup~~ 3.		~~3~~ Design	4
	4.	Implementation	30
	5.	Testing	10
	6.	Example programs	2
	7.	Final report	15
		Total	84

Table 1.1: Effort estimation

For each one of the top-level tasks in the list above, Table 1.1 provides an estimation of the time needed for the completion, using an effort of eight hours per person, per day (8h/p/d).

Even though there is only one resource executing the tasks, some techniques from agile development methodologies are used. Namely:

- From Scrum, the concepts of *iteration* and *sprints*, with their respective planning and review seasons. Daily stand-up meeting are not used, and there is no *scrum master*: none of those would make make sense provided that there is only one person in the team.

- The *Kanban* methodology is used in order to keep an always up to date dashboard with the status of the tasks.

The Kanban method was invented by Toyota to keep the status of ~~productions lines,~~ production lines. This methodology keeps a board (physical, in the original incarnation of the method) where each element is a task, and elements are distributed in columns depending on their status. For example, applied to software development, the columns could be "Pending", "In Progress", "Testing", and "Finished". All the tasks are always visible in the board, so this allows to know the overall status of a project intuitively by glancing at the board.

Chapter 2

Contextualization

Computing would not be understood without the accompanying tools which enable IT professionals to actually *do something* with computers: from simple switches and lights in the early times, to the sophisticated programming languages and tools of the present times, all of them enable humans to *instruct machines to do things.*

2.1 Dynamic Programming Languages

Dynamic languages are a family of high-level programming languages which, at runtime, execute programming behaviors that other programming languages perform during compilation. Runtime behaviors could include extension of the program, by adding new code, by extending objects and definitions, or by modifying the type system. Support for these operations is provided directly by the language. Most dynamic languages are also dynamically typed, and are frequently called "scripting languages".

Add bibliographic reference

Popular contemporary scripting languages include Perl, Python, PHP, the ubiquitiuos JavaScript, and of course Lua (described in subsection 2.1.4). Many of their features were first implemented as native features of the Lisp programming language, which itself is dynamic.

Dynamic programming languages have grown in popularity in the last decades, programmers. Programmers like them for their expressiveness, which allows for higher productivity, and the ever increasing computing power of computers makes it feasible to use them for performance-critical tasks traditionally left for static statically compiled languages. The development of novel compilation techniques aimed at this family of lan-

guages, and the relentless improvement of their virtual machines (see subsection 2.1.1), has contributed as well to increase widespread adoption.

2.1.1 Virtual Machines as Runtime Environments

A VM is an emulation of a particular computer system based on its architecture. *System virtual machines* provide a complete substitute for the real machine, ~~are~~ and re targeted towards the execution of complete operating systems and software stacks. On the other hand, *process virtual machines* execute a single computer program by providing an execution environment suitable for a particular programming language, which can be platform-independent.

Process VMs provide a so called *runtime environment*. They run as a normal application inside the host operating system. This approach has several advantages:

- Provides a platform-independent programming environment, abstracting away details of the underlying hardware or operating system, potentially allowing a program to execute in the same way on any platform.

- The level of abstraction provided by the VM is higher than that of a low-level Instruction Set Architecture (ISA), which allows it to provide services rarely available in real machines (e.g. automatic memory management).

- There is an additional level of isolation between the operating system and the execution environment. This allows discretionary control over the executed code, which is confined to the bounds allowed by the VM.

The main downside of virtual machines is the lower performance compared to the execution of native code. ~~To achieve levels of performance~~ Performance levels comparable to compiled languages can be obtained using a combination ~~using~~ of Just-In-Time (JIT) compilation (see subsection 2.1.2~~below~~), and compiler-based optimization techniques ~~especifically~~ specifically designed for them.

In some regards, the additional level of isolation provided by a VM could be a nuisance due to the fact that it could prevent programs from accessing resources (either hardware-based, or provided by the host system) needed for its operation. For this reason, many virtual machines provide a Foreign Function Interface (FFI): a mechanism

to call-out native code and re-gain access to the whole system, while still being under the control and supervision of the VM.

2.1.2 JIT Compilers

2.1.3 Foreign Function Interfaces

2.1.4 The Lua programming language

The Lua language is a "powerful, fast, lightweight, embeddable scripting language" [7]. It was initially created as a data description language at Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), to be used for in-house software development, and has since evolved into a general purpose programming language. It has been used in proffessional applications (e.g. Adobe Lightroom) and it has seen widespread usage in the video games industry (e.g. World Of Warcraft). The

The Lua logo. "Lua" means "moon" in Portuguese.

The main programming paradigm is imperative, but the language supports functions as first–class values and closures, making it possible to easily write programs in a functional programming style. Like in Pascal, English words (DIFadd{|function|}DIFaddend ,DIFadd{|then|}, }Mlua|end|) are used as delimiters for language constructs. Another defining characteristic of the language is that, by design, it only provides one compound data structure, the *table*, which is the basis for all user–defined types. Tables can be used as arrays (listing 2), structures, and objects (listing 1).

An unique and powerful feature of Lua is its support for *metatables*: values may have an associated table (the so-called *metatable*) which allows to extend the semantics of language constructs, allowing to define how tables behave when arithmetic and relational operators are applied to tables, or how table fields are accessed. Listing 2 on page 11 demostrates how customizing table access can be used to define a seemingly–infinite array which contains the nth Fibonacci number at index n. A common use for metatables is enabling support for object–oriented programming, using them to define object inheritance chains (listing 3) — as Lua itself does not have the notion of classes, prototypes are used instead, in the Self or JavaScript languages.

Lua, starting in version 5.0 [9], uses a register-based virtual machine. This allows for improved performance by avoiding excessive copying of values on stack *pop* and *push* operations. Traditionally, most virtual machines intended for execution of languages are stack based, including heavyweight, enterprise-proven systems like the Java™ JVM, and Microsoft's .NET environment.

2.2 Binding Native Code to Lua

2.2.1 Lua C API

2.2.2 Binding Generators

Binding generators are tools that can be used to create a binding to a library in an automated way. Often they fall into the category of transpilers: they take as input the source code of the code to generate a binding for, and generate a new set of source files which contain the code of the binding. This set of source files are themselves compiled into a loadable module for the target programming language or virtual machine, making it a *build-time* solution.

More than often, binding generators do *not* include a full parser for the ~~origin programming language~~ programming language of origin, and they require to be fed a simplified version of the code being wrapped. This can be a nuisance for code bases which use complex language constructs unsupported by the binding generator.

Mention binding generators: SWIG, ToLua(++)

2.2.3 Foreign Function Interfaces

Mention: GObject-Introspection, LuaJIT FFI

2.3 Executable Formats

2.3.1 ELF

The "Executable and Linkable Format" (ELF, formerly called "Extensible Linking Format") is a common standard file format for executable programs, object code, shared libraries, and even core dumps. Since its publication as part of the System V Release 4 (SVR4) Application Binary Interface (ABI) specification [1, c. 4] it has been adopted by many Unix-like (Solaris, most of the BSD variants, GNU/Linux), and non-Unix operating systems (most notably, OpenVMS, BeOS, and its successor Haiku).

2.3.2 DWARF

The DWARF Specification [2]

```
    \DIFadd{-- Create a table, with one key, "age" and 7 as value
    animal = }{ \DIFadd{age = 7 }}
\DIFaddend

    \DIFdelbegin \DIFdel{Lua}\DIFdelend \DIFaddbegin \DIFadd{--
    ↪   Associate a string value to the "kind" table key
    animal}[\DIFadd{"kind"}] \DIFadd{= "cat"
}

    \DIFadd{-- Keys which are valid identifiers can be accessed
    ↪   with "."
    animal.name = "Doraemon"
}

    \DIFadd{-- The dot "." syntax workds for adding functions to
    ↪   tables
    function animal.describe(self)
      print(self.name .. " is a " .. tostring(self.age) ..
           "-year old " .. self.kind)
    end
}

    \DIFadd{-- This is equivalent to: animal.describe(animal)
    animal:describe()   --> Doraemon is a 7-year old cat
}

    \DIFadd{-- Adding a function with colon ":" adds an implicit
    ↪   "self"
    function animal:furryness()
      return self.kind == "cat" and "high" or "unknown"
    end
}

    \DIFadd{animal:furryness()   --> high
```

Listing 1: Lua tables being used as objects

```
\DIFadd{fib = }{ \DIFadd{1, 1 }}
\DIFadd{setmetatable(fib, }{
  \DIFadd{__index = function (values, n)
    -- Calculate and memoize the Fibonacci(n)
    values}[\DIFadd{n}] \DIFadd{= values}[\DIFadd{n - 1}]
     ↪  \DIFadd{+ values}[\DIFadd{n - 2}]
    \DIFadd{return values}[\DIFadd{n}]
  \DIFadd{end
}}\DIFadd{)
print(fib}[\DIFadd{10}]\DIFadd{)  --> 55
```

Listing 2: Memoization and dynamic programming using a Lua metatable

```
\DIFadd{-- Base object describing an unnamed living creature
animal = }{
  \DIFadd{name = "Unnamed",
  kind = "living creature",
  describe = function (self)
    print(self.name .. " is a " .. self.kind)
  end,
}}

\DIFadd{-- When indexing the table passed as first argument,
 ↪  fields will
-- be looked up from the "animal" table associated to the
 ↪  "__index"
-- key of the metatable. The function returns the first
 ↪  argument.
cat = setmetatable(}{ \DIFadd{kind = "cat", name = "Doraemon"
 ↪  }}\DIFadd{,
                    }{ \DIFadd{__index = animal }}\DIFadd{)
dog = setmetatable(}{ \DIFadd{kind = "dog", name = "Snowy",
 ↪  }}\DIFadd{,
                    }{ \DIFadd{__index = animal }}\DIFadd{)
}

\DIFadd{-- The :describe() method is searched in "animal"
cat:describe()  --> Doraemon is a cat
dog:describe()  --> Snowy is a dog
}

\DIFadd{-- Chained key lookup can be used to make the values
 ↪  from the
-- base object the default ones
tom = setmetatable(}{ \DIFadd{name = "Tom" }}\DIFadd{, }{
 ↪  \DIFadd{__index = animal  }}\DIFadd{)
tom:describe()  --> Tom is a living creature
```

Listing 3: Lua metatables used for object inheritance

Chapter 3

Analysis & Design

3.1 Analyzing DWARF

The DWARF format was first developed by the Bell Labs for the `sdb` debugger of System V Unix. Nowadays the formal specification is available under the GNU Free Documentation License (FDL), and its new versions have been discussed using public channels of communication, following a community-oriented process. Downloadable copies of all the version of the specification are available at `http://dwarfstd.org`.

~~All~~ In DWARF, all the data provided by debugging information is stored in a hierarchical tree-like structure, and each ~~nodes~~ node of the tree is called a Debugging Information Entry (DIE). Each DIE consists of an identifying tag, and a series of attributes. The tag specifies the class to which an entry belongs, and the attributes define the characteristics of the entry. An entry, or a group of entries together, provide a description of an entity in the corresponding source code. The entries are contained in the `.debug_info` and `.debug_types` sections of an object file.

The attributes can reference another DIE, as shown in Figure 3.1, making it possible to create arbitrary links between nodes of the tree. Those explicit links are used extensively to group related entries together (for example the `DW_TAG_formal_parameter` entries, which describe the parameters of a function, are chained using `DW_AT_sibling` attributes), and to perform data deduplication of the debug information (for example,
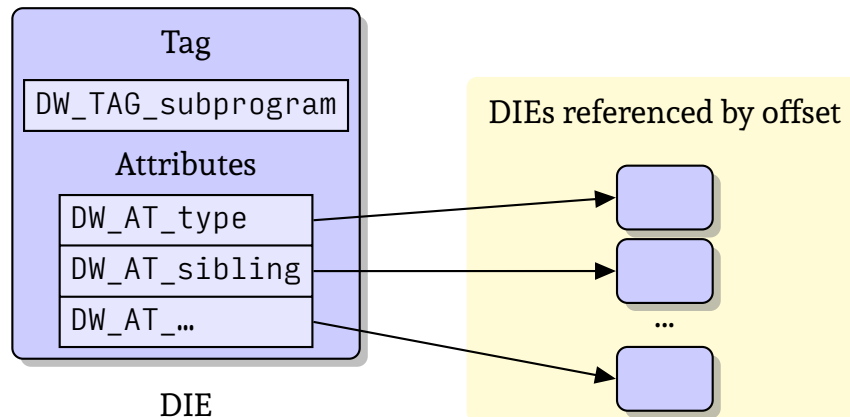
Figure 3.1: DIE attribute references.

instead of making a new entry for the `int` type, only one is created and then referenced from other entries).

3.1.1 Debug Information Structure

This section provides simplified overview of the tree structure formed by the debug information entries of a program, which is enough for the goals of this project. For complete, detailed information, ~~it is recommended to read~~ we refer to the DWARFv4 Specification [?] .

Location of the Debug Information

~~objects have the ability of describing their contents~~ The contents of ELF objects are described using *segments*, and *sections*. Segments contain information used at runtime for the execution of the code, and sections contain data about the code itself. Sections contain data used *offline* (i.e. not at runtime). Sections have arbitrary names and contents. Debugging information is not strictly needed at runtime for the execution of the program: it is considered ancillary, and is stored in sections.

As per the specification, the DWARF debugging information must be stored in the ELF objects in sections with the `.debug_` prefix. Each one of those sections stores a particular kind of information, as seen on Table 3.1.

Section	Contents
`.debug_types`	Stores DIEs for types.
`.debug_info`	Stores DIEs for executable program code (functions, mostly)
`.debug_line`	Maps of object code positions to source code line numbers
`.debug_pubnames`	Public function names and entry offsets in `.debug_info`
`.debug_pubtypes`	Public type names and entry offsets in `.debug_types`
`.debug_str`	String data (e.g. type, variable and function names)

Table 3.1: Main ELF sections used to store DWARF debugging information

Types

A ~~types~~ type is represented as a DIE with one of the following tags:

- `DW_TAG_base_type`

- `DW_TAG_pointer_type`

- `DW_TAG_typedef`

- `DW_TAG_const_type`

- `DW_TAG_array_type`

- `DW_TAG_structure_type`

- `DW_TAG_union_type`

- `DW_TAG_enumeration_type`

Base Types

Base types (Figure 3.2) are represented by DIEs with a `DW_TAG_base_type` tag. This covers all the C/C++ numeric types: signed and unsigned integers, floating point types (`float`, `double`), the `char` type, and the new integer-based types of C99 (`_Bool`, `int32_t`, etc.)

The size of the values ~~in~~ is given using a `DW_AT_byte_size` attribute, in bytes. Sizes are the same reported by the C `sizeof` operator. A `DW_AT_encoding` attribute specifies how the values are used in the program. For example, `DW_ATE_boolean` corresponds with the `bool` type (or `_Bool`) in the source program. The following table summarizes how C types are represented by a base type DIE for the x86_64 architecture
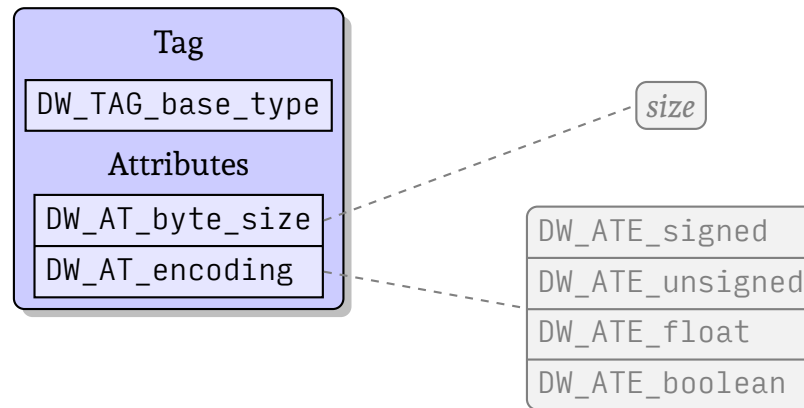
Figure 3.2: DIE describing a base type.

(sizes may vary in other architectures):

C Type	DW_AT_byte_size	DW_AT_encoding
bool	1	DW_ATE_boolean
char	1	DW_ATE_signed_char
unsigned char	1	DW_ATE_unsigned_char
short int	2	DW_ATE_signed
unsigned short int	2	DW_ATE_unsigned1
int	4	DW_ATE_signed
unsigned int	4	DW_ATE_unsigned
long int	8	DW_ATE_signed
unsigned long int	8	DW_ATE_unsigned
float	4	DW_ATE_float
double	8	DW_ATE_float
long double	16	DW_ATE_float

The rest of C/C++ base types are defined as aliases of these using `typedef`.

Pointer Types

Pointer types (Figure 3.3) are represented by DIEs with a `DW_TAG_pointer_type` tag, and a lone `DW_AT_type` attribute points to the DIE of the pointed-to type. This allows to represent pointers of/to any type. Multiple levels of indirection are represented
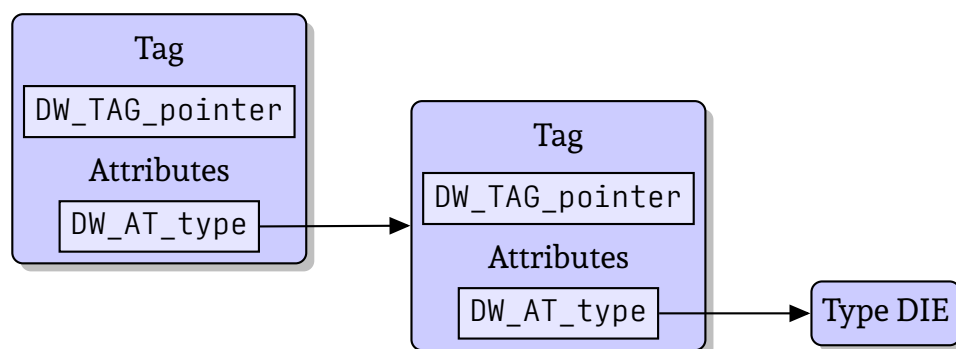
Figure 3.3: DIEs describing a Pointer-to-pointer-to type.
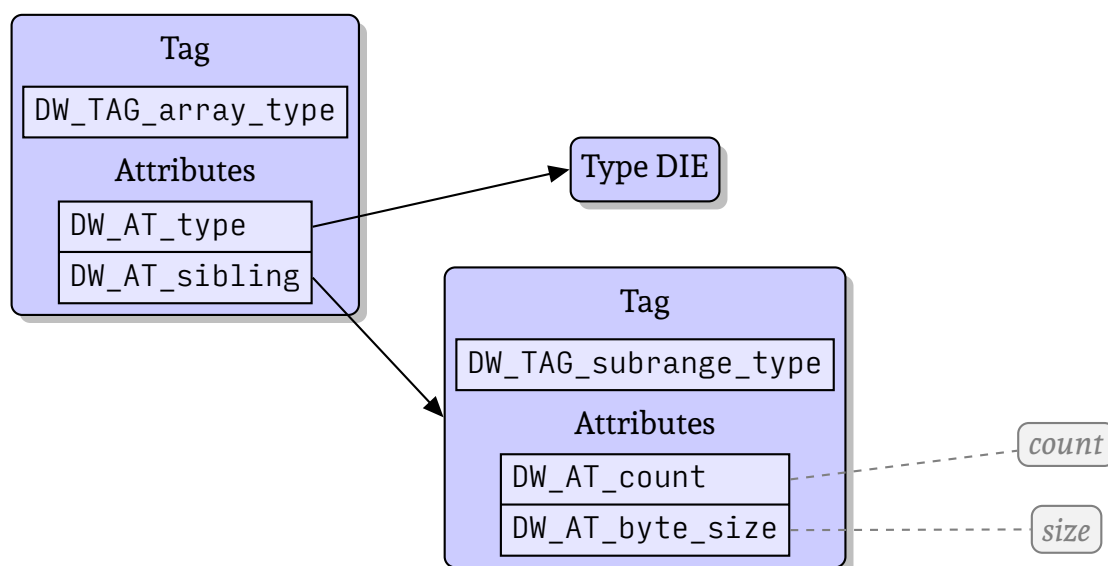
Figure 3.4: DIEs describing an array type.

by chains of `DW_TAG_pointer_type` DIEs. The example in Figure 3.3 exemplifies this situation, in what could be the representation of the `int**` when the rightmost "Type DIE" contains the information for the `int` type.

Constant Types

Flagging values of a type as constant is done in the same way as representing a pointer type: a DIE with a `DW_TAG_const_type` contains a `DW_AT_type` attribute with reference pointing to a type DIE. This way, the pointed type is marked as immutable.

Figure 3.5: DIE describing a type alias.

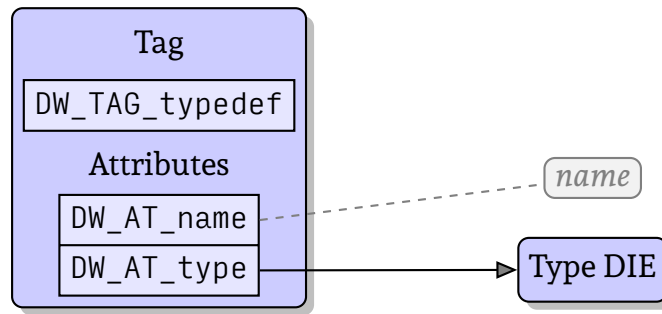### Array Types

Array types (Figure 3.4) are represented by a DIE with a `DW_TAG_array_type` tag. A `DW_AT_type` attribute contains a reference to the type of the elements of the array. The space reserved for attribute values can be insufficient to store the number of elements in the array, so instead a chain of related DIEs is referenced using a `DW_AT_sibling` attribute, and one of the elements in the chain is `DW_TAG_subrange_type` DIE. The latter specifies the *size* —using a `DW_AT_byte_size` attribute— of the type needed to store the *count* of items, and the location of the value itself using a `DW_AT_count` attribute.

Type Aliases

As a convenience, programming languages usually allow defining new user-defined names for types. This is particularly handy to avoid repeating complex type declarations in the code of a program. In C type aliases are introduced with the `typedef` keyword:

```
/* "compare_function_t" is an alias to a function pointer
↪   type */
typedef int (*compare_function_t) (const void* a, const
↪   void*b);
```

A type alias (Figure 3.5) is represented by a DIE with tag `DW_TAG_typedef`[1] tag. The aliased type is referenced using a `DW_AT_type` attribute, and a `DW_AT_name` attribute provides the *name* of the aliased type.

---

[1]The name of the tag hints that the DWARF format was designed with the C language in mind.
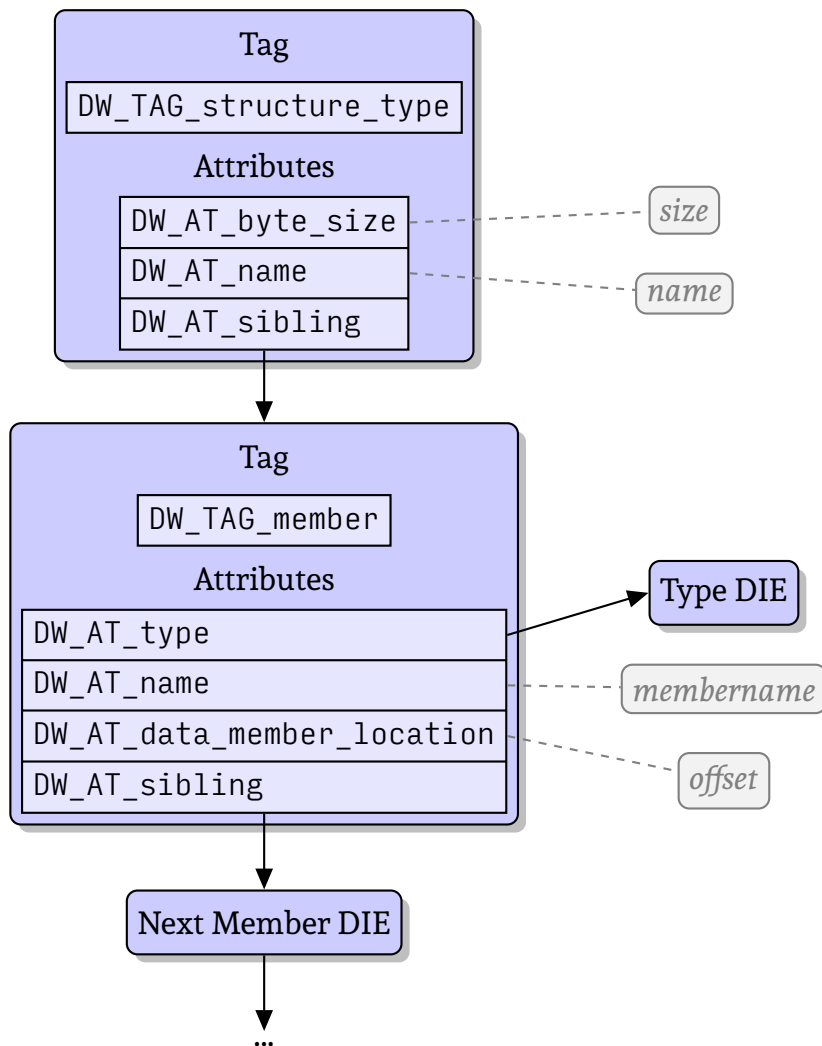
Figure 3.6: DIEs describing a structured type

Structured Types

Structured types, also known as *record types* or *compound data types* depending on the programming languages, are used-defined data structures which contain a collection of related elements, which can be accessed using a numeric index or (most commonly) by names given to them. Each element may also be called *field* or *member*. In C records are defined using the `struct` keyword:

```c
struct Point {
    int x;  /* First member  */
```

```
    int y;  /* Second member */
};
```

A record type (Figure 3.6) is described using a set of related DIEs. At the top level, a DIE with tag `DW_TAG_structure_type` provides the size of the record type in bytes, by means of a `DW_AT_byte_size` attribute, and the name of the record type using a `DW_AT_name` attribute.

In order to describe the members, a DIE with tag `DW_TAG_member` is used for each of them. These DIEs contain a `DW_AT_type` attribute which references the DIE of the member type, a `DW_AT_name` attribute with name of the member, an attribute of type `DW_AT_data_member_location` specifies the *offset* of the member in memory, counted from the starting address of the record. The member DIEs are linked from the top level DIE using a chain of `DW_AT_sibling` links.

Some programming languages allow defining *opaque* record types. The layout and fields of the type are only visible in the program module where the type is implemented. Such type is defined in C by omitting the specification of the `struct` fields in `.h` a header, and writing its complete description in the `.c` implementation:

```
/* File: opaque.h */
typedef struct _Opaque Opaque;
...


/* File: opaque.c */
struct _Opaque {
  uint8_t data_blob[100];
  ...
};
...
```

In this case, an additional DIE with tag `DW_TAG_structure_type` is present, *without* specifying the size of the data type with a `DW_AT_byte_size` attribute. Instead, a `DW_AT_declaration` attribute is added, flagging the type as declared, but not neccessarily defined. Optionally, if the complete definition ~~of the~~ is known by the compiler, it might ~~adds~~ add `DW_AT_specification` attribute pointing to the top level DIE which describes the type in full.

Union Types

Union types use the same structure of DIEs as record types, with a couple of small differeces: the tag for the top-level DIE is `DW_TAG_union_type`, and ~~the~~ a `DW_AT_byte_size` attribute which indicates the size of the *largest member type*.

Enumeration Types

The representation of ~~enumeration shares some~~ enumerations (Figure 3.7) shares a number of similarities with the representation of record and enumeration types: a top level DIE, in this case with tag `DW_TAG_enumeration_type`, describes the size of the integral type needed for values of the enumerated type using a `DW_AT_byte_size` attribute, and a `DW_AT_name` attribute contains the name of the type.

The set of values ~~are~~ is described by a DIE each, with tag `DW_TAG_enumerator`. Enumerators contain a `DW_AT_name` attribute with the name of the enumerator, and its associated value in a `DW_AT_constvalue` attribute.

Functions

The representation functions using DIEs uses the same structure as record and enumeration types: the top level entry contains general information about the function itself, using attributes, plus a link to a ~~chains~~ chain of DIEs. Function entries come in different flavors, depending on their tag:

- `DW_TAG_entry_point`
  Describes a piece of executable that can be invoked in the same way as a function, which does not have entity as a function in the source program. For example, this can be used by a Pascal compiler to represent the code inside the `program` block.

- `DW_TAG_inlined_subroutine`
  Describes a function ~~whose~~ for which the code has been copied by the compiler inside another part of the program (i.e. *inlined*) as a performance optimization.

- `DW_TAG_subroutine`
  Describes normal functions. In object oriented languages is also used to describe methods, with the type the method applies to linked as type DIE of the first pa-
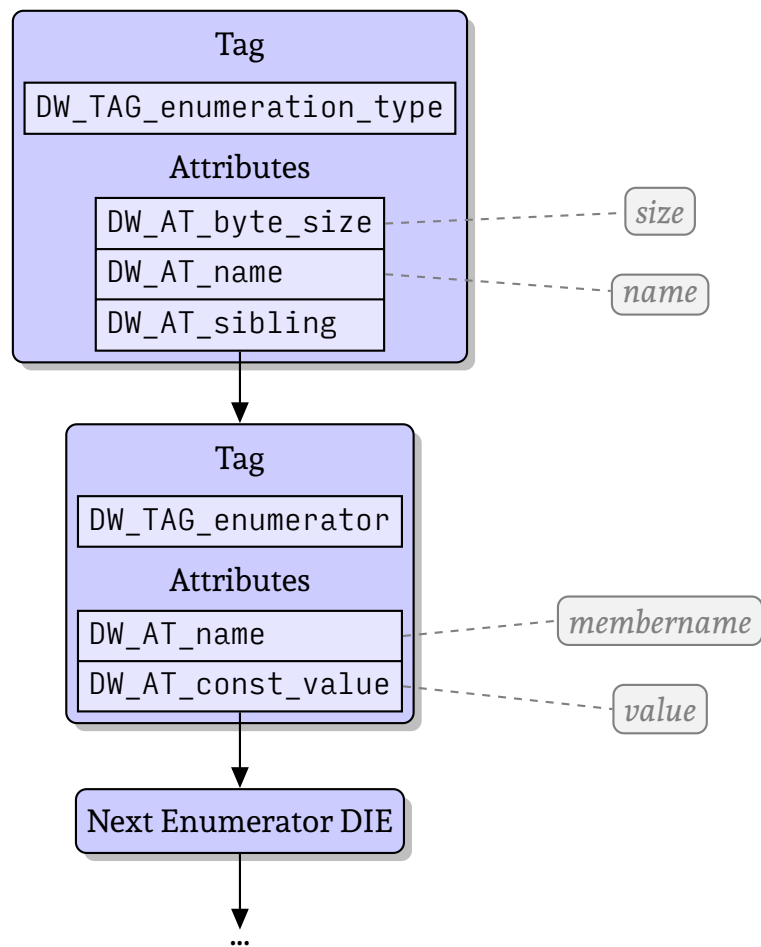
Figure 3.7: DIEs describing an enumeration type

rameter.

The basic structure is shared among the three types, with the following attributes in the top level DIE:

- A `DW_AT_name` attribute provides the name of the function.

- A `DW_AT_type` attribute references the return type of the function. This is only present if the function returns a value.

- A `DW_AT_external` attribute, which contains a flag indicating whether the function is available to be used from compilation units other than the one where its definition lives. This flag is optional, and only required to be present (and have a non-zero value) for functions which are referenced from the `.debug_pubnames` ELF section.

From the top-level DIE, a `DW_AT_sibling` attribute references the first entry of the chain, which provides additional information about the function and its source code. Among all the entries in the chain, the ones with the `DW_TAG_formal_parameter` describe the parameters of the function. It is guaranteed that the entries describing the parameters will be in the chain in the same order as they appear in the source program, but they may not be consecutive. Each parameter entry contains the following attributes:

- A `DW_AT_name` attribute provides the name of the parameter.

- A `DW_AT_type` attribute references the DIE for the type of the parameter.

3.2 Design

3.2.1 Naming

In the Lua community there is a certain tradition of naming projects after celestial bodies, or terms related to them. After all, Lua means *moon* in Portuguese.
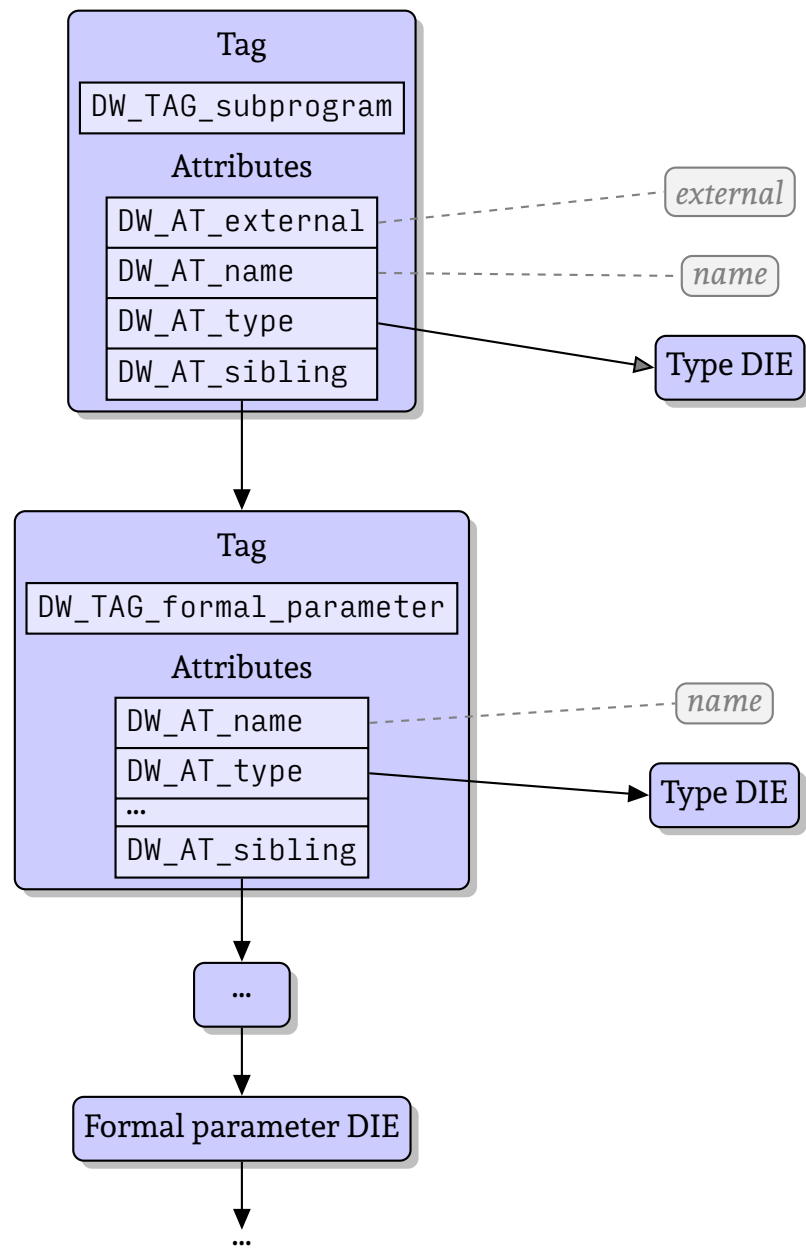
Figure 3.8: DIEs describing a function type

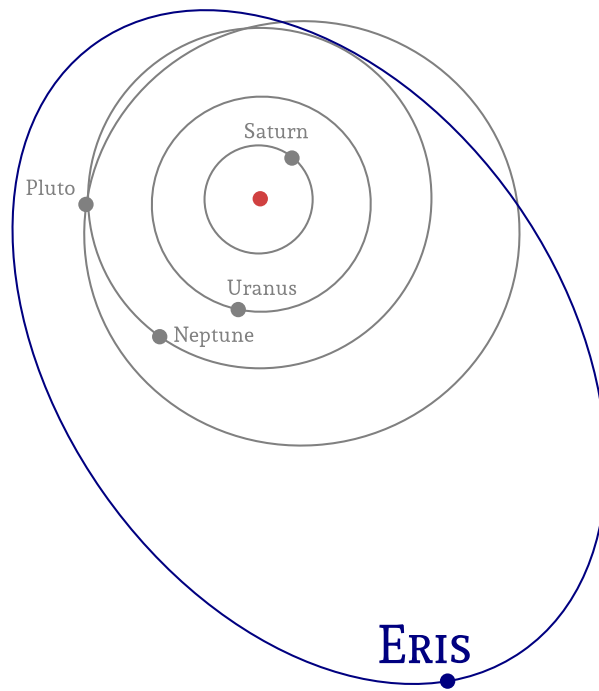Figure 3.9: Orbit of the 136199 Eris dwarf planet

    Following this tradition, it seemed fitting to choose the name of the dwarf planet Eris. Dwarf planets are neither planets not natural satellites, but something in between. The name Eris beautifully encompasses the name of the DWARF debugging information format, and the fact that it is an entity that is almost a moon
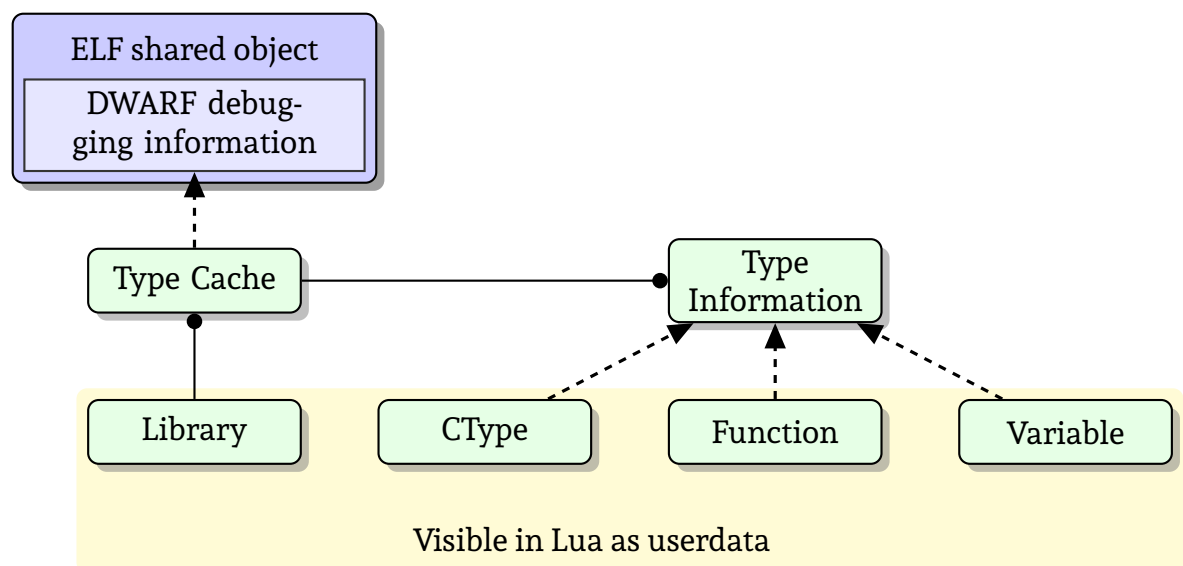
Figure 3.10: Architecture of ERIS.

Chapter 4

Implementation

4.1 Prerequisites

> Move this to an appendinx with manual / installation notes

Instead of providing its own implementation for certain functionality, ERIS uses existing, proved software components.

Component	Version	Required	Optional	Bundled
Lua	5.3	⋆		⋆
libdwarf	20150507	⋆		⋆
libelf	0.152	⋆		
readline	5.0		⋆	
libffi	3.1	⋆		

Table 4.1: Dependencies

Table 4.1 shows the dependencies expected to be installed in the system. The items marked (⋆) as *bundled* are not ~~including~~ included in the source repository, but the build system includes support for downloading tarballs with the source code and doing a local build. When enabled, bundled dependencies will be automatically downloaded, built, and used ~~,~~ instead of the versions provided by the system. In the case of using libdwarf bundled, it will be statically linked. See subsection 4.2.1 for instructions for enabling bundled libraries. This is particularly useful for systems

Distribution	Installation Command	Packages
Debian, Ubuntu [1]	`apt-get install`	`libdwarf-dev ninja-build`
Arch Linux	`pacman -S`	`libdwarf ninja lua`

Table 4.2: Dependency packages in popular GNU/Linux distributions.

which do not provide Lua 5.3 packages (for example, the case Debian and Ubuntu at the time of writing).

Table 4.2 shows required packages as provided by popular GNU/Linux distributions. Some versions of Debian (and derivatives like Ubuntu) include only a static version of `libdwarf` in the packages, most likely not built as Position-Independent Code (PIC), which is a requirement.

4.2 Build Tools

4.2.1 Autoconfiguration

4.3 Project Source Structure

The ERIS source code

```
eris/
├── doc/ ..............Documentation and API reference
├── examples/
│   └── *.lua ......................Module usage examples
├── tools/ .........................Build & test utilities
│   ├── ninja/ ..................Ninja build support files
│   └── make/ ..............GNU Make build support files
├── test/
│   └── *.lua .......................................Unit tests
├── uthash.h ............................... Copy of UT-hash
├── eris-*.c ...............................Module sources
└── eris-*.h ...............................Module sources
```
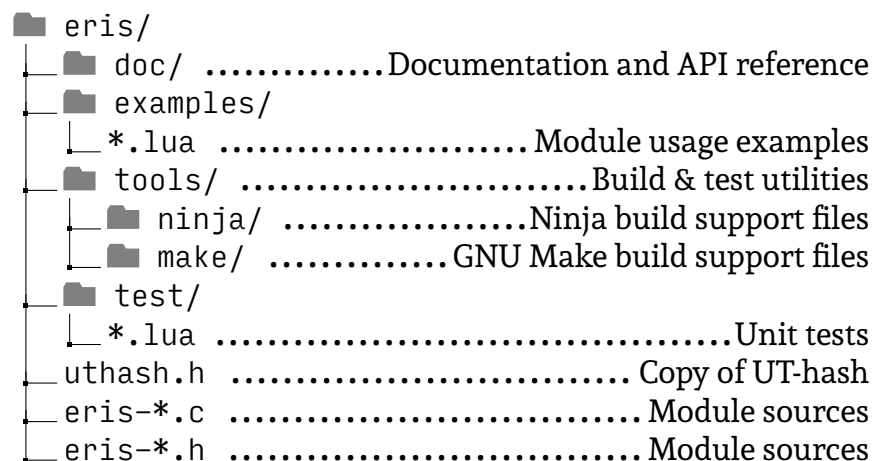
Figure 4.1: Source tree structure.

4.4 Type Representation

Converting values from C to Lua, and vice versa, is one of the most important tasks performed by Eris: C values need to be made accessible from Lua. Therefore, this information needs to be read from the DWARF debugging information (see Debug Information Structure), and kept around in a suitable data structure. This structure must be:

- Exhaustive, to hold all the needed information.
- Compact, to minimize memory usage.

Describing base types is possible using just an enumerated type: there is a fixed amount of them, and the characteristics (size, name, etc) are well known. The challenging part is representing user defined types (`struct`, `enum`, `union`), and derived types (pointers, arrays).

The data structure for describing types is `ErisTypeInfo` (listing 4 on the next page). It is a tagged `struct`, with the tag indicating the type kind (`ERIS_TYPE_S32` for 32-bit signed integers, `ERIS_TYPE_STRUCT` for a `struct`, etc; the complete list of values can be seen in listing 5 on page 36). The contained data will vary depending on the value of the *kind* tag. The members for all possible values are grouped in an `union` in order to make them share the same memory space.

```
\DIFaddend struct _ErisTypeInfo {
  ErisType type;
  union {
    struct TI_base     ti_base;
    struct TI_pointer  ti_pointer;
    struct TI_typedef  ti_typedef;
    struct TI_const    ti_const;
    struct TI_array    ti_array;
    struct TI_compound ti_compound;
  };
};
typedef struct _ErisTypeInfo ErisTypeInfo;
\DIFdelbegin %DIFDELCMD < \end{minted}
%DIFDELCMD <    %%%
```

Listing 4: `ErisTypeInfo`.

The following sections describe in detail the members of `ErisTypeInfo`.

4.4.1 Base Type Representation

```
struct TI_base {
  char              *name;
  uint32_t           size;
};
```

Even though it is sufficient to provide type kind codes for all the base types as discussed before, providing the possibility of querying their `name` and `size` is a ~~nice detail~~convenient feature, at a very small cost: the `ErisTypeInfo` value for each one of the base types is a singleton, defined as follows:

```
/* File: eris-typing.h */
extern const ErisTypeInfo* eris_typeinfo_u32;

/* File: eris-typing.c */
const ErisTypeInfo* eris_typeinfo_u32 = &((ErisTypeInfo) {
  .kind         = ERIS_TYPE_U32,
  .ti_base.name = "uint32_t",
  .ti_base.size = sizeof (uint32_t),
});
```

In practice, to avoid ~~having to write~~ writing the definitions of all the base types, the ~~aid of the~~ C preprocessor and a couple generator macros are used (see subsection 4.6.1).

4.4.2 Pointer Representation

```
struct TI_pointer {
  const ErisTypeInfo *typeinfo;
};
```

Pointers are represented by referencing the `ErisTypeInfo` of the pointed-to type. Thus, it is the only member in `struct TI_pointer`. The size of a pointer value is ~~platform-dependant, but well-known~~ platform dependant, but well known and constant for each platform, and is the value of the C expression `sizeof(void*)`.

4.4.3 Array Representation

```
struct TI_array {
  const ErisTypeInfo *typeinfo;
  uint64_t           n_items;
};
```

Arrays are represented by referencing the `ErisTypeInfo` of the array items, plus the number of items (`n_items`) present in the array. The size of an array value can be calculated multiplying the size of the item type by the number of items in the array.

4.4.4 User Defined Type Representation

```
struct TI_compound {
  char             *name;
  uint32_t          size;
  uint32_t          n_members;
  ErisTypeInfoMember members[];
};
```

This record type ~~will represent all user-defined~~ represents all user defined types: enumerated types (`enum`), record types (`struct`), and union types (`union`):

name

> ~~User-defined~~ User defined types are usually given a name, but it is optional and in this case the value will be `NULL`.

size

> Contains the size of the type, in bytes.

`n_members` / `members`

> Count of members (or enumerators, for `ERIS_TYPE_ENUM`) in the type, and an array contaning their descriptions. Using a flexible array member, allows usage of a single chunk of memory for the `ErisTypeInfo` itself and the items in the array.

The auxiliar `ErisTypeInfoMember` type is defined as follows:

```
typedef struct {
  const char            *name;
  union {
    int64_t              value; /* enum */
    struct {                    /* union, struct */
      uint32_t           offset;
      const ErisTypeInfo *typeinfo;
    };
  };
} ErisTypeInfoMember;
```

This always contains the (optional) `name` of the types, and usage of the remaining fields varies with the type being described:

- For `ERIS_TYPE_STRUCT`, the `offset` of the member (in bytes, from the beginning of the record) and a pointer to its type information (`typeinfo`) are used.

- For `ERIS_TYPE_UNION`, the `offset` is ignored, and only the type information of the member (`typeinfo`) is used.

- For `ERIS_TYPE_ENUM`, only the `value` associated with the enumerator is used.

An `union` is used to make fields share the same memory space.

4.4.5 Type Alias Representation

```
struct TI_typedef {
  char                *name;
  const ErisTypeInfo *typeinfo;
};
```

Type aliases assign a name to an arbitrary type. They are represented by the name and a pointer to the `ErisTypeInfo` of the type.

4.4.6 Read-only Type Representation

```
struct TI_const {
  const ErisTypeInfo *typeinfo;
};
```

Flagging a type as read-only (i.e. using the `const` type qualifier in C) is represented in the same way as pointers (subsection 4.4.2): by keeping a pointer to the `ErisTypeInfo` that is read-only.

4.5 Memory owners and life-cycle

Problem: functions that allocate memory

```
struct point {
        int x;
        int y;
};
```

In Lua, we could create an instance like this:

```
local Geometry = eris.wrap("libgeometry.so")
-- Creates heavy userdata, the Lua GC handles freeing memory
local point = Geometry.point { x = 1, y = -1 }
```

Complete this section

4.6 Miscellanea

This section describes assorted techniques used in the implementation of ERIS which do not fall under a common umbrella, yet they deserve to be mentioned.

4.6.1 Preprocessor "Generator Macros"

This is a programming pattern used thorough the code of ERIS: the C preprocessor is used in a convoluted way as a rudimentary code generator using lists of related elements. First, a macro of related elements is defined (*enumerator macro*, from now on), and it must accept the identifier for another macro (the *generator macro*) as a parameter. Each element in the enumerator macro is an expansion of the generator, passing the parameters needed by the generator.

In order to better understand how generator macros work, let us walk through a complete example adapted from the ERIS source code. The following macro expands into a function which checks the type of an `ErisTypeInfo` — it is the *generator*:

```
#define MAKE_TYPEINFO_IS_TYPE(suffix, name, ctype)        \
    bool eris_typeinfo_is_ ## name (const ErisTypeInfo *info) \
    { return info->type == ERIS_TYPE_ ## suffix; }
```

In generator macros like this, the concatenation operator (##) of the preprocessor is used extensively to build pieces of valid C code. The example shows how the `name` parameter is concatenated to create the name of the generated function, and the `suffix` parameter is concatenated to create a valid `ErisType` (listing 5 on page 36) value. A valid expansion of the above macro is:

```
MAKE_TYPEINFO_IS_TYPE (S32, s32, int32_t)
```

which generates the following valid C function:

```
bool eris_typeinfo_is_s32 (const ErisTypeInfo *info)
{ return info->type == ERIS_TYPE_S32; }
```

The *enumerator macro* is made by grouping a set of macro expansions like the one above. The key is using a generic name for the generator macro, which will be passed as a parameter. The next listing defines an enumerator which expands a generator `F` for each signed integer type:

```
#define INTEGER_S_TYPES(F) \
    F (S8,  s8,  int8_t  ) \
    F (S16, s16, int16_t ) \
    F (S32, s32, int32_t ) \
    F (S64, s64, int64_t )
```

Using the above definition, an expansion of the *enumerator macro* causes multiple expansions at once of the *generator macro* passed as F, which in turn creates as many functions as elements in the enumerator macro. In this example, using generator macros reduces the amount of code that the programmer must write manually close to one fourth of the original.

Another use case for generator macros is creating the code for cases in a `switch` statement. Instead of constructing the code for an entire function at a time, only a single `case` label and its associated ~~is~~ statements are generated. This is done in the following example:

```
#define MAKE_SIGNED_TYPE_CASE(suffix, name, ctype) \
    case ERIS_TYPE_ ## suffix: return true;

bool eris_type_is_signed (ErisType type) {
  switch (type) {
    INTEGER_S_TYPES (MAKE_SIGNED_TYPE_CASE)
    default: return false;
  }
}
```

```
\DIFaddend typedef enum {
  ERIS_TYPE_VOID,     /* void        */
  ERIS_TYPE_BOOL,     /* _Bool       */
  ERIS_TYPE_S8,       /* int8_t      */
  ERIS_TYPE_U8,       /* uint8_t     */
  ERIS_TYPE_S16,      /* int16_t     */
  ERIS_TYPE_U16,      /* uint16_t    */
  ERIS_TYPE_S32,      /* int32_t     */
  ERIS_TYPE_U32,      /* uint32_t    */
  ERIS_TYPE_S64,      /* int64_t     */
  ERIS_TYPE_U64,      /* uint64_t    */
  ERIS_TYPE_FLOAT,    /* float       */
  ERIS_TYPE_DOUBLE,   /* double      */
  ERIS_TYPE_TYPEDEF,  /* typedef … T */
  ERIS_TYPE_CONST,    /* const T     */
  ERIS_TYPE_POINTER,  /* T*          */
  ERIS_TYPE_ARRAY,    /* T …[n]      */
  ERIS_TYPE_STRUCT,   /* struct …    */
  ERIS_TYPE_UNION,    /* union …     */
  ERIS_TYPE_ENUM,     /* enum …      */
} ErisType;
\DIFdelbegin %DIFDELCMD < \end{minted}
%DIFDELCMD <    %%%
```

Listing 5: `ErisType` enumeration.

C Construct	DWARF DIE	ERIS Type
void	∅	ERIS_TYPE_VOID
bool	DW_TAG_base_type	ERIS_TYPE_BOOL
int8_t	DW_TAG_base_type	ERIS_TYPE_S8
uint8_t	DW_TAG_base_type	ERIS_TYPE_U8
int16_t	DW_TAG_base_type	ERIS_TYPE_S16
uint16_t	DW_TAG_base_type	ERIS_TYPE_U16
int32_t	DW_TAG_base_type	ERIS_TYPE_S32
uint32_t	DW_TAG_base_type	ERIS_TYPE_U32
int64_t	DW_TAG_base_type	ERIS_TYPE_S64
uint64_t	DW_TAG_base_type	ERIS_TYPE_U64
float	DW_TAG_base_type	ERIS_TYPE_FLOAT
double	DW_TAG_base_type	ERIS_TYPE_DOUBLE
typedef…	DW_TAG_typedef	ERIS_TYPE_TYPEDEF
const…	DW_TAG_const_type	ERIS_TYPE_CONST
…*	DW_TAG_pointer_type	ERIS_TYPE_POINTER
…[n]	DW_TAG_array_type	ERIS_TYPE_ARRAY
struct…	DW_TAG_structure_type	ERIS_TYPE_STRUCT
union…	DW_TAG_union_type	ERIS_TYPE_UNION
enum…	DW_TAG_enumration_type	ERIS_TYPE_ENUM

Table 4.3: Mapping of C types, DWARF DIEs and `ErisType`.

Chapter 5

Conclusions

Glossary

C

closure

Technique for implementing lexically scoped name binding in languages with first–class functions.. 7

D

data deduplication

Any technique which eliminates duplicate copies of repeating data in order to improve storage utilization. 13

dynamic programming

Problem solving method —and programming technique— which solves a complicated problem by breaking it up in smaller problems in a recursive manner . 11

E

emulation

Piece of hardware or software that enables one computer system (called the *host*) to behave like another computer system (called the *guest*) which enables the host system to run software or use peripheral devices designed for the guest system. *6*

F

Fibonacci number

> Number from the sequence $1, 1, 2, 3, 5, 8, 13, ...$, given by the recurrence relation $F_n = F_{n-1} + F_{n-2}$, with $F_1 = 1$, and $F_2 = 1$, as defined by the Italian mathematician Leonardo Fibonacci. 7

first–class value

> In programming language design, an entity which supports all the operations generally available to other entities of a laguage, typically: being passed as a parameter, returned from a function, and assigned to a variable. 7

flexible array member

> Feature introduced in the C99 standard of the C programming language which allows the last member of a `struct` to be an array of an unspecified dimension. Space needed by the array does not contribute to the size of the `struct` type, and must be manually accounted for when allocating the `struct` from the heap. 32

I

Instruction Set Architecture

> Part of the computer architecture related to programming, including the native data types, instructions, registers, addressing modes, memory architecture, interrupt and exception handling, and external I/O. An ISA includes a specification of the machine language, and the native commands implemented by a particular processor.. 6

M

memoization

> Optimization technique which stores the results of expensive function calls, and returns the previously calculated value when the same inputs occur again. 11

O

object oriented

> Programming paradigm based on the concept of *objects*, which are data structures that encapsulate both data, and its behavior. 23

P

Pascal

Procedural programming language designed in the late 60s by Niklaus Wirth to encourage good programming practices. 7, 23

T

Toyota

Japanese car manufacturer. 4

transpiler

Type of compiler that takes source code of a programming language as its input, and produces a different source code as output, usually in a different programming language. Also known as *source-to-source compiler*, or *transcompiler*. 8

Acronyms

D

DIE

Debugging Information Entry. 13

DWARF

Debugging With Attributed Record Formats. 2, 3, 13, 25

E

ELF

Executable and Linkable Format. 2, 3, 14

F

FDL

Free Documentation License. 13

FFI

Foreign Function Interface. 6

I

ISA

Instruction Set Architecture. 6, *Glossary:* Instruction Set Architecture

J

JIT

Just-In-Time. 6

P

PIC

Position-Independent Code. 28

PUC-Rio

Pontifícia Universidade Católica do Rio de Janeiro. 7

T

TUE

Type Unit Entry. *Glossary:* Type Unit Entry

V

VM

Virtual Machine. vii, 3, 6, 7

Bibliography

[1] System V Application Binary Interface Edition 4.1
The Santa Cruz Operation, AT&T, and *The 88open Consortium*
`http://www.sco.com/developers/devspecs/gabi41.pdf`
Checked: May 3rd, 2015.

[2] DWARF Debugging Information Format Committee
DWARF Debugging Information Format Version 4
`http://dwarfstd.org/doc/DWARF4.pdf`
Checked: May 5th, 2015.

[3] Introduction to the DWARF Debugging Format
Michael J. Eager
`http://dwarfstd.org/doc/Debugging%20using%20DWARF-2012.pdf`
Checked: May 5th, 2015.

[4] How Debuggers Work: Part 3 - Debugging Information
Eli Bendersky
`http://eli.thegreenplace.net/2011/02/07/`
`how-debuggers-work-part-3-debugging-information/`
Checked: May 5th, 2015.

[5] Programming in Lua
Roberto Ierusalimschy
Lua.org, Third Edition (January 3rd, 2013), ISBN 859037985X.

[6] Programming in Lua
Roberto Ierusalimschy
Lua.org, First Edition (December 2003), ISBN 8590379817.
`http://www.lua.org/pil/contents.html`

[7] Lua: About
`http://www.lua.org/about.html`
Checked April 20th, 2015.

[8] Lua 5.3 Reference Manual
Roberto Ierusalimschy, Luiz Henrique de Figueiredo, and *Waldemar Celes*
`http://www.lua.org/manual/5.3/manual.html`, Checked: 29th April, 2015.

[9] The Implementatin of Lua 5.0
Roberto Ierusalimschy, Luiz Henrique de Figueiredo, and *Waldemar Celes*
Journal of Universal Computer Science 11 #7 (2005)
`http://www.jucs.org/jucs_11_7/the_implementation_of_lua`

[10] ffi.* API Functions
Mike Pall
`http://luajit.org/ext_ffi_api.html`
Checked May 11th, 2015.

[11] FFI Semantics
Mike Pall
`http://luajit.org/ext_ffi_semantics.html`
Checked: May 11th, 2015.

[12] Getting Started with Scrumban
`http://www.aboutscrumban.com/how-to-start-using-scrumban/`
Checked: May 5th, 2015.

[13] TAP Specification
Michael G. Schwern, and *Andy Lester*
`http://testanything.org/tap-specification.html`
Checked: May 4th, 2015.

[14] A Consumer Library Interface to DWARF
David Anderson
`https://github.com/Distrotech/libdwarf/blob/`
`distrotech-libdwarf/libdwarf/libdwarf2.1.pdf`
Checked: May 11th, 2015.

[15] A Producer Library Interface to DWARF

David Anderson
`https://github.com/Distrotech/libdwarf/blob/`
`distrotech-libdwarf/libdwarf/libdwarf2p.1.pdf`
Checked: May 11th, 2015.

[16] Ninja documentation
Evan Martin
`http://martine.github.io/ninja/manual.html`
Checked: May 11th, 2015.

[17] GNU Make: A Program for Directing Recompilation
Free Software Foundation, ISBN 1-882114-83-3.
`https://www.gnu.org/software/make/manual/make.pdf`
Checked: May 13th, 2015.

[18] `uthash` User Guide
Troy D. Hanson
`https://troydhanson.github.io/uthash/userguide.html`
Checked: May 15th, 2015.