The DWARF Debugging Standard

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2020-05-20

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A normal day in a programmer’s life

- Imagine you are debugging a program and you can’t find a bug...
- You decide to single-step it in a **debugger**
- You get:
  - Evaluation of variables and expressions
  - Examination of stack frames
  - Current instruction pointer shown in the source code

A normal day in a programmer's life

- Imagine you are debugging a program and you can't find a bug...
- You decide to single-step it in a **debugger**
- You get:
  - Evaluation of variables and expressions
  - Examination of stack frames
  - Current instruction pointer shown in the source code
- **How does it all work?**

Inside the debugger

Debuggers consist of 2 parts:

1. A **monitor** component
   - Implements controlling the program
   - Start, Stop, Restart
   - **Breakpoints**, Single-Stepping...
   - Platform-dependent and operating-system dependent
2. An **analysis** component
   - Collects information about where things are in the program
   - Memory layout, data types...
   - Memory address for each source code line

Inside the debugger

The analysis components needs to get the information from somewhere...

And it cannot simply reimplement the compiler inside itself!

The user may have compiled their code however they liked, reversing the transformations done by the compiler is next to impossible.

We need a **data structure** that tells us where things are inside the compiled executable!

Inside the debugger

This data structure should be:

- Extensible
- Language-independent
- Compact
- Self-contained within the executable, or optionally delivered separately

Inside the debugger

We are talking about the **debugging information**

Basically it's the data that the compiler adds when you specify the `-g` flag

The specification that describes this data structure is called **DWARF**.

"Debugging With Attributed Record Formats"
Yeaaah we all believe that...

DWARF

- Originally developed at Bell Labs together with the ELF object file format in 1988
- Standardized in 1992, but takes its current form in 1993 (DWARF 2).
  - Adoption is not istantaneous, DWARF coexists with a simpler format named “stabs”
- Becomes an open standard roughly at the turn of the century, adoption continues to grow
- Nowadays DWARF is the most used debugging format
  - All Unixes use DWARF as the standard debugging information format
  - Open-source compiler toolchains (GDB, LLVM) use DWARF in embedded development
  - DWARF is stored in standard sections in the executable, and it is loaded alongside the code: even OSes or binary formats not explicitly designed for it can support its usage

Other debugging formats

- Windows uses the CodeView debugging format. It is usually stored in separate files (`.pdb` extension)
- “stabs” is still available for use in most Unixes but nobody uses it anymore
- Other debugging formats exist but are either outdated or nobody uses them

The structure of DWARF

At the highest level of abstraction, DWARF consists of a **tree** structure.

Each **node** in the tree corresponds to an element of the program.

General idea is similar to a compiler's AST.

These nodes are named **DIEs** (Debugging Information Entries).

Every DIE has:

1. a **type** (named **tag**)
2. a set of **key-value** pairs containing the debug information itself

The structure of DWARF

You can examine the DIEs in an object file by using **`dwarfdump`**

In the following discussion we will often see output from `llvm-dwarfdump`

Same thing as normal GNU `dwarfdump`, but formats output in a clearer way

The DWARF version we will use as reference is **DWARF 4**

DWARF 5 is already out, but most compilers do not output it yet. It changes quite a number of details ~~for no reason~~ to improve efficiency.

Up next...

1. We will see **how DWARF models the memory of the program** using DIEs
   - Where data is stored
   - Where the code is stored
   - Other miscellaneous information
2. Then we will briefly go over how **DWARF serializes this information inside the object files**

Let’s get started!

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Describing Data

A debugger like `gdb` is capable of **evaluating expressions**.

To do that, the debugger must be able to resolve each symbol to its current memory location, in order to read its value.

This is not as simple as it sounds!

Where is my data?

- Programming language symbols $\neq$ symbols in executable!
  - Even though ELF already includes symbol names for several objects, they are meant for the **linker**, and are not useful to the debugger!
  - Names might have changed (some platform prepend an underscore to all symbol names)
  - `static` globals do not have a symbol name
  - Stack allocated variables are not symbolicated at all (the linker does not care about them)

$\Rightarrow$ DWARF must contain additional symbolication info!

Where is my data?

- The debugger does not have any intrinsic knowledge of the data types being used
  - Obvious example: custom `structs`
  - Non-obvious examples: floating point formats, big-endian vs. little-endian ints

  ⇒ DWARF must describe in detail all data types!

- A variable associated to a symbol may be moved to **different locations** during the execution of the program!
  - A frequently-used variable may be moved from the stack to a register, and then back to the stack

  ⇒ Each variable location must be relative to a certain region of code!

Data Types in DWARF

To support all this, DWARF uses specific kinds of DIE:

DW_TAG_base_type	A base type (int, char, float...)
DW_TAG_unspecified_type	An unknown type (void)
DW_TAG_typedef	A renamed type
DW_TAG_pointer_type	A pointer to another type
DW_TAG_array_type	An array
DW_TAG_structure	A structure
DW_TAG_union	An union
...	...

Let’s look at some examples...

Data Types in DWARF

Integer scalar

```
int int_global;

DW_TAG_base_type
  DW_AT_byte_size (0x04)
  DW_AT_encoding  (DW_ATE_signed)
  DW_AT_name      ("int")
```

Integer pointer

```
int *p;

DW_TAG_pointer_type
  DW_AT_byte_size (0x08)
  DW_AT_type      (0x00000042 "int")
```

Integer array

```
int int_global_array[10];

DW_TAG_array_type
  DW_AT_type    (0x00000042 "int")
  DW_AT_sibling (0x00000075)

  DW_TAG_subrange_type
    DW_AT_type (0x00000075
                "long unsigned int")
    DW_AT_upper_bound (0x09)

DW_TAG_base_type
  DW_AT_byte_size (0x08)
  DW_AT_encoding  (DW_ATE_unsigned)
  DW_AT_name  ("long unsigned int")
```

Data Types in DWARF

Additional attributes (`volatile`, `const`...)
are represented by separate types

These separate types always point to the base type
(no parent-child relationships)

Constant integers

```
const int int_const = 5;

DW_TAG_base_type
  DW_AT_byte_size (0x04)
  DW_AT_encoding  (DW_ATE_signed)
  DW_AT_name      ("int")

DW_TAG_const_type
  DW_AT_type  (0x00000042 "int")
```

Variables in DWARF

As opposed to types, **variables** & co. are represented by just 3 DIE classes:

DW_TAG_variable	A variable
DW_TAG_formal_parameter	A function parameter (i.e. inside the function)
DW_TAG_constant	A constant

Conceptually, there’s nothing special here as well...

Variables in DWARF

Global integer scalar

```
int int_global;

DW_TAG_variable
  DW_AT_name  ("int_global")
  DW_AT_type  (0x00000042 "int")
  DW_AT_external  (true)
  DW_AT_location  (DW_OP_addr 0x0)
```

Local integer scalar

```
int int_local;

DW_TAG_variable
  DW_AT_name  ("int_local")
  DW_AT_type  (0x00000042 "int")
  DW_AT_location  (DW_OP_fbreg -28)
```

- Apart from the obvious `name` and `type` attributes, the `external` and `location` attributes appeared
- `external` specifies if the symbol is visible from outside the compilation unit
- **`location`** specifies where the data is located using a **DWARF expression**

DWARF expressions

- DWARF expressions are composed of **sequences of commands**
- They are interpreted by a simple **stack-based evaluator**
- Commands can optionally take parameters, use **prefix notation**
- There are commands for branches, function calls...
- The values in the evaluator are either **void pointers** or **base types** supported by the target machine
- All results of commands are pushed on top of the stack
- Commands are evaluated in the order they appear (bar jumps / calls)
- It’s a mini assembly language!

DWARF expressions

DWARF expressions are powerful, but this power is seldom used or needed.

Most used commands:

`DW_OP_fbreg` x	The value of the current frame pointer plus x
`DW_OP_reg`n	The location of register n (0 to 31, represented in an opaque encoding)
`DW_OP_addr` x	The absolute address x

Remember: the DWARF data sections are
linked together with the rest of the program
⇓
Any address that appears in them can be fixed up
by a static or a dynamic linker!

DWARF Location Descriptors

Actually, `DW_AT_location` attributes can be associated to two kinds of values:

1. One DWARF expression describing where the data is allocated (*Single location descriptions*)

   Used when the data is always allocated in the same place

2. A map between code ranges and DWARF expressions (*Location lists*)

   Used when the data changes its location during its lifetime

DWARF Location Descriptors

C code

```
int *p = buf;
int a = 0;
for (int i=0; i<10; i++) {
  a += *p++;
}
```

Debug Info

```
DW_TAG_variable
  DW_AT_name     ("p")
  DW_AT_type     (0x00000117 "int*")
  DW_AT_location (0x00000072
     [0x22,  0x2b): DW_OP_reg3 RBX
     [0x2b,  0x3c): DW_OP_reg5 RDI)
```

Assembly Code (-g -O2)

```
     5: leaq 16(%rsp), %rbx
    22: leaq 40(%rbx), %rdx   p: %rbx
    26: xorl %eax, %eax       p: %rbx
    28: movq %rbx, %rdi       p: %rbx
/-> 30: addq $4, %rdi         p: %rdi
|   34: addl -4(%rdi), %eax   p: %rdi
|   37: cmpq %rdx, %rdi       p: %rdi
\-- 3a: jne  -12 <main+0x30> p: %rdi
    3c: leaq 12(%rsp), %rdi
    41: movl %eax, 12(%rsp)
```

GCC optimized out the `i` variable and moved p to two different registers.

DWARF Declaration Coordinates

All of these DIEs (along with many others) support specifying where each type is declared using specific attributes:

`DW_AT_decl_file`	File where the declaration was found
`DW_AT_decl_line`	Line number (1-based) of the declaration
`DW_AT_decl_column`	Column number (1-based)

Declaration Coordinates

```
DW_TAG_variable
  DW_AT_name      ("int_global")
  DW_AT_decl_file ("/media/sf_example/dwarf-test.c")
  DW_AT_decl_line (1)
  DW_AT_type      (0x00000042 "int")
  DW_AT_external  (true)
  DW_AT_location  (DW_OP_addr 0x0)
```

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Describing Code

We have seen how DWARF describes **data**. Of equal importance in a debugger is analyzing the **code being executed**.

Obvious requirements:

- Map to instruction to line of code in the source code
    - Essential for breakpoints, single stepping

Less obvious requirements:

- Map from code spans to compilation units
- Map from code spans to functions
- Identification of every function call in a function
    - Used for breakpoints on functions, to parse backtraces, to resolve imported functions
- Grouping of lexical blocks in a function
    - Used to determine the scope of variables

Describing Code

- Compilation units, functions and function calls are part of the DIE tree
  - Just like a compiler AST!
- The line number table is its own separate structure
  - This helps saving space inside the executable, as DIEs are not as space-efficient

Describing Code: Compilation Units

A compilation unit (`DW_TAG_compile_unit`) represents the result of a single compilation process (duh).

Common attributes:

`DW_AT_name`	File name that was compiled
`DW_AT_comp_dir`	Working directory where the compiler was invoked
`DW_AT_language`	Language of the source code file
`DW_AT_stmt_list`	Pointer to the line number table for this file
`DW_AT_low_pc`	Range of addresses of the
`DW_AT_high_pc`	compilation unit’s code

Describing Code: Functions

A subprogram (`DW_TAG_subprogram`) represents a function. Function arguments are described by children `DW_TAG_formal_parameter` DIEs.

Common attributes:

`DW_AT_name`	Function name (as it appears in the source)
`DW_AT_type`	Type of the return value
`DW_AT_frame_base`	Expression establishing the address of the frame pointer (`DW_OP_fbreg`)
`DW_AT_low_pc`	Range of addresses of the function’s code
`DW_AT_high_pc`	

Describing Code: Blocks

`DW_TAG_lexical_blocks` DIEs represent a block, in languages that support this concept. Not strictly required, but helps the debugger in handling local variables with a restricted scope.

Common attributes:

`DW_AT_low_pc` `DW_AT_high_pc`	Range of addresses of the function's code

And that's it!

Note that every time the `DW_AT_low_pc` and `DW_AT_high_pc` attributes are used together, they can be replaced by a single `DW_AT_ranges` attribute.

`DW_AT_ranges` supports describing multiple discontiguous ranges.

Describing Code: Line Numbers

The **line number table** is its own data structure.

- Maps each instruction to a line number and more
- Consecutive instructions mapping to the same line number are represented by just the first instruction
- Internal representation consists of a **line number program** that builds the table (and allows for compact representation of similar rows)
  - We will enter into details about this representation later

The GNU assembler supports building this data automatically using specific `.loc` directives.

Describing Code: Line Numbers

Address	Address of the instruction
Op. Index	0 for non-VLIW architectures
File	File where the line is found (index in a list of files)
Line	Line in the file (1-based)
Column	Column in the file (1-based)
Is Statement	True if position is at the beginning of a statement
Basic Block	True if at the beginning of a basic block
End Sequence	True in the last row of the table (ending marker)
Prologue End	True in the last instruction of a function prologue
Epilogue Begin	True in the first instruction of a function epilogue
ISA	The instruction set of the code
Discriminator	Disambiguates multiple blocks on the same line

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Other information in DWARF

DWARF also provides some extra useful but not essential information:

- Call Frame Information
- Macro information (!)
- Identifier index for faster lookups

Call Frame Information

DWARF Call Frame Information (aka CFI) allows the debugger to reliably perform backtraces.

Why we need it?

1. The ABI already provides a way to perform backtraces without it, but it prevents optimizations like tail calls or (in the x86 architecture) using the EBP register for other purposes
2. DIEs by themselves do not contain any information about the size of the activation record of each function, just how to access variable values

Call Frame Information

DWARF defines an activation record as the following set of values:

- The return address (for past frames) or the current PC (for the current frame)
- The area of memory in the stack corresponding to the call frame of the function (described as a single base pointer: the Canonical Frame Address)
- The set of registers that are preserved across the call correponding to the activation record

Call Frame Information

The CFI maps each instruction in the program to a table that specifies:

- how to reconstruct each register value from the activation record alone, as it appears in that point of the subroutine
- where the Canonical Frame Address pointer is

This information is compressed using a bytecode system similar to DWARF expressions and the line number table.

The GNU assembler supports building this data inline (like the line number table) using specific `.cfi_XXX` directives.

Fun fact: the same tables used by DWARF are used as a method for implementing stack unwinding for C++ exceptions (hence why they are so slow!)

Macro Information

You wish you could **debug your C macros**?

DWARF includes a **Macro Information** section which specifies to the debugger where a macro declaration can be found in the source.

There is nothing else in there... which limits its usefulness. It's also 100% optional.

The format of macro information has changed in DWARF 5.

Accelerated Access

DWARF has a facility for building an index of symbols to make lookup of large DIE trees easier. It’s implemented as a hashtable.

The index can contain references to:

- Subprograms
- Labels
- Variables
- Types
- Namespaces

(we didn’t see some of these DIEs earlier, but they exist)

The index must be complete, this simplifies the lookup logic in case it exists (it’s optional).

Just like with macro information, the format of the index has changed in DWARF 5.

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The physical reality (?) of DWARF

DWARF debug info is scattered in different sections, whose names all start with `.debug`:

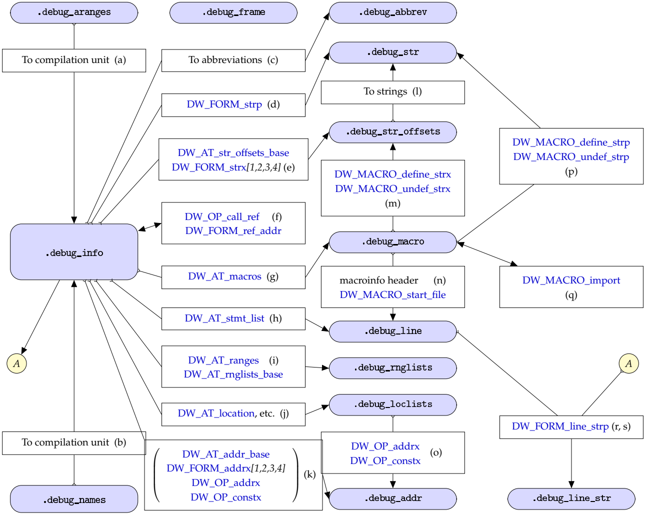
`.debug_info`, `.debug_abbrev`	DIE tree
`.debug_line`	Line number table
`.debug_frame`	Call Frame Information
`.debug_macro`	Macro information
`.debug_pubnames`,`.debug_pubtypes`	Index

The physical reality (?) of DWARF

The information for some structures is **scattered further** (for a mix of backwards compatibility and data compactness reasons) into **more sections**:

`.debug_addr`	Constant pool for DWARF expressions
`.debug_aranges`	Address ranges for compilation units
`.debug_line_str`	String pool for `.debug_line`
`.debug_loc`	Location lists addressed by `.debug_info`
`.debug_ranges`	Range list addressed by `.debug_loc`
`.debug_str`	String pool for `.debug_info`
…	…

A simple and logical organization



.debug_aranges

.debug_frame

.debug_abbrev

To compilation unit (a)

To abbreviations (c)

.debug_str

To strings (l)

DW_FORM_strp (d)

.debug_str_offsets

DW_AT_str_offsets_base
DW_FORM_strx*[1,2,3,4]* (e)

DW_MACRO_define_strp
DW_MACRO_undef_strp
(p)

DW_MACRO_define_strx
DW_MACRO_undef_strx
(m)

.debug_info

DW_OP_call_ref (f)
DW_FORM_ref_addr

.debug_macro

DW_AT_macros (g)

macroinfo header (n)
DW_MACRO_start_file

DW_MACRO_import
(q)

DW_AT_stmt_list (h)

.debug_line

A

DW_AT_ranges (i)
DW_AT_rnglists_base

.debug_rnglists

A

DW_AT_location, etc. (j)

.debug_loclists

DW_FORM_line_strp (r, s)

To compilation unit (b)

DW_AT_addr_base
DW_FORM_addrx*[1,2,3,4]*
DW_OP_addrx
DW_OP_constx
(k)

DW_OP_addrx
DW_OP_constx
(o)

.debug_names

.debug_addr

.debug_line_str

A simple and logical organization

We will focus on:

- Representation of the main DIE structure
- The line number table

These two structures are the most important anyway.

The `.debug_info` section

This section contains the main structure of DWARF: the tree of Debug Information Entries.

It contains:

1. An header
2. The serialized DIEs, enumerated in depth-first order
   - Each DIE has a flag specifying if it has children
   - A special flag marks the end of a chain of children

This structure is repeated for each compilation unit in the file (in the case of a non-linked object file there is always just one compilation unit)

The `.debug_info` section

The header of a `.debug_info` is simple:

`uint32_t length;`	Size of the info for this unit
`uint16_t version;`	DWARF version
`uint32_t abbrev_offset;`	Offset in the **abbreviation table**
`uint8_t address_size;`	Size of a pointer (in bytes)

Wait... what’s an **abbreviation table**?

The `.debug_abbrev` section

The **abbreviation table** is the main element of the **compression scheme** used by DWARF to represent DIEs.

- The typical DIEs produced by a compiler have similarities
  - The same type of DIE often has the same type of attributes
  - Similarly structured DIEs will have different attributes values
- The format of a DIE may change in the future
  - We need to allow old implementations to read new DWARF records without getting confused

The abbreviation table **decouples the tag, the attributes, the order of appearance of the attributes, and the type of each attribute in the DIE from the values of the attributes**

The .debug_abbrev section

The abbreviation table contains a flat list of DIE patterns, in the following format:

Abbreviation table in pseudo-C

```
struct debug_abbrev {
  struct {
    uleb128 id;
    uint8_t has_children;
    struct {
      uleb128 attr_id;
      uleb128 format_id;
    } [M];
    uint16_t terminator = 0;
  } [N];
  uint8_t terminator = 0;
}
```

- M is the number of attribute-value pairs in the abbreviated DIE, it changes for each abbreviation
- N is the total number of abbreviations

The `uleb128` format

uleb128 is a **variable length numeric representation** used in DWARF for compactness.

It reduces the number of leading zero bytes in the representation by using bit 7 as a stop marker. Maximum length of 128 bits gives it its name.

- Bit 7 = 0 ⇒ This is the last and most significant byte
- Bit 7 = 1 ⇒ This is not the last byte, read another one

uleb128 example

```
0x0001 = 0b0000000_0000000_0000001 = 0x01
0x007F = 0b0000000_0000000_1111111 = 0x7F
0x0080 = 0b0000000_0000001_0000000 = 0x80 0x01
0xAA55 = 0b0000010_1010100_1010101 = 0xD5 0xD4 0x02
```

The `.debug_info` section

Back to the `.debug_info` section...

After the header, for each DIE the section contains:

- The identifier of the matching abbreviation, encoded as `uleb128`
- The values of the attributes, in the same order as in the abbreviation
  - Not all attribute types use the same number of bytes! There is no alignment, and some types use **zero bytes**.

Abbreviation number zero does not exist; zero is used as the **end-of-children mark**.

Whether a DIE has children or not, it's specified in the abbreviation!

The `.debug_line` section

In constrast with the `.debug_info` section, the `.debug_line` section is much simpler. It encodes the **line number table**.

It begins with a header specifying:

- Length, version (like `.debug_info`)
- Whether by default each line contains a statement (usually true)
- The list of include directories used by the compiler
- The list of files that are referenced by the line number table

(not an exhaustive list)

The list of files and include directories are specified as offsets of strings in the `.debug_line_str` section.

The `.debug_line` section

After the header, the **line number program** begins.

Every instruction can either:

- Modify a cell in the current row of the table
  - Each opcode corresponds to a different column
  - `DW_LNS_advance_pc`, `DW_LNS_advance_line`, `DW_LNS_set_file`, ...
- Create the next row by (mostly) copying the next row
  - `DW_LNS_copy`
  - The **Basic Block**, **Prologue End**, **Epilogue Begin** and **Discriminator** rows are set to zero regardless

- Instructions either take no operands, or a single `uleb128`.

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Conclusion

We have seen:

- A brief history of debugging formats, why they are needed, what DWARF is
- What is the big idea behind DWARF
- How DWARF is actually represented inside an object file

Conclusion

With this knowledge you could:

- Build your own compiler from scratch with debugging info support
- Build your own source-level debugger
- Improve debugging support in other compilers

One last note!

If you are a LLVM user... the implementation details are **abstracted** from you!

LLVM represents debug information using a more generic data structure known as **metadata**.

Debug information is important, and it is **up to the passes** to mantain its correctness, so keep this in mind when you work with LLVM.

LLVM documentation about debugging information:
`https://llvm.org/docs/SourceLevelDebugging.html`

I want to know more about dwarves!

`http://dwarfstd.org`

Or get in contact with your local DM `;)`

Thank you!

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