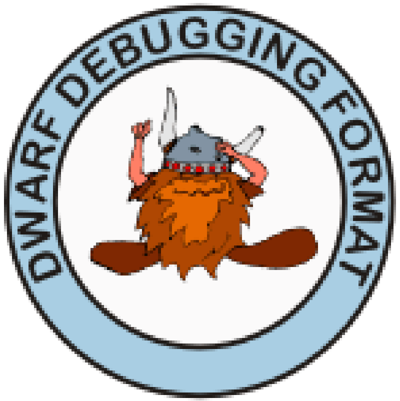
DWARF Debugging Format



How the Compiler Tells Its Secrets to the Debugger

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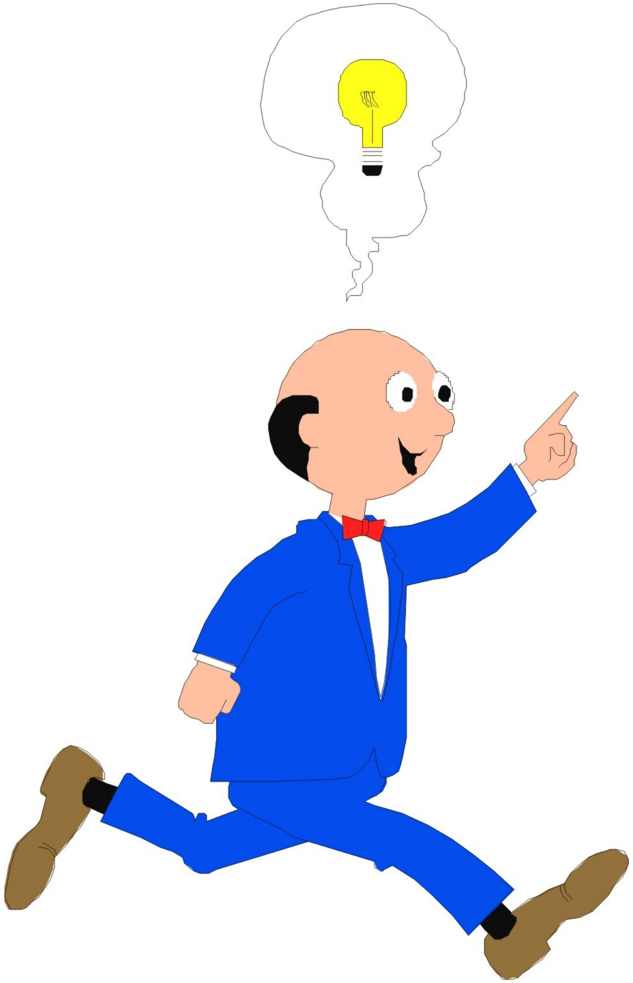
How Program Development is Supposed to Work

Developer Has **Great Idea**



Translates **Great Idea** into C code

Compiler translates C code to machine language

Everything works!!

Real World Program Development

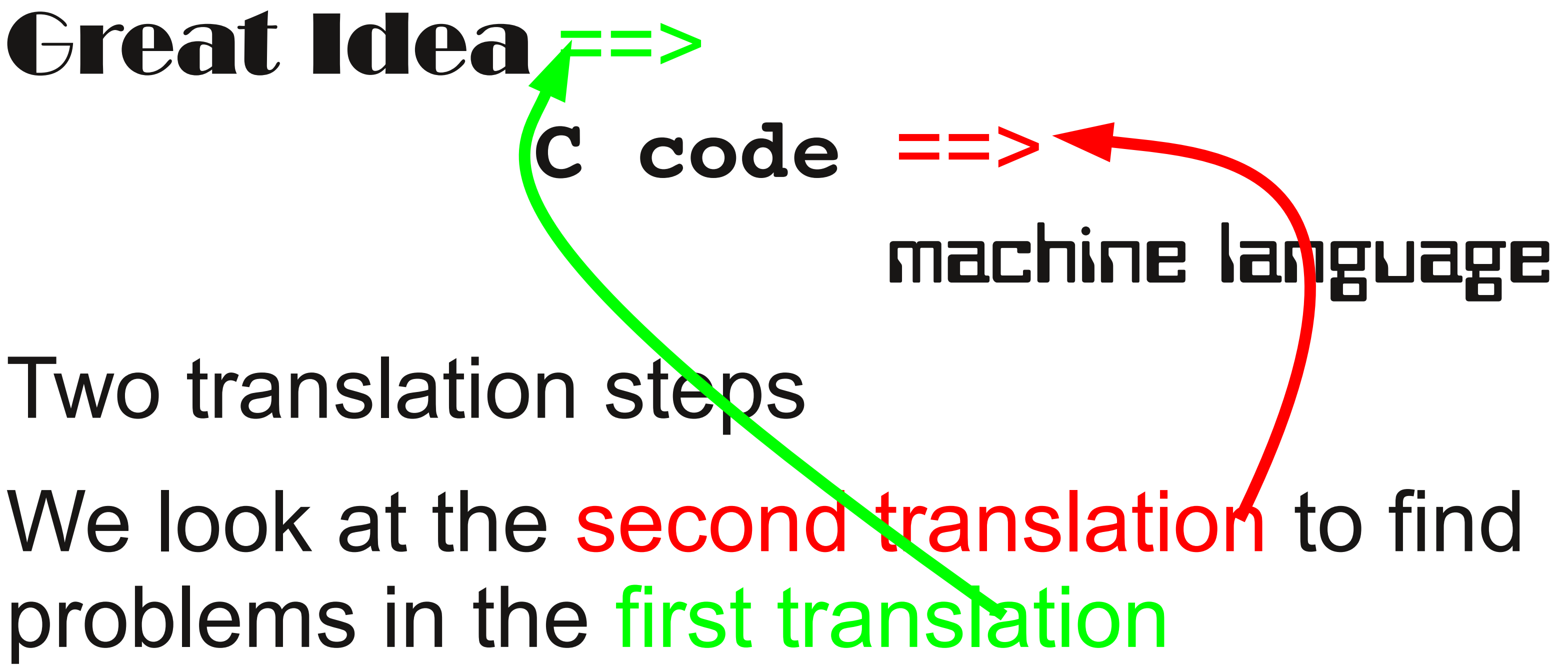
- Developer Has **Great Idea**
- Translates **Great Idea** into C code
- Compiler translates C to machine language

Something Unexpected Happens

Developer uses debugger to understand the translation from **Great Idea** to machine language

Many hours and many cups of coffee later translation error is fixed

Debugging



Great Idea ==>

C code ==>

machine language

- Two translation steps
- We look at the second translation to find problems in the first translation

What We Think the Compiler Does

- Reads clear and complete program source
- Linear translation from C code into machine language
- Follows programmer's directions to the letter

What Really Happens

- Compiler believes it knows better than the developer. Reorders and reorganizes the program to improve performance
  - If it isn't prohibited, it's permitted
  - If it isn't defined, compiler free to do anything
- Multi-step process of incremental optimization
- Each time a change is made, a little bit of information is lost

Goals of the Compiler

- Correctly interpret C (or other) language
  - Compare with language standard
  - Verify with test suite and regression tests
- Generate correct machine language
  - Defined by architecture manual
  - Verify with test suite
- Optimize code
  - Optimized result is the same as unoptimized code
  - Verify with test suite
- Generate debugging info

What the Debugger Knows

- Info from object file (executable, obj, library)
    - Symbol names and addresses
        - Global
        - Local (some)
- Info from processor
    - Memory contents
    - Register contents
- Info from system
    - Library locations
    - How to control programs

What DWARF Tells the Debugger

- Source files – name and path
- Names of functions, arguments, globals, locals
- Type descriptions
- Types of functions, variables, and parameters
- Block structure of program
- Mapping between source and object (line<=> address)
- Variable location (registers/memory)
- How to unwind stack

What DWARF Doesn't Tell

- Machine characteristics
    - Registers, address size, instructions
- OS characteristics
- ABI
    - Calling conventions
- Program flow
- Semantics

DWARF History

- Developed at AT&T as part of Unix SVR4
- PLSIG (Programming Languages SIG) of Unix International, Inc. formed in 1988
- DWARF version 1 (standard published 1992)
  - Compatible with AT&T SVR4 DWARF format
- DWARF version 2 (draft standard released 1993)
  - Not compatible with DWARF version 1
  - Broader functionality
  - More compact representation
- DWARF Committee reconstituted October, 1999
- DWARF version 3 (standard published 2005)
  - Compatible with DWARF version 2
- DWARF version 4 (standard published 2010)

DWARF Philosophy

- Permissive standard
  - Describes what various DWARF constructs mean
  - Does not mandate generation of specific constructs
- Extensible
  - Supports user extensions
  - Allows novel uses of existing attributes
- Upward compatible
  - Consumers (i.e. debuggers) can read later versions
  - Skip over unknown DIEs

DWARF Goals

- Permit accurate and complete description of source to object translation
  - Whether a particular compiler generates good or poor DWARF is a Quality of Implementation issue
- Compact data representation
- Efficient generation
- Open standard, transparent process

Languages and Processors

- Block structured procedural languages

C
C++
Cobol
Java

Ada
Fortran
Modula
Pascal

- Von Neuman or Harvard architecture

x86
IA32
ARM

IA64
PowerPC
MIPS

Basic Concepts

- DWARF can be used in any object file
  - Most commonly associated with ELF
- Multiple data sections
  - DWARF sections start with .debug_
    - .debug_info – Program organization
      - Functions & Variables
    - .debug_line – Line <=> address mapping
    - Several other sections
      - Compression – strings, abbreviations, types
      - Other info – call frames, indexes – address and name

Basic Data Structure

- Debugging Information Entry (DIE)
  - Each DIE has a TAG which identifies purpose
    - `DW_TAG_compile_unit` – Describe a compilation unit
    - `DW_TAG_subprogram` – Describe a subroutine
    - `DW_TAG_variable` – Describe a variable
    - `DW_TAG_pointer_type` – Describe various types
    - `DW_TAG_formal_parameter` – Describe arguments

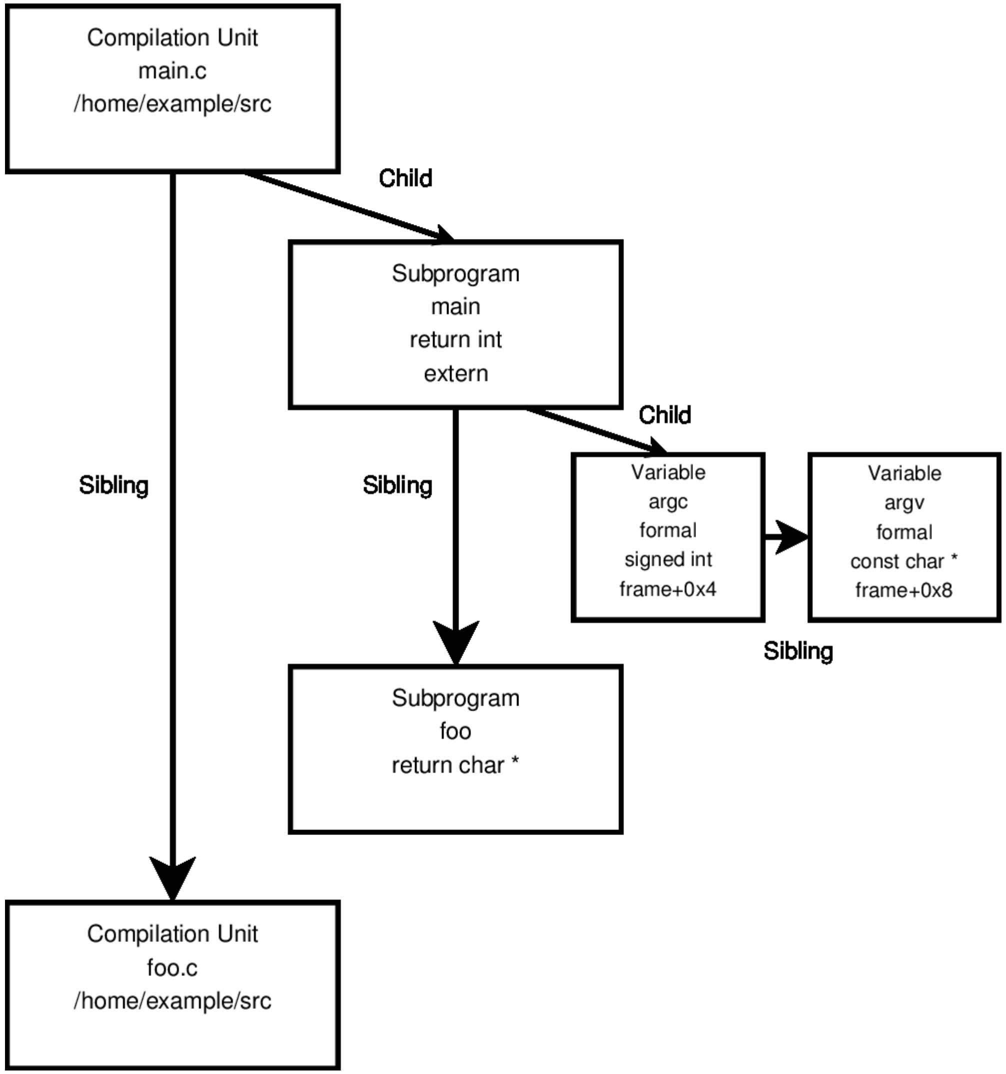
Basic Data Structure

- Each DIE has one or more attribute/value pairs
- Each attribute has a name
  - Describes meaning of attribute
  - Value specified for each attribute
  - Data format specified in attribute encoding
- Examples
  - `DW_AT_name` – Name of object DIE describes
  - `DW_AT_location` – Source location of object
  - `DW_AT_low_pc` – Start address of object
  - `DW_AT_high_pc` – End address of object
  - `DW_AT_type` – Pointer to DIE describing type

DWARF Info Tree Structure

- Match block structure of source program
- Each DIE has zero or more sibling DIEs
- Each DIE has zero or more children
- Each Compilation is represented by a Compilation Unit DIE
  - Everything is a child of the Comp Unit DIE

DWARF Info Tree Structure



Compilation Unit
main.c
/home/example/src

Child

Subprogram
main
return int
extern

Child

Variable
argc
formal
signed int
frame+0x4

Variable
argv
formal
const char *
frame+0x8

Sibling

Sibling

Sibling

Subprogram
foo
return char *

Compilation Unit
foo.c
/home/example/src

Compile Unit DIE

- Describe compilation
- Source location
- Compilation directory
- Producer info
- Programming language
- Low and high PC range
- Pointers to other data
    - Line number info
    - Macro info
- Children DIEs describe the program

Compile Unit DIE

```
b3: DW_TAG_compile_unit
  DW_AT_producer    : GNU C 4.6.1 20110627
  DW_AT_language    : 1 (ANSI C)
  DW_AT_name        : bzip2.c
  DW_AT_comp_dir    : /ext/yocto/.../bzip2-1.0.6
  DW_AT_low_pc      : 0x0
  DW_AT_entry_pc    : 0x0
  DW_AT_ranges      : 0x260
  DW_AT_stmt_list   : 0x82
```

Subroutine DIE

- `DW_TAG_subprogram`
  - Describe subroutine, function, inlined subroutine, entry point, declaration vs. definition
  - Subroutine name and source location
  - Visibility – whether it is external
  - Reference to return type DIE
  - Low and high PC
  - Prototyped flag
- “Owns” children DIEs: arguments, variables, types, and blocks within subroutine

Subroutine DIE

```
1ba2: DW_TAG_subprogram
  DW_AT_external    : 1
  DW_AT_name        : main
  DW_AT_decl_file   : 1
  DW_AT_decl_line   : 1776
  DW_AT_prototyped  : 1
  DW_AT_type        : <0x683>
  DW_AT_low_pc      : 0x80491e0
  DW_AT_high_pc     : 0x8049d90
  DW_AT_frame_base  : 0x22e3 (location list)
  DW_AT_sibling     : <0x212a>
```

Variable DIE

- Describe data object
  - Variable name
  - Reference to type DIE
  - Source location
  - Declaration vs. definition
  - Run time location
  - Default value
  - Constant value

Variable DIE

```
1c28: DW_TAG_variable
  DW_AT_name          : decode
  DW_AT_decl_file     : 1
  DW_AT_decl_line     : 1782
  DW_AT_type          : <0x657>
  DW_AT_location      : 0x24ed (location list)
...
213b: 71 (DW_TAG_variable)
  DW_AT_name          : stdin
  DW_AT_decl_file     : 5
  DW_AT_decl_line     : 165
  DW_AT_type          : <0x465>
  DW_AT_external      : 1
  DW_AT_declaration   : 1
```

Base Type DIE

- Describe data type that is directly implemented by machine hardware
- Name of type
  - Examples: int, long, unsigned char, etc.
- Encoding
  - Example: address, boolean, signed, float, decimal
- Size
  - Size in bytes or bits needed to hold value
  - Offset within storage unit

Base Type DIE

```
d4: DW_TAG_base_type
  DW_AT_byte_size   : 2
  DW_AT_encoding    : 7 (unsigned)
  DW_AT_name        : short unsigned int
db: DW_TAG_base_type
  DW_AT_byte_size   : 4
  DW_AT_encoding    : 7 (unsigned)
  DW_AT_name        : unsigned int
...
6d: DW_TAG_base_type
  DW_AT_byte_size   : 1
  DW_AT_encoding    : 8 (unsigned char)
  DW_AT_name        : unsigned char
...
f7: DW_TAG_base_type
  DW_AT_byte_size   : 4
  DW_AT_encoding    : 5 (signed)
  DW_AT_name        : int
```

Composite Type DIEs

- Type DIE constructed from references to other type DIEs, either Base Type or Composite Type
- Const_type, volatile_type
    - Represent “const” or “volatile” qualifier
- Pointer_type
    - Represent pointer to qualifier (“*”)
- Typedef
- Eventually reach Base Type

Composite Type DIEs

```
260: DW_TAG_structure_type
  DW_AT_name          : _IO_FILE
  DW_AT_byte_size     : 148
  DW_AT_decl_file     : 6
  DW_AT_decl_line     : 271
  DW_AT_sibling       : <0x421>
26d: DW_TAG_member
  DW_AT_name          : _flags
  DW_AT_decl_file     : 6
  DW_AT_decl_line     : 272
  DW_AT_type          : <0x190>
  DW_AT_data_member_location: (DW_OP_plus_uconst: 0)
...
657: DW_TAG_typedef
  DW_AT_name          : Bool
  DW_AT_decl_file     : 1
  DW_AT_decl_line     : 162
  DW_AT_type          : <0x16d>
```

Type Tree

```
const unsigned char * volatile p;
```

A volatile pointer to a constant character.

This is encoded in DWARF as:

```
DW_TAG_variable (p) →
  DW_TAG_volatile_type →
    DW_TAG_pointer_type →
      DW_TAG_const_type →
        DW_TAG_base_type (unsigned char)
```

Data Structures

- `DW_TAG_struct_type, DW_TAG_class_type, DW_TAG_union_type, DW_TAG_interface_type`
  - Define structure, class, union, Java interface
  - DIE “owns” members of the struct/class/union/interface
  - `DW_TAG_member`
    - Similar to a variable definition
    - Instead of memory location, has offset from start of object
- `DW_TAG_array_type`
  - Define array of same type object
  - Index is a subrange. In C, [0..n).

Locating Data

- `DW_AT_location` – location description
  - Single location description – fixed lifetime
    - Simple location – contiguous location (reg or memory)
    - Composite location – data split into pieces
    - Omitted – “variable optimized away”
  - Multiple location description – Location lists
    - Reference to `.debug_loc`
    - Define where data is located for specific PC ranges
    - Object can change location over its lifetime
- DWARF expressions
  - Complete stack-oriented expression evaluation

Locating Code

- `DW_AT_low_pc` – starting or only address
- `DW_AT_high_pc` – ending address
- `DW_AT_ranges` – non-contiguous range
  - Reference to `.debug_ranges`
  - Pairs of (beginning,ending) offset from base address
  - Base Address
    - Default to start of compilation unit
    - May be explicitly specified

Mapping Address to Source

- Needed to set breakpoints, identify fault location, step through source
- `.debug_line` section
- Conceptual contents
  - One row for each code memory address
  - Source file name, line number, column
  - Flag beginning of statement
  - Flag beginning of basic block
  - Flag end of prologue, start of epilogue
  - Instruction set (e.g., ARM vs Thumb)
- Problem – unencoded table would be huge

Compressing Line Information

- Finite State Machine generates line info table
- Line Number Program
  - Operations drive FSM to generate next row
  - Duplicate rows are eliminated
  - Each value described as register, copied to next row unless changed
  - Example ops
    - Add integer to source line number
    - Set statement, block, prologue, epilogue flag
    - Advance PC

Speeding Up Debugging

- `.debug_pubnames`
  - Names of global objects and functions
  - Reference to DIE defining object or function
- `.debug_pubtypes`
  - Names of types
  - Reference to DIE describing type
- `.debug_aranges`
  - Address start and length
  - Reference to compilation unit

Call Frame Information

- Describe details of function call
  - Locate previous frame
  - Locate saved register values
- Permit unwinding/walking stack
- CIE – Common Information Entry
- FDE – Frame Description Entry
  - Finite State Machine indexed by PC address
- Variant (.eh_frame) used to implement C++ exception handling

Compressed DWARF

- Uncompressed TAG/Attribute/Value huge
  - Major impetus for DWARF 1 to DWARF 2 migration
- Multiple approaches to compression
  - Data encoding – uleb, sleb
  - Indirection – references to other tables
  - Abbreviation table
  - Implicit sibling pointers
- Separate data for duplicate elimination

GCC Debug Options

- -g
  - Generate default debug info (DWARF)
- -g3
  - Generate debug info including macro descriptions
- -ggdb
  - Generate debug info for gdb (most expressive)
- -gdwarf[234]
  - Generate DWARF 2, 3, 4 debug info
  - May use some extensions from later versions
  - DWARF 4 requires gdb-7.0 for best results
- -gstrict-dwarf
  - Disallow extensions from later standard versions

Printing DWARF with Readelf

- `readelf -w`
  - Dump all DWARF data
- `readelf -w[lLiaprmfFsoRt]`
  - Print selected DWARF data
    - raw line table, decoded line table, info, abbrev, pubnames, aranges, macro, raw frames, frames-interp, str, location, ranges, public types

DWARF version 4

- Released June 10, 2010
- Extensive review and update of documentation
- Support for VLIW architectures (IA64)
- Separate type units – improved compression
- Improved language support
  - Fortran – identify main subprogram
  - C++ -- rvalue references, constant exprs, template aliases, template parameters, strong enum types
  - Generalize packed array descriptions
  - Support profile-based optimizations

DWARF version 5

- Anticipated release date late 2013
- Support C++11 features: atomic
- Separate debug data from object files
- Improved macro description
- Improve debug of optimized code
  - Optimized variables
- Improved debugger accelerator data
- Restructure documentation

DWARF Committee

- Committee website: `dwarfstd.org`
- Independent, no membership fees
- Open standard available without charge
- Broad based
  - Companies represented:
    - Apple ARM Concurrent Computer
    - Eager Consulting Google HP
    - IBM Intel RedHat Rogue Wave

Questions/Answers

- Michael Eager – `eager@eagercon.com`
- DWARF Website – `dwarfstd.org`
  - Submit question/suggestion about standard
    - `dwarfstd.org/Comment.php`
- DWARF wiki – `wiki.dwarfstd.org`
- DWARF Discussion List
  - `dwarf-discuss@lists.dwarfstd.org`