A deep dive into DEX file format

Rodrigo Chiossi

Bio

- ## Rodrigo Chiossi

  - Android Engineer @ Intel OTC

  - AndroidXRef

    - www.androidxref.com

  - Dexterity

    - https://github.com/rchiossi/dexterity

Overview

- DEX File Structure
  - Characteristics
  - LEB128
  - Relative Indexing
  - MUTF-8
  - The "Big" Header and the data.
- DEX Instrumentation
  - The "String Add" case
- DEX Limitations
  - Bitness restrictions

DEX Structure

Header
string_ids
type_ids
proto_ids
field_ids
metrods_ids
class_defs
data
link_data
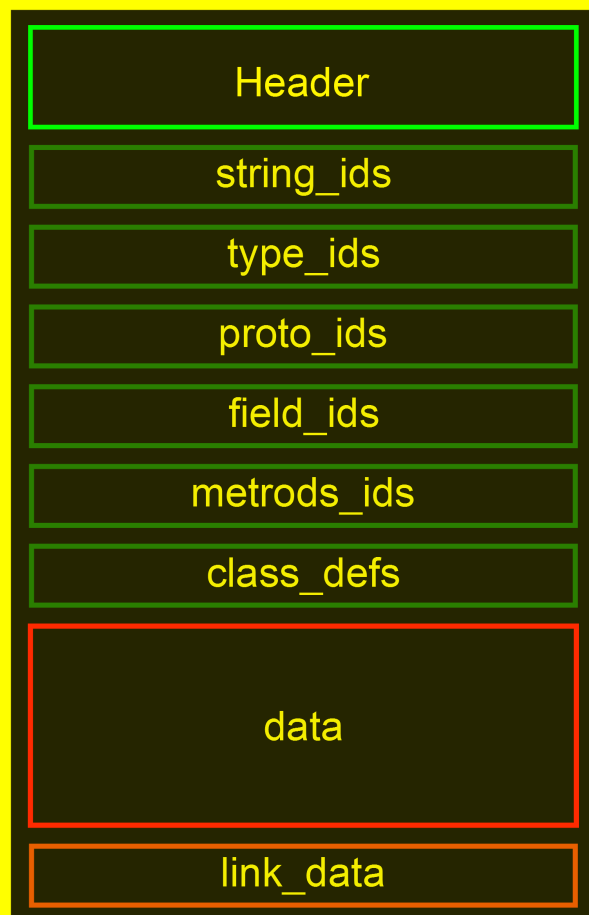
Header :

magic	ubyte[8]
checksum	uint
signature	ubyte[20]
file_size	uint
header_size	uint
endian_tag	uint
link_size	uint
link_off	uint
map_off	uint
string_ids_size	uint
string_ids_off	uint
type_ids_size	uint
type_ids_off	uint
proto_ids_size	uint
proto_ids_off	uint
field_ids_size	uint
field_ids_off	uint
method_ids_size	uint
method_ids_off	uint
class_defs_size	uint
class_defs_off	uint
data_size	uint
data_off	uint

map_item:

type	ushort
unused	ushort
size	uint
offset	uint

Type Codes:

HEADER_ITEM	0x0000
STRING_ID_ITEM	0x0001
TYPE_ID_ITEM	0x0002
PROTO_ID_ITEM	0x0003
FIELD_ID_ITEM	0x0004
METHOD_ID_ITEM	0x0005
CLASS_DEF_ITEM	0x0006
MAP_LIST	0x1000
TYPE_LIST	0x1001
ANNOTATION_SET_REF_LIST	0x1002
ANNOTATION_SET_ITEM	0x1003
CLASS_DATA_ITEM	0x2000
CODE_ITEM	0x2001
STRING_DATA_ITEM	0x2002
DEBUG_INFO_ITEM	0x2003
ANNOTATION_ITEM	0x2004
ENCODED_ARRAY_ITEM	0x2005
ANNOTATIONS_DIRECTORY_ITEM	0x2006

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DEX Properties

- Reduced Memory Footprint
  - LEB128 encoding
  - Relative Indexing
  - Single file for all classes (vs. 1 file per class in .class format)
  - No duplicate strings
- Modified UTF-8 String Encoding
- Strict requirements for alignment
- Even more strict runtime verifier (DexOpt)

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LEB128

- Encoding format from DWARF3.

- Used to encode signed (SLEB128 and ULEB128p1) and unsigned (ULEB128) numbers.

- Used in DEX for encoding 32-bit numbers.

- **Numbers are encoded using 1 to 5 bytes.**

  - Depending on the highest **'1'**-bit

LEB128 - Example

HEX	BIN	SLEB128	ULEB128	ULEB128p1
00	00000000	0	0	-1
01	00000001	1	1	0
7f	01111111	-1	127	126
80 7f	10000000 01111111	-128	16256	16255

- <mark>-1 is used to represent the NO_INDEX value.</mark>
- Encoded as ULEB128p1, NO_INDEX requires only one byte to be encoded.

Relative Indexing

- Many DEX objects are represented by its index into a list.

- Encoded object lists use that index value as representation for the first object and diffs for representing the rest of the list.

- Using the delta usually yields smaller numbers with smaller representation in bytes when LEB128 is used.

- Ex:

  – In **class_data_item** structure, **static_fields**, **instance_fields**, **direct_methods** and **virtual_methods** are all represented by the index delta.

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Relative Indexing - Example

Field ID	Field Name
...	
1024	field_1
1025	field_2
...	
1036	field_3
...	

- Field List:
  - Field_1, field_2, field_3

- Encoding:
  - 1024, 1, 11

Modified UTF-8

- Used for encoding all strings in the DEX format.

- Characters may have 1, 2 or 3 bytes.

- Strings are terminated by a single null byte.

- When parsing string_data_item, the uft16_size field cannot be used to calculate the size of the following data as it only represents the number of characters in the MUTF-8 string.

- ASCII strings are MUTF-8 legal strings

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The "Big Header"

- Besides the header_item, we have six other structures that describe the DEX file:
    - string_id_item list
    - type_id_item list
    - proto_id_item list
    - field_id_item list
    - method_id_item list
    - class_def_item list
- This structures define all the functional content of the DEX file.

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The Map

- The DEX file may contain an optional structure called the Map, composed by map_item structures.

- The Map structure contains information about all the offsets in the file and what is the type of content in that offset.

- **Although optional according to the file format specification, the existence and correctness of the map is enforced by DexOpt.**

The Data

- All the content of the DEX file not in the "big header" goes to the Data area.

- Offsets to structures in the data area must be bigger than the end of the "big header". This property is enforced by DexOpt.

- It is ok to have gaps in the middle of the data section.

- The map is part of the data area.

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The Link Data

- Optional area at the end of the Data area.
- Format unspecified.
- Never present in "Normal" apks.

DEX Instrumentation

- Case Study: String add

  – String manipulation is required for most obfuscation/deobfuscation techniques.

  – Can be extended for replacing and removing strings.

- Objective:

  – Keep the DEX valid after adding the new string.

  – Pass DexOpt checking.

String Structure

- Represented by the pair (**string_id_item**, **string_data_item**)

- **string_id_item** list must be sorted
  - Sorted by the utf16 code points of the string

- Strings are referenced by its index position in the **string_id_item** list.

```
string_id_item:
string_data_off                              uint
```

```
string_data_item:
utf16_size                              ULEB128
data                              ubyte[utf16_size]
```

Adding a string_id_item

- Must be added in the position of the list that will keep the list sorted.

- Header adjustments:
  - Data offset.
  - File size.

- Maps adjustments:
  - **string_id_item** map size.

- Entire file adjustments:
  - Offsets references in data area must be shifted 4 bytes.
  - String references equal or bigger than the added string must be increased by 1.

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LEB128 Expansion

- Some offsets are encoded as ULEB128.

  – E.g. **code_off** inside **encoded_method** object.

- Some string_id_item references are encoded as ULEB128.

  – E.g. **name_idx** inside **annotation_element** object.

- After shifting offsets or increasing **string_id_item** references, the size of the LEB128 in bytes may increase.

- If the expansion occurs, further shifting of offsets is needed in the file.

- Maps size and offset must be updated.

Alignment

- Some structures in the DEX file must be 4-byte aligned.

    – E.g., **code_item**.

- **string_id_item** is 4-byte in size, so adding a new object will not misalign the DEX.

- LEB128 expansion will often add 1 byte shifting, which will break alignment.

- If realignment is required, offset references must be updated.

- Maps size and offset must be updated.

Adding a string_data_item

- Must be inside the data area.
- Header adjustments:
  - Data size.
  - File size.
- Maps adjustments:
  - **string_data_item** map size.
- Entire file adjustments:
  - Offsets references after the offset of the new **string_data_item** must be shifted by the size of the added object.
  - String references equal or bigger than the added string must be increased by 1.
- Check for LEB128 expansion and apply shifting.
- Check for alignment and apply shifting.

DEX Bit Restrictions

- 32 bits encoding

  – Static fields with fixed 32 bit size (E.g. string_id_item).

  – Offsets expected to be within 32 bit range.

- Less than 32 bits encoding

  – Class, type, proto and other lists alike are limited to 16 bits in size.

Rodrigo Chiossi

r.chiossi@androidxref.com

@rchiossi