ART虚拟机，了解一下

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大纲

1. 研究环境介绍
2. 信息的转换和表达
3. Java方法的执行
4. 讨论

1 研究环境介绍

研究环境介绍——了解你的“敌人”

了解你的“敌人”

Android 7.0 Nougat源码

- 源码路径：AOSP/art
- C++代码：1071个文件。
  - ✓ .cc文件共236744行（不包含注释，空行）
  - ✓ .h文件共74710行
- 汇编代码：1704个文件。
  - ✓ 代码行19955行（去除注释，空行及mterp/out）
  - ✓ 覆盖x86，arm、mips 32和64位共6个平台

必备基础知识：C++11

https://blog.csdn.net/innost/article/details/52583732

研究环境介绍——准备好的工具

准备好的工具

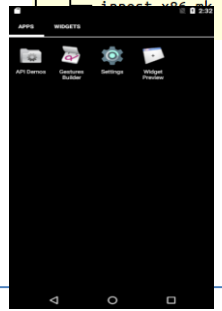
- Vmware+Ubuntu 14.04
- 自建x86模拟器镜像
- 保留最少量的应用

```
innost@innost:~/workspace/aosp/android-7.0$ lunch

You're building on Linux

Lunch menu... pick a combo:
     1. aosp_arm-eng
     2. aosp_arm64-eng
     3. aosp_mips-eng
     4. aosp_mips64-eng
     5. aosp_x86-eng
     6. aosp_x86_64-eng
     7. innost_arm64-userdebug
     8. innost_x86-userdebug

Which would you like? [aosp_arm-eng]
```

```
innost@innost:~/workspace/aosp/android-7.0/device/innost$ tree
.
├── board
│   ├── Android.mk
│   ├── innost_arm64
│   │   ├── BoardConfig.mk
│   │   ├── device.mk
│   │   ├── README.txt
│   │   └── system.prop
│   └── innost_x86
│       ├── BoardConfig.mk
│       ├── device.mk
│       ├── README.txt
│       ├── sepolicy
│       │   ├── domain.te
│       │   ├── healthd.te
│       │   ├── init.te
│       │   ├── installd.te
│       │   └── zygote.te
│       └── system.prop
├── product
│   ├── AndroidProducts.mk
│   ├── aosp_base.mk
│   ├── aosp_base_telephony.mk
│   ├── core_base.mk
│   ├── core_minimal.mk
│   ├── core.mk
│   ├── emulator.mk
│   ├── full_base.mk
│   ├── full_base_telephony.mk
│   ├── full_x86.mk
│   ├── generic_no_telephony.mk
│   ├── innost_arm64_device.mk
│   ├── innost_arm64.mk
│   ├── innost_x86_64.mk
```

Why x86 emulator?

- 模拟器启动速度快
- 相关资料多
- 汇编代码行数/总代码行数≈6.02%



2 信息的转换和表达

——从java源码到虚拟机内部表示

java源码的处理流程

.java

```
class Test{
    public int iField;
    public Object objField;

    public int myMethod() {
        return 0;
    }
}
```

javac → .class → dx → .dex → dex2oat → .oat / .art

mirror::Object

ArtField

ArtMethod

mirror::Class

mirror::String

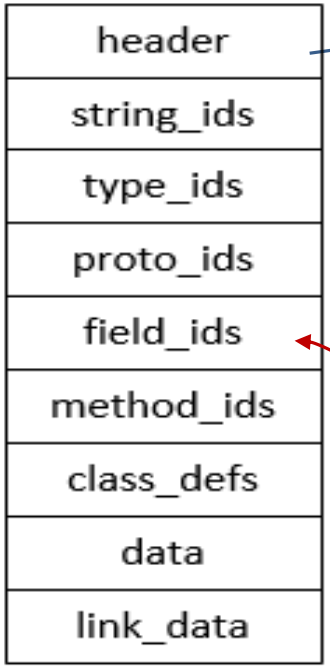
mirror::Array

mirror::Throwable

.....

dex文件格式（1）

.dex文件




```
struct header_item {
    public ubyte[] magic = new ubyte[8];
    public uint checksum;
    public ubyte[] signature = new ubyte[20];
    public uint file_size;
    public uint header_size;
    public uint endian_tag;

    public uint link_size;  public uint link_off;
    public uint map_off;

    public uint string_ids_size; public uint string_ids_off;

    public uint type_ids_size; public uint type_ids_off;

    public uint proto_ids_size; public uint proto_ids_off;

    public uint field_ids_size; public uint field_ids_off;

    public uint method_ids_size;  public uint method_ids_off

    public uint class_defs_size; public uint class_defs_off;

    public uint data_size; public uint data_off;
}
```

dex文件格式（2）

Class基本信息

```
struct class_def {
    uint class_idx;
    uint access_flags;
    uint superclass_idx;
    uint interfaces_off;
    uint source_file_idx;
    uint annotations_off;
    uint class_data_off;
    uint static_values_off;
}
```

Class的成员变量和成员函数信息

```
struct class_data_item{
    uleb128 static_fields_size;
    uleb128 instance_fields_size;
    uleb128 direct_methods_size;
    uleb128 virtual_methods_size;
    encoded_field[]  static_fields;
    encoded_field[]  instance_fields;
    encoded_method[]  direct_methods;
    encoded_method[]  virtual_methods;
}
```

所实现的接口类信息

```
struct type_list  {
    uint        size;
    type_item[] list;
}
struct type_item {
    ushort type_idx;
}
```

成员变量和方法信息

```
struct encoded_field {
    uleb128 field_idx_diff;
    uleb128 access_flags;
}
struct encoded_method {
    uleb128 method_idx_diff;
    uleb128 access_flags;
    uleb128 code_off;
}
```

成员方法的细节

```
struct code_item {
    ushort      registers_size;
    ushort      ins_size;
    ushort      outs_size;
    ushort      tries_size;
    uint        debug_info_off;
    uint        insns_size;
    ushort[]    insns;
    ushort      padding;
    try_item[] tries;
    encoded_catch_handler_list handlers;
}
```

dex指令码

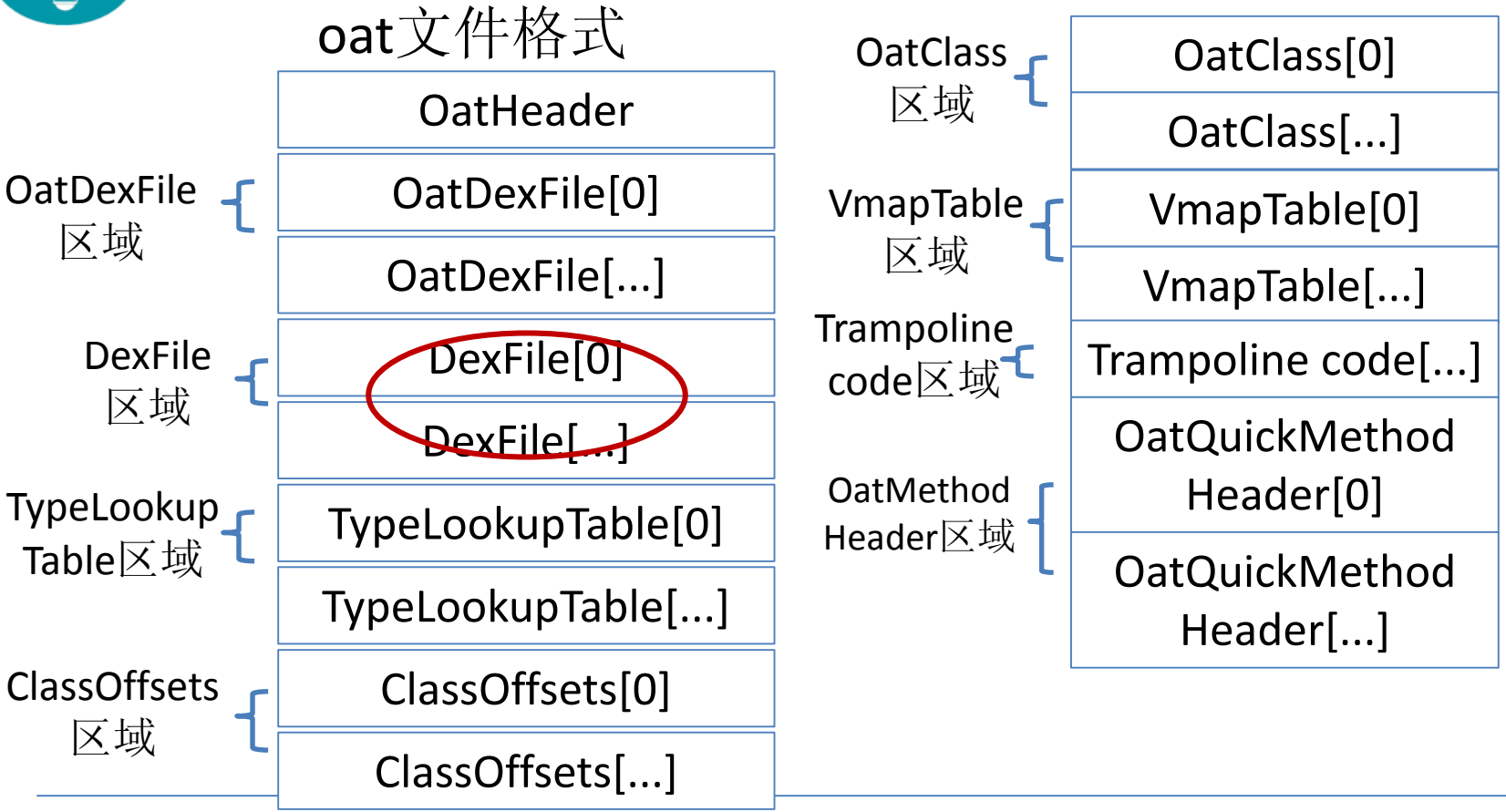
oat文件格式（1）

.oat文件是一个定制化的ELF文件

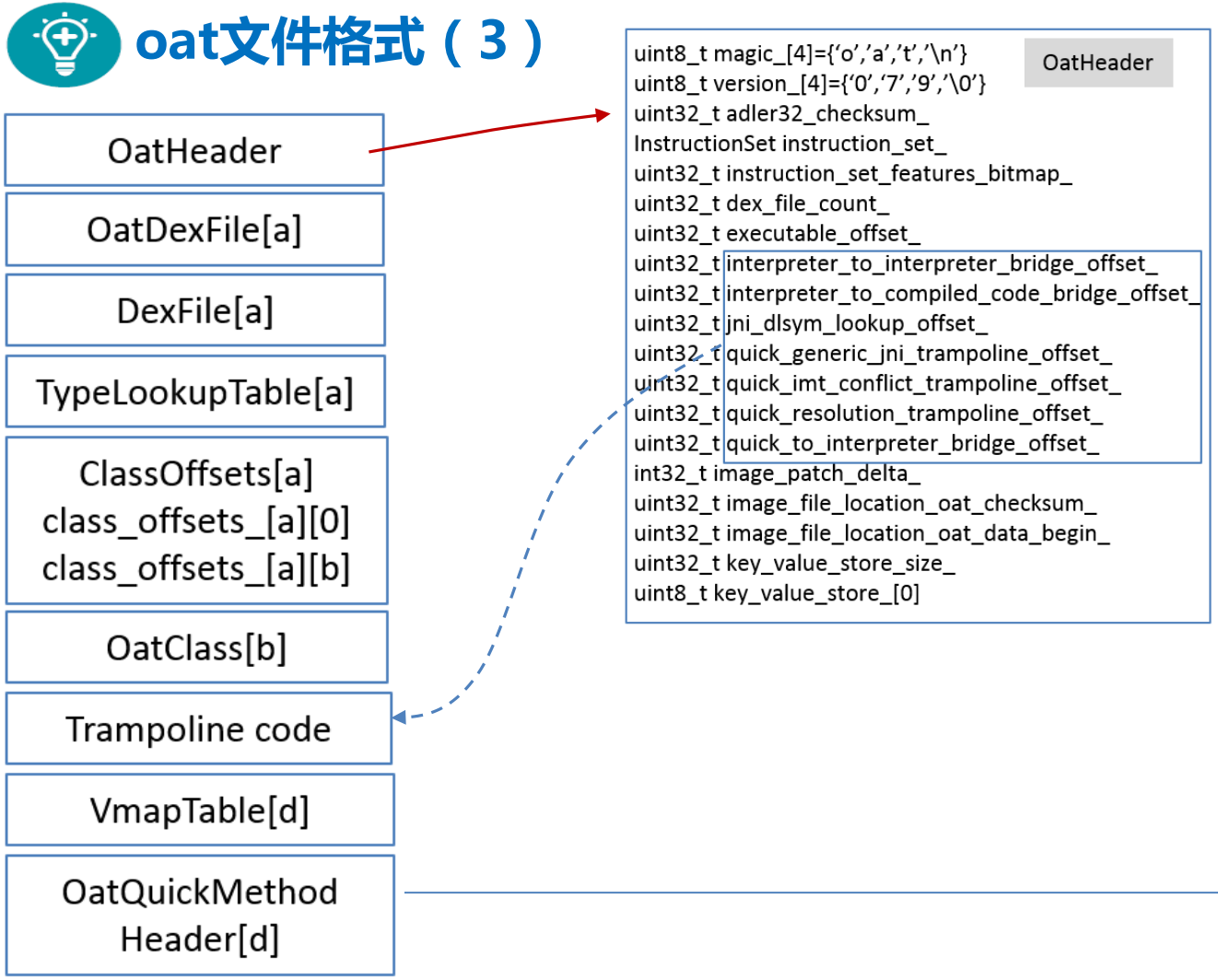
```
Section Headers:
  [Nr] Name              Type            Addr     Off    Size   ES Flg Lk Inf Al
  [ 0]                   NULL            00000000 000000 000000 00      0   0  0
  [ 1] .rodata           PROGBITS        713b7000 001000 273e000 00   A  0   0 4096
  [ 2] .text             PROGBITS        73af5000 273f000 18ace5f 00  AX  0   0 4096
  [ 3] .dynstr           STRTAB          753a2000 3fec000 000037 00   A  0   0 4096
  [ 4] .dynsym           DYNSYM          753a2038 3fec038 000040 10   A  3   0  4
  [ 5] .hash             HASH            753a2078 3fec078 00001c 04   A  4   0  4
  [ 6] .dynamic          DYNAMIC         753a3000 3fed000 000038 08   A  3   0 4096
  [ 7] .shstrtab         STRTAB          00000000 3fee000 000038 00      0   0 4096
```

```
Symbol table '.dynsym' contains 4 entries:
   Num:    Value  Size Type    Bind   Vis      Ndx Name
     0: 00000000     0 NOTYPE  LOCAL  DEFAULT  UND
     1: 713b7000 0x273e000 OBJECT  GLOBAL DEFAULT    1 oatdata
     2: 73af5000 0x18ace5f OBJECT  GLOBAL DEFAULT    2 oatexec
     3: 753a1e5b     4 OBJECT  GLOBAL DEFAULT    2 oatlastword
```

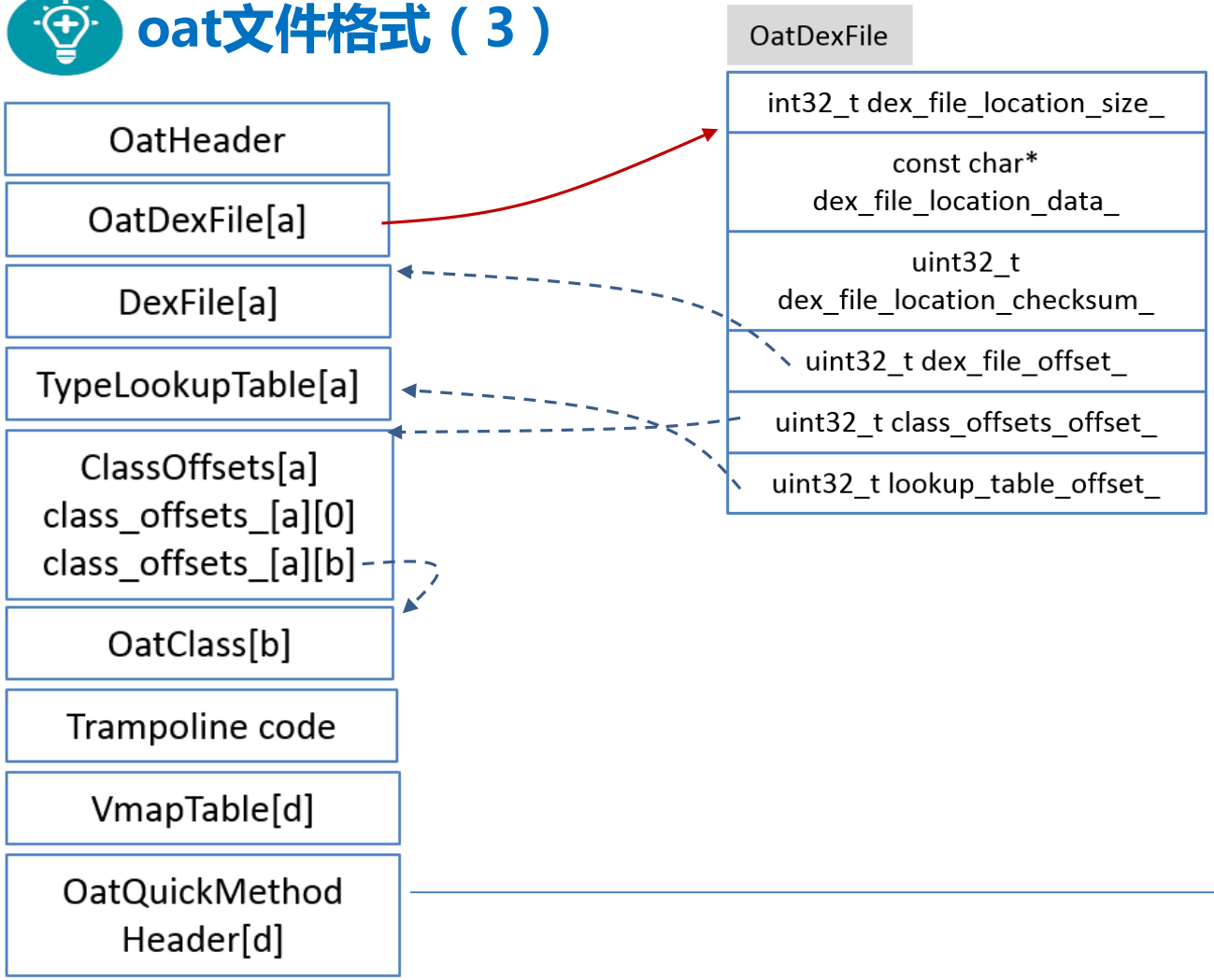
oat文件格式（2）


oat文件格式
OatHeader
OatDexFile区域
OatDexFile[0]
OatDexFile[...]
DexFile区域
DexFile[0]
DexFile[...]
TypeLookup Table区域
TypeLookupTable[0]
TypeLookupTable[...]
ClassOffsets区域
ClassOffsets[0]
ClassOffsets[...]
OatClass区域
OatClass[0]
OatClass[...]
VmapTable区域
VmapTable[0]
VmapTable[...]
Trampoline code区域
Trampoline code[...]
OatMethod Header区域
OatQuickMethod Header[0]
OatQuickMethod Header[...]

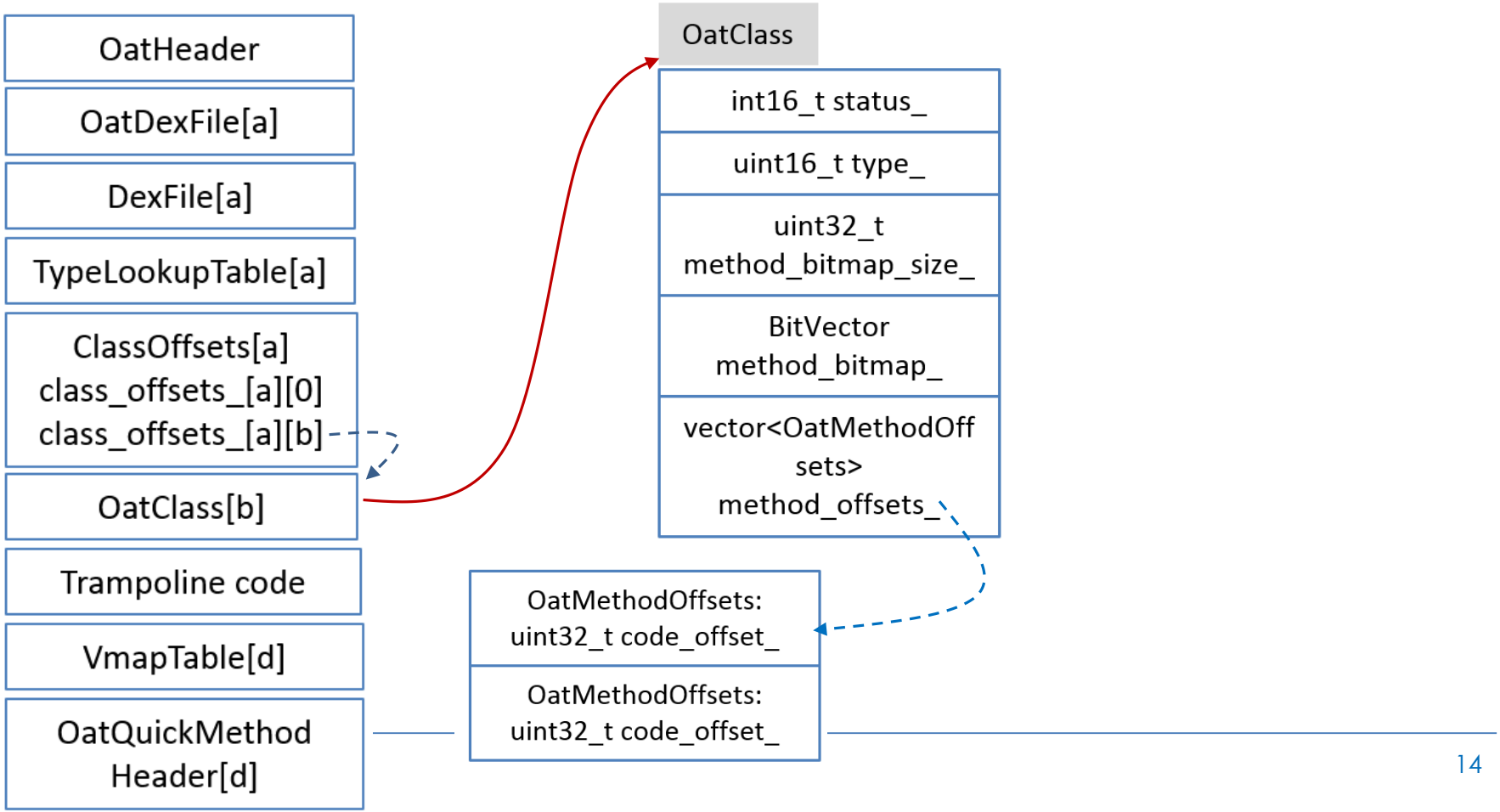
oat文件格式（3）


OatHeader
OatDexFile[a]
DexFile[a]
TypeLookupTable[a]
ClassOffsets[a]
class_offsets_[a][0]
class_offsets_[a][b]
OatClass[b]
Trampoline code
VmapTable[d]
OatQuickMethod
Header[d]
OatHeader
uint8_t magic_[4]={'o','a','t','\n'}
uint8_t version_[4]={'0','7','9','\0'}
uint32_t adler32_checksum_
InstructionSet instruction_set_
uint32_t instruction_set_features_bitmap_
uint32_t dex_file_count_
uint32_t executable_offset_
uint32_t interpreter_to_interpreter_bridge_offset_
uint32_t interpreter_to_compiled_code_bridge_offset_
uint32_t jni_dlsym_lookup_offset_
uint32_t quick_generic_jni_trampoline_offset_
uint32_t quick_imt_conflict_trampoline_offset_
uint32_t quick_resolution_trampoline_offset_
uint32_t quick_to_interpreter_bridge_offset_
int32_t image_patch_delta_
uint32_t image_file_location_oat_checksum_
uint32_t image_file_location_oat_data_begin_
uint32_t key_value_store_size_
uint8_t key_value_store_[0]

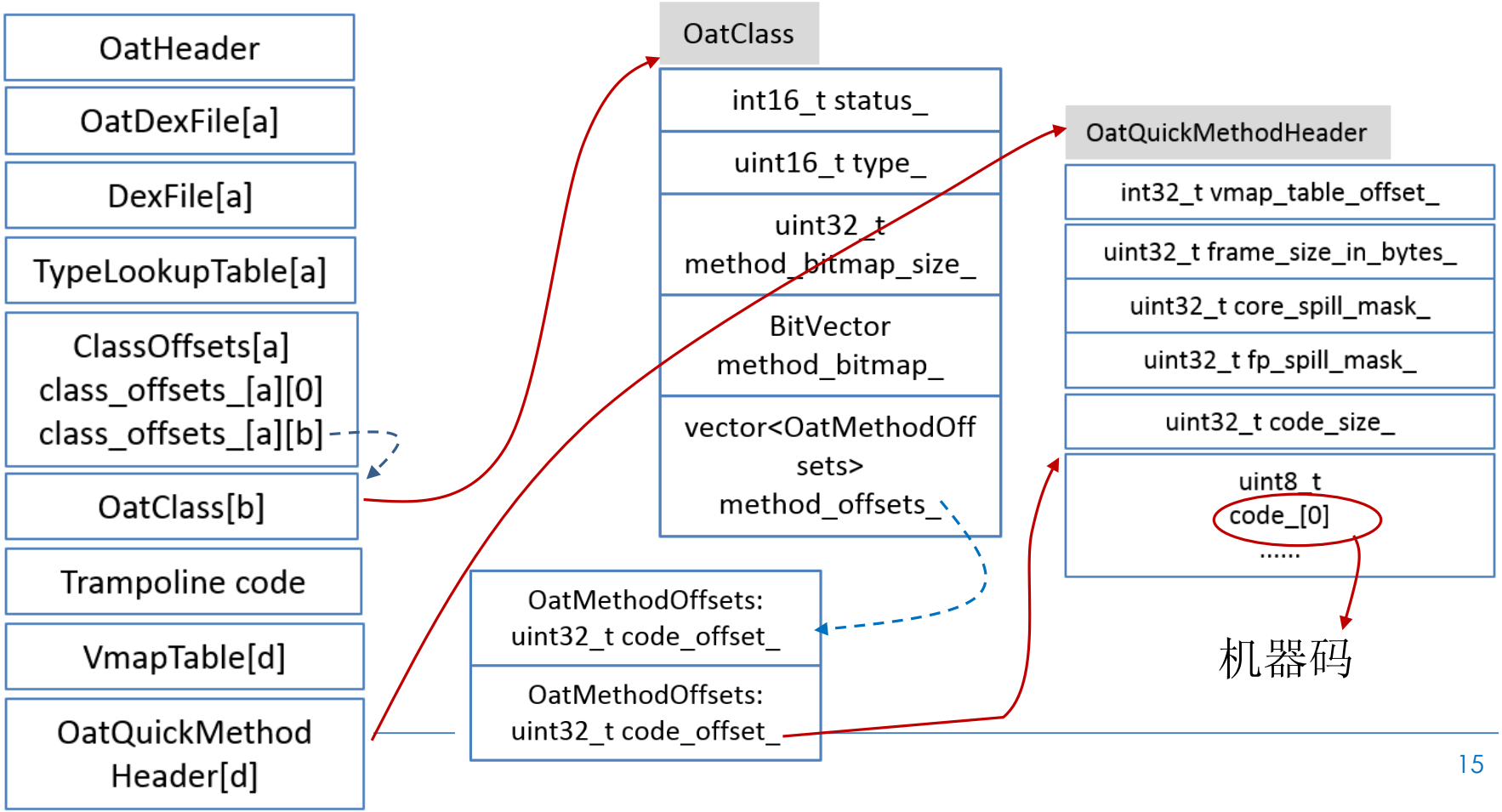
oat文件格式（3）


OatDexFile
int32_t dex_file_location_size_
const char*
dex_file_location_data_
uint32_t
dex_file_location_checksum_
uint32_t dex_file_offset_
uint32_t class_offsets_offset_
uint32_t lookup_table_offset_
OatHeader
OatDexFile[a]
DexFile[a]
TypeLookupTable[a]
ClassOffsets[a]
class_offsets_[a][0]
class_offsets_[a][b]
OatClass[b]
Trampoline code
VmapTable[d]
OatQuickMethod
Header[d]

oat文件格式（3）


OatHeader
OatDexFile[a]
DexFile[a]
TypeLookupTable[a]
ClassOffsets[a]
class_offsets_[a][0]
class_offsets_[a][b]
OatClass[b]
Trampoline code
VmapTable[d]
OatQuickMethod
Header[d]
OatClass
int16_t status_
uint16_t type_
uint32_t
method_bitmap_size_
BitVector
method_bitmap_
vector<OatMethodOff
sets>
method_offsets_
OatMethodOffsets:
uint32_t code_offset_
OatMethodOffsets:
uint32_t code_offset_

oat文件格式（3）


OatHeader
OatDexFile[a]
DexFile[a]
TypeLookupTable[a]
ClassOffsets[a]
class_offsets_[a][0]
class_offsets_[a][b]
OatClass[b]
Trampoline code
VmapTable[d]
OatQuickMethod
Header[d]
OatClass
int16_t status_
uint16_t type_
uint32_t
method_bitmap_size_
BitVector
method_bitmap_
vector<OatMethodOff
sets>
method_offsets_
OatMethodOffsets:
uint32_t code_offset_
OatMethodOffsets:
uint32_t code_offset_
OatQuickMethodHeader
int32_t vmap_table_offset_
uint32_t frame_size_in_bytes_
uint32_t core_spill_mask_
uint32_t fp_spill_mask_
uint32_t code_size_
uint8_t
code_[0]
.....
机器码

Java Class及Object在ART虚拟机里的内存布局

原则：

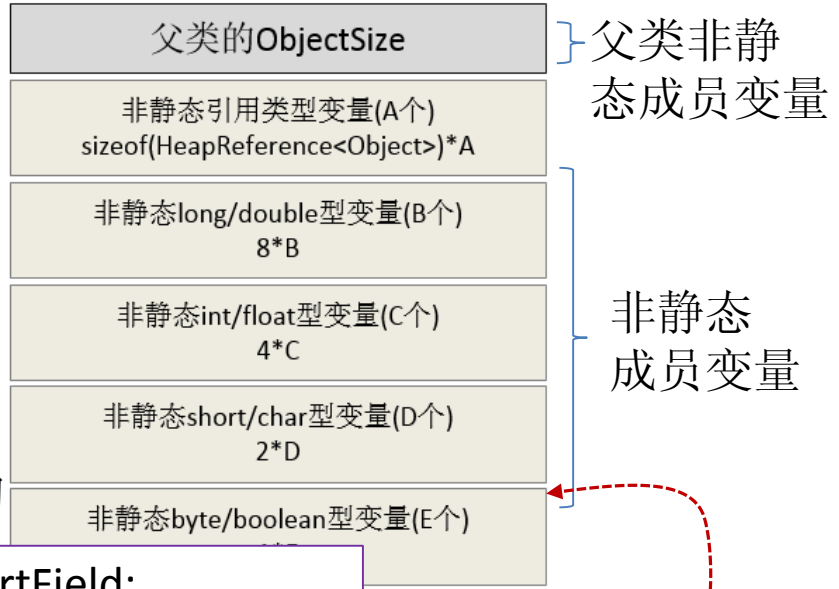
✓ 方法、静态成员变量是类的属性

✓ 非静态成员变量归属为类的实例

Java Class及Object在ART虚拟机里的内存布局

Java Class对象在ART虚拟里的内存占用

Java某Class的实例对象在ART虚拟里的内存占用

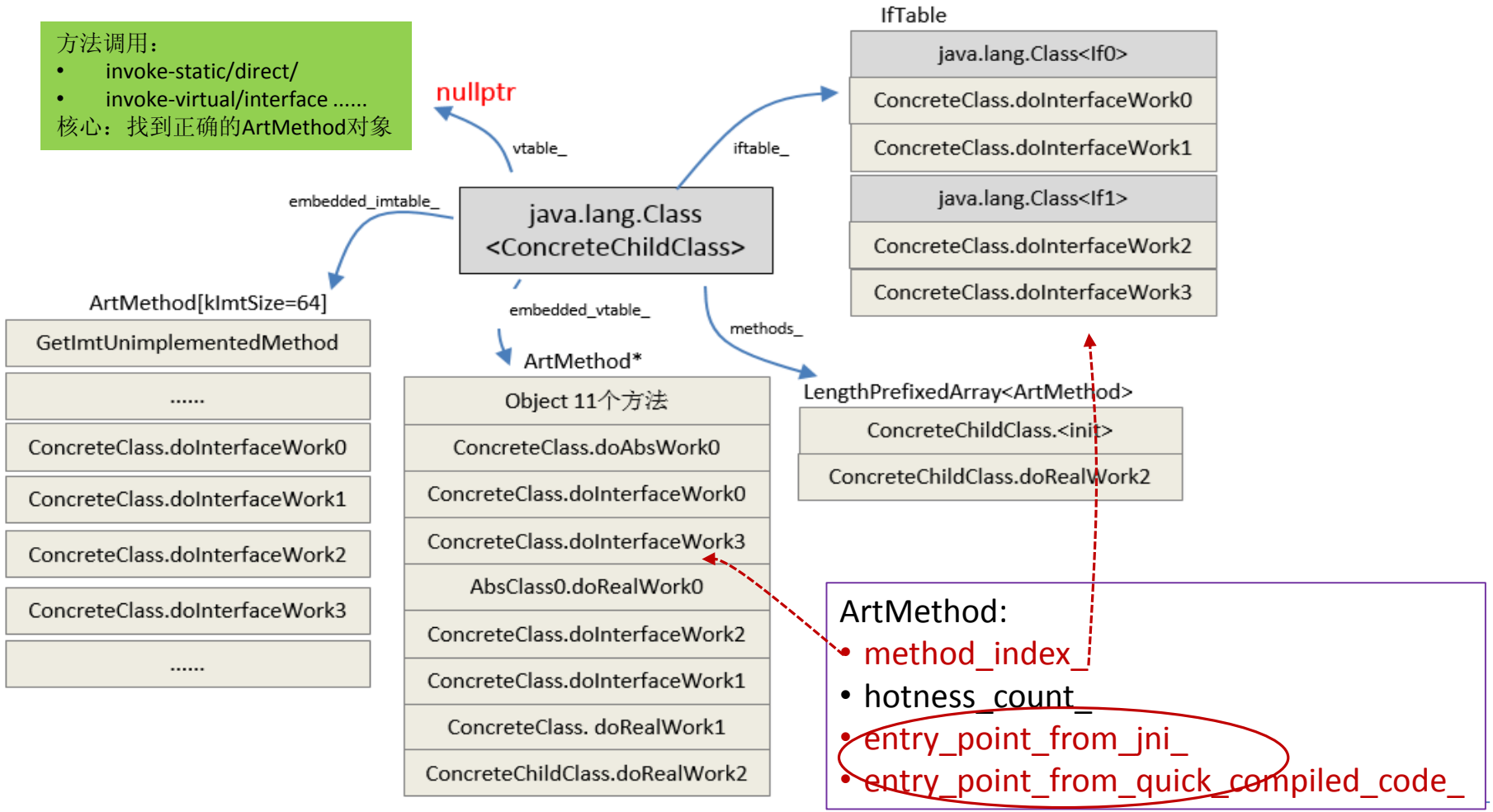


ArtField:

- declaring_class_
- access_flags_
- field_dex_idx_
- offset_

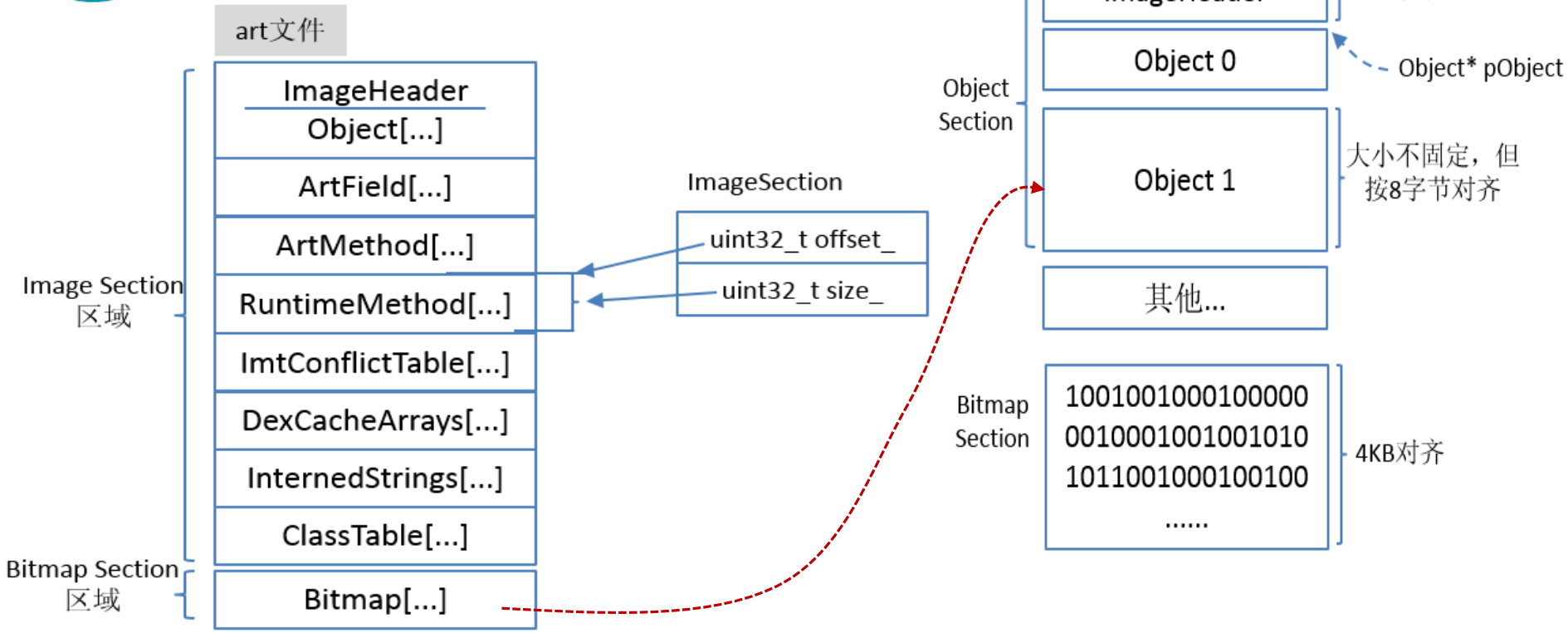
方法调用：
- invoke-static/direct/
- invoke-virtual/interface .....

核心：找到正确的ArtMethod对象

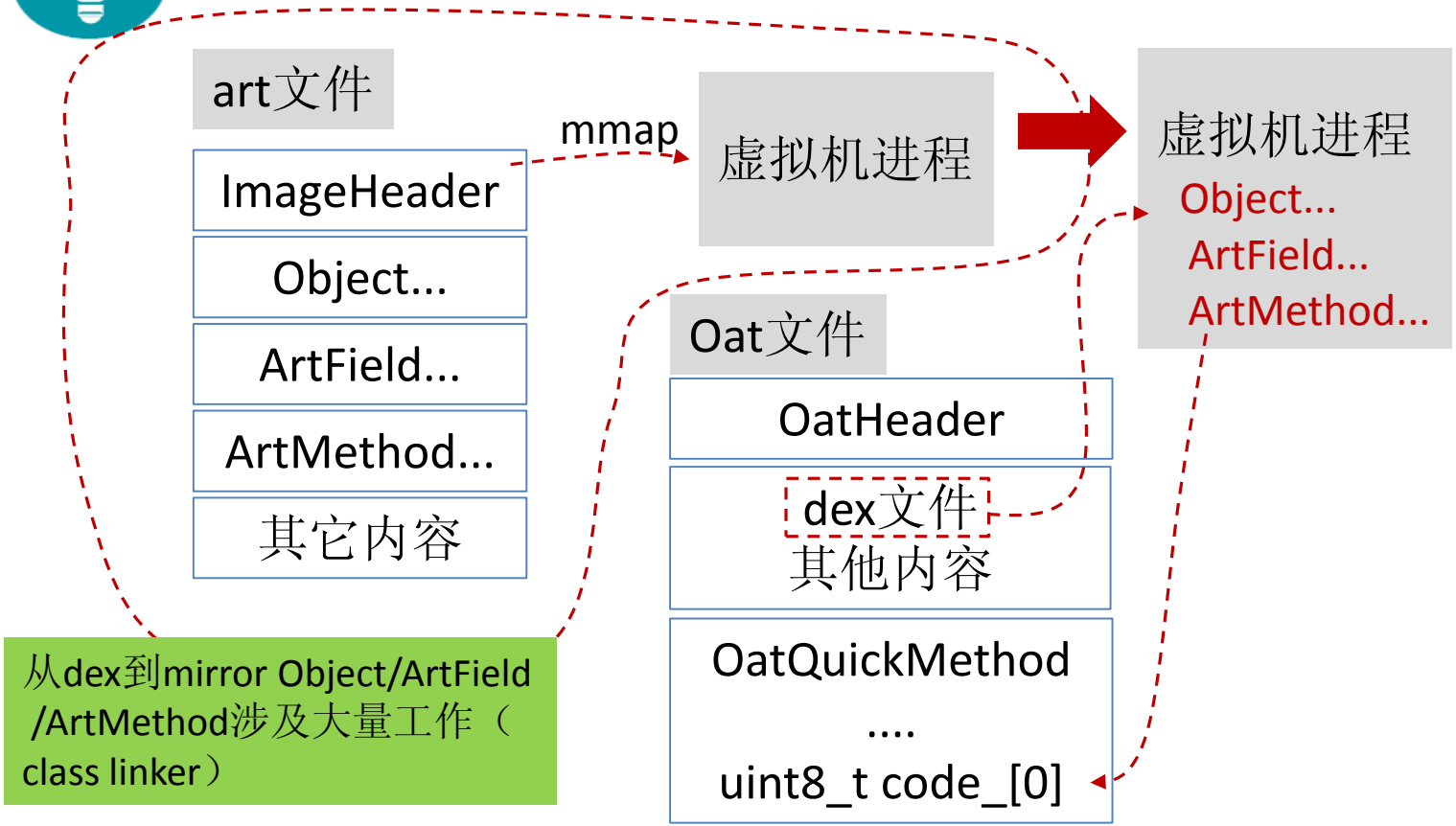


ArtMethod:
- method_index_
- hotness_count_
- entry_point_from_jni_
- entry_point_from_quick_compiled_code_

art文件格式（1）


art文件
ImageHeader
Object[...]
ArtField[...]
ArtMethod[...]
RuntimeMethod[...]
ImtConflictTable[...]
DexCacheArrays[...]
InternedStrings[...]
ClassTable[...]
Bitmap[...]
Image Section
区域
Bitmap Section
区域
ImageSection
uint32_t offset_
uint32_t size_
ImageHeader
200字节
Object 0
Object* pObject
Object
Section
Object 1
大小不固定，但
按8字节对齐
其他...
Bitmap
Section
1001001000100000
0010001001001010
1011001000100100
.....
4KB对齐

art文件格式（2）——art文件的作用



art文件格式（3）——oatdump

adb shell oatdump --image=/system/framework/boot.art **--header-only**

```
art_file_bytes = header_bytes + object_bytes + alignment_bytes
  header_bytes           =       200 ( 0% of art file bytes)
  object_bytes           =   5070453 (46% of art file bytes)
  art_field_bytes        =    619656 ( 6% of art file bytes)
  art_method_bytes       =   2303328 (21% of art file bytes)
  dex_cache_arrays_bytes =   2455340 (22% of art file bytes)
  interned_string_bytes  =    351608 ( 3% of art file bytes)
  class_table_bytes      =     37528 ( 0% of art file bytes)
  bitmap_bytes           =     81920 ( 1% of art file bytes)
  alignment_bytes        =    122783 ( 1% of art file bytes)

object_bytes breakdown:
    Landroid/accounts/Account$1;        8 bytes      1 instances (   8 bytes/instance)  0% of object_bytes
Landroid/animation/ArgbEvaluator;       8 bytes      1 instances (   8 bytes/instance)  0% of object_bytes
Landroid/animation/FloatEvaluator;      8 bytes      1 instances (   8 bytes/instance)  0% of object_bytes
Landroid/animation/IntEvaluator;        8 bytes      1 instances (   8 bytes/instance)  0% of object_bytes
Landroid/animation/RectEvaluator;      12 bytes      1 instances (  12 bytes/instance)  0% of object_bytes
Landroid/app/ActivityManager$MemoryInfo$1;       8 bytes      1 instances (   8 bytes/instance)  0% of object_bytes
Landroid/app/ActivityManager$RunningAppProcessInfo$1;       8 bytes      1 instances (   8 bytes/instance)  0% of object_bytes
Landroid/app/ActivityManager$TaskDescription$1;       8 bytes      1 instances (   8 bytes/instance)  0% of object_bytes
Landroid/app/ActivityManagerNative$1;      12 bytes      1 instances (  12 bytes/instance)  0% of object_bytes
Landroid/app/ApplicationErrorReport$1;       8 bytes      1 instances (   8 bytes/instance)  0% of object_bytes
Landroid/app/ApplicationLoaders;      12 bytes      1 instances (  12 bytes/instance)  0% of object_bytes
Landroid/app/IActivityManager$ContentProviderHolder$1;       8 bytes      1 instances (   8 bytes/instance)  0% of object_bytes
    Landroid/app/Notification$1;        8 bytes      1 instances (   8 bytes/instance)  0% of object_bytes
Landroid/app/Notification$Action$1;       8 bytes      1 instances (   8 bytes/instance)  0% of object_bytes
   Landroid/app/PendingIntent$1;        8 bytes      1 instances (   8 bytes/instance)  0% of object_bytes
Landroid/app/ResourcesManager$1;        8 bytes      1 instances (   8 bytes/instance)  0% of object_bytes
      Landroid/app/ResultInfo$1;        8 bytes      1 instances (   8 bytes/instance)  0% of object_bytes
```

art文件格式（3）——oatdump

```
0x708ac170: java.lang.String "startRecognition() failed with error code "
  shadow$_klass_: 0x705fc268   Class: java.lang.String
  shadow$_monitor_: 0 (0x0)
  count: 42 (0x2a)
  hash: -832870278 (0xce5b687a)
0x708ac1d8: java.lang.String "android.permission.BIND_QUICK_SETTINGS_TILE"
  shadow$_klass_: 0x705fc268   Class: java.lang.String
  shadow$_monitor_: 0 (0x0)
  count: 43 (0x2b)
  hash: -1354439018 (0xaf44e696)
0x708ac240: java.lang.String "Notification listener service not yet bound."
  shadow$_klass_: 0x705fc268   Class: java.lang.String
  shadow$_monitor_: 0 (0x0)
  count: 44 (0x2c)
  hash: -1583507273 (0xa19d98b7)
0x708ac2a8: java.lang.String "attach() called after dream already finished"
  shadow$_klass_: 0x705fc268   Class: java.lang.String
  shadow$_monitor_: 0 (0x0)
  count: 44 (0x2c)
  hash: -1895380700 (0x8f06c924)
0x708ac310: java.lang.String "android.service.chooser.ChooserTargetService"
  shadow$_klass_: 0x705fc268   Class: java.lang.String
  shadow$_monitor_: 0 (0x0)
  count: 44 (0x2c)
  hash: 1727114772 (0x66f1ae14)
```

art文件格式（3）——oatdump

```
0x7064d140: java.lang.Class "java.util.concurrent.locks.ReadWriteLock" (StatusInitialized)
  shadow$_klass_: 0x705fbdb8   Class: java.lang.Class
  shadow$_monitor_: 0 (0x0)
  accessFlags: 537396737 (0x20080601)
  annotationType: null   sun.reflect.annotation.AnnotationType
  classFlags: 1 (0x1)
  classLoader: null   java.lang.ClassLoader
  classSize: 128 (0x80)
  clinitThreadId: 0 (0x0)
  componentType: null   java.lang.Class
  copiedMethodsOffset: 2 (0x2)
  dexCache: 0x7050c110   java.lang.DexCache
  dexCacheStrings: 1892852196 (0x70d2a1e4)
  dexClassDefIndex: 1579 (0x62b)
  dexTypeIndex: 1883 (0x75b)
  iFields: 0 (0x0)
  ifTable: null   java.lang.Object[]
  methods: 1890465988 (0x70ae38c4)
  name: 0x707ce6c0   String: "java.util.concurrent.locks.ReadWriteLock"
  numReferenceInstanceFields: 0 (0x0)
  numReferenceStaticFields: 0 (0x0)
  objectSize: 8 (0x8)
  primitiveType: 131072 (0x20000)
  referenceInstanceOffsets: 0 (0x0)
  sFields: 0 (0x0)
  status: 10 (0xa)
  superClass: 0x705fc588   Class: java.lang.Object
  verifyError: null   java.lang.Object
  virtualMethodsOffset: 0 (0x0)
  vtable: null   java.lang.Object
```

art文件格式（4）——art文件的来源

boot镜像
|->boot.oat
|->boot.art

```
dex2oat: option[0]=--image=/data/dalvik-cache/x86/system@framework@boot.art
dex2oat: option[1]=--dex-file=/system/framework/core-oj.jar
dex2oat: option[2]=--dex-file=/system/framework/core-libart.jar
dex2oat: option[3]=--dex-file=/system/framework/conscrypt.jar
dex2oat: option[4]=--dex-file=/system/framework/okhttp.jar
dex2oat: option[5]=--dex-file=/system/framework/core-junit.jar
dex2oat: option[6]=--dex-file=/system/framework/bouncycastle.jar
dex2oat: option[7]=--dex-file=/system/framework/ext.jar
dex2oat: option[8]=--dex-file=/system/framework/framework.jar
dex2oat: option[9]=--dex-file=/system/framework/telephony-common.jar
dex2oat: option[10]=--dex-file=/system/framework/voip-common.jar
dex2oat: option[11]=--dex-file=/system/framework/ims-common.jar
dex2oat: option[12]=--dex-file=/system/framework/apache-xml.jar
dex2oat: option[13]=--dex-file=/system/framework/org.apache.http.legacy.boot.jar
dex2oat: option[14]=--oat-file=/data/dalvik-cache/x86/system@framework@boot.oat
dex2oat: option[15]=--instruction-set=x86
dex2oat: option[16]=--instruction-set-features=smp,ssse3,-sse4.1,-sse4.2,-avx,-avx2,-lock_add,-popcnt
dex2oat: option[17]=--base=0x70942000
dex2oat: option[18]=--runtime-arg
 dex2oat: option[19]=-Xms64m
dex2oat: option[20]=--runtime-arg
 dex2oat: option[21]=-Xmx64m
dex2oat: option[22]=--image-classes=/system/etc/preloaded-classes
dex2oat: option[23]=--compiled-classes=/system/etc/compiled-classes
dex2oat: option[24]=--instruction-set-variant=x86
Unexpected CPU variant for X86 using defaults: x86
dex2oat: option[25]=--instruction-set-features=default
Mismatch between dex2oat instruction set features (ISA: X86 Feature string: smp,-ssse3,-sse4.1,-sse4.2,
```

APP镜像
|->xxx.dex

yyy.jar
zzz.apk

3 Java方法的执行

main函数的调用流程

虚拟机启动

↓

找到目标方法的ArtMethod

↓

调用ArtMethod.Invoke

```
/* start the virtual machine */
JniInvocation jni_invocation;
jni_invocation.Init(NULL);
JNIEnv* env;
if (startVm(&mJavaVM, &env, zygote) != 0) {
    return;
}
```

```
char* slashClassName = toSlashClassName(className);
jclass startClass = env->FindClass(slashClassName);
if (startClass == NULL) {
    ALOGE("JavaVM unable to locate class '%s'\n", slashClassName);
    /* keep going */
} else {
    jmethodID startMeth = env->GetStaticMethodID(startClass, "main",
        "([Ljava/lang/String;)V");
    if (startMeth == NULL) {
        ALOGE("JavaVM unable to find main() in '%s'\n", className);
        /* keep going */
    } else {
        env->CallStaticVoidMethod(startClass, startMeth, strArray);

0
```

ArtMethod里的入口地址

ArtMethod
|
|-> ptr_sized_fields_
　　|->entry_point_from_jni_
　　|->entry_point_from_quick_compiled_code_

方法类型	机器码入口	jni机器码入口
jni方法	art_quick_generic_jni_trampoline或对应机器码	art_jni_dlsym_lookup_stub
非jni方法	art_quick_to_interpreter_bridge或对应机器码	ImtConflictTable

ArtMethod Invoke

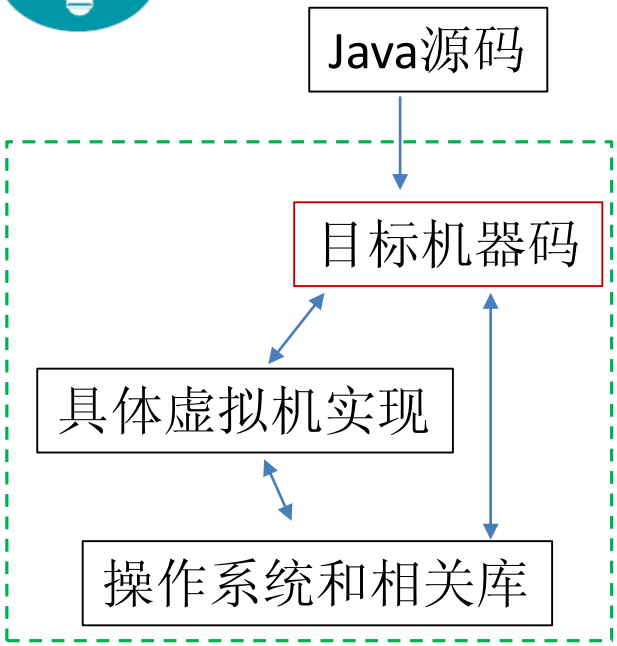
```
void ArtMethod::Invoke(Thread* self, uint32_t* args, uint32_t args_size, JValue* result,
                       const char* shorty) {
  ......

  if (UNLIKELY(!runtime->IsStarted() || Dbg::IsForcedInterpreterNeededForCalling(self, this
      ......

  } else {
    bool have_quick_code = GetEntryPointFromQuickCompiledCode() != nullptr;
    if (LIKELY(have_quick_code)) {
      ......
      if (!IsStatic()) {
        (*art_quick_invoke_stub)(this, args, args_size, self, result, shorty);
      } else {
        (*art_quick_invoke_static_stub)(this, args, args_size, self, result, shorty);
      }
```

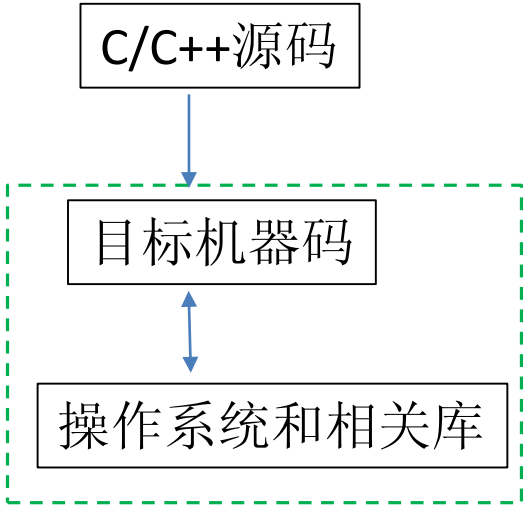
```
DEFINE_FUNCTION art_quick_invoke_stub
    // Save the non-volatiles.
    PUSH ebp                          // save ebp
    PUSH ebx                          // save ebx
    PUSH esi                          // save esi
    PUSH edi                          // save edi
    ......
Lgpr_setup_finished:
    mov 20(%ebp), %eax                // move method pointer into eax
    call *ART_METHOD_QUICK_CODE_OFFSET_32(%eax) // call the method
    mov %ebp, %esp                    // restore stack pointer
    CFI_DEF_CFA_REGISTER(esp)
    POP edi                           // pop edi
    POP esi                           // pop esi
```

4 讨论

1. Java VS C++，谁更快
2. ART虚拟机研究路线推荐

Java VS C++，谁更快





- java进程的内容=虚拟机的内容+自身的内容
- java的目标机器码强依赖于虚拟机，并受虚拟机监管（ ManagedCode ）
- 某些情况下将转入虚拟机内执行（SlowPathCode）

ART虚拟机研究路线推荐

基础知识
- .dex文件格式
- ELF文件格式
- C++11

dex2oat
- compiler相关知识
- ART基础模块
- 信息的转换和表达
- .oat/.art文件格式

执行相关
- 栈的管理
- 解释执行
- JIT等
- JNI
- 线程同步，锁等

内存管理
- ……

谢谢！