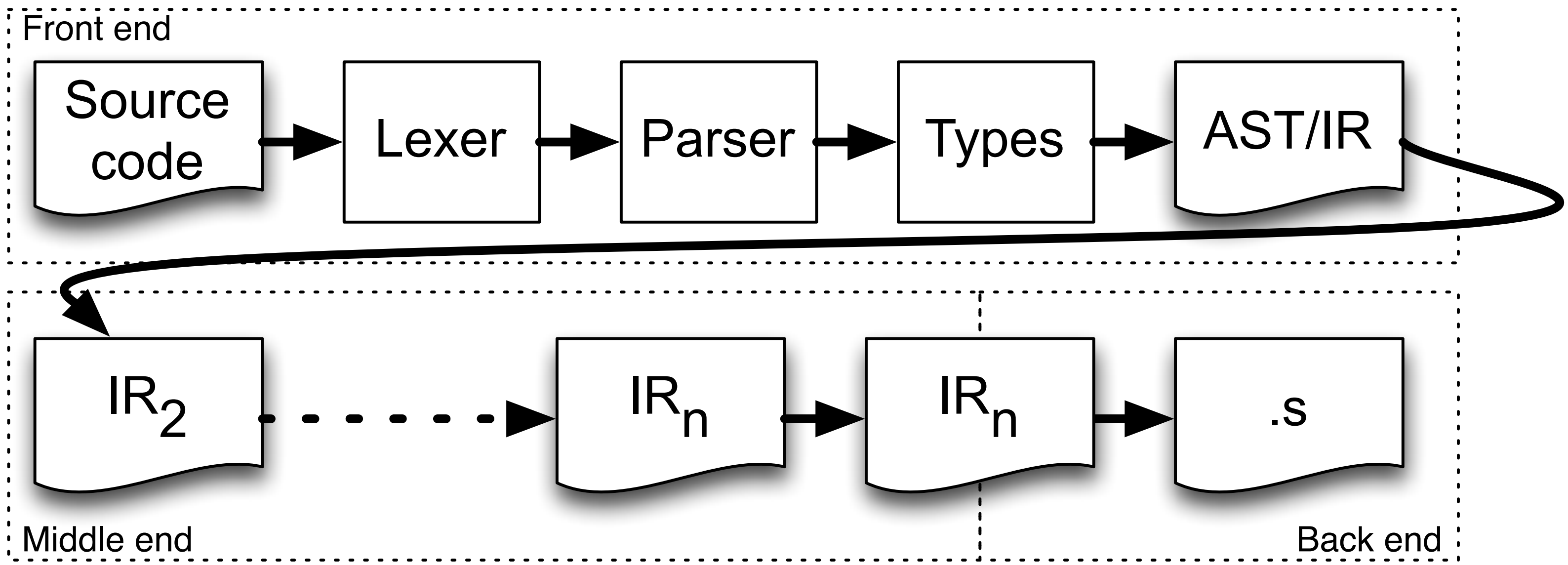
CMSC 430
Introduction to Compilers
Fall 2015

Intermediate Representations
and
Bytecode Formats

Introduction



- Front end — syntax recognition, semantic analysis, produces first AST/IR
- Middle end — transforms IR into equivalent IRs that are more efficient and/or closer to final IR
- Back end — translates final IR into assembly or machine code

Three-address code

- Classic IR used in many compilers (or, at least, compiler textbooks)
- Core statements have one of the following forms
  - x = y *op* z binary operation
  - x = op y unary operation
  - x = y copy statement
- Example:

```
z = x + 2 * y;
```

⇨

```
t = 2 * y
z = x + t
```

  - Need to introduce *temporarily variables* to hold intermediate computations
  - Notice: closer to machine code

Control Flow in Three-Address Code

- How to represent control flow in IRs?
  - l: statement — labeled statement
  - goto l — unconditional jump
  - if x rop y goto l — conditional jump (rop = relational op)

- Example

```
if (x + 2 > 5)
  y = 2;
else
  y = 3;
x++;
```

⇨

```
    t = x + 2
    if t > 5 goto l1
    y = 3
    goto l2
l1: y = 2
l2: x = x + 1
```

Looping in Three-Address Code

- Similar to conditionals

```
x = 10;
while (x != 0) {
  a = a * 2;
  x++;
}
y = 20;
```

```
    x = 10
l1: if (x == 0) goto l2
    a = a * 2
    x = x + 1
    goto l1
l2: y = 20
```

- The line labeled l1 is called the *loop header*, i.e., it's the target of the backward branch at the bottom of the loop
- Notice same code generated for

```
for (x = 10; x != 0; x++)
  a = a * 2;
y = 20;
```

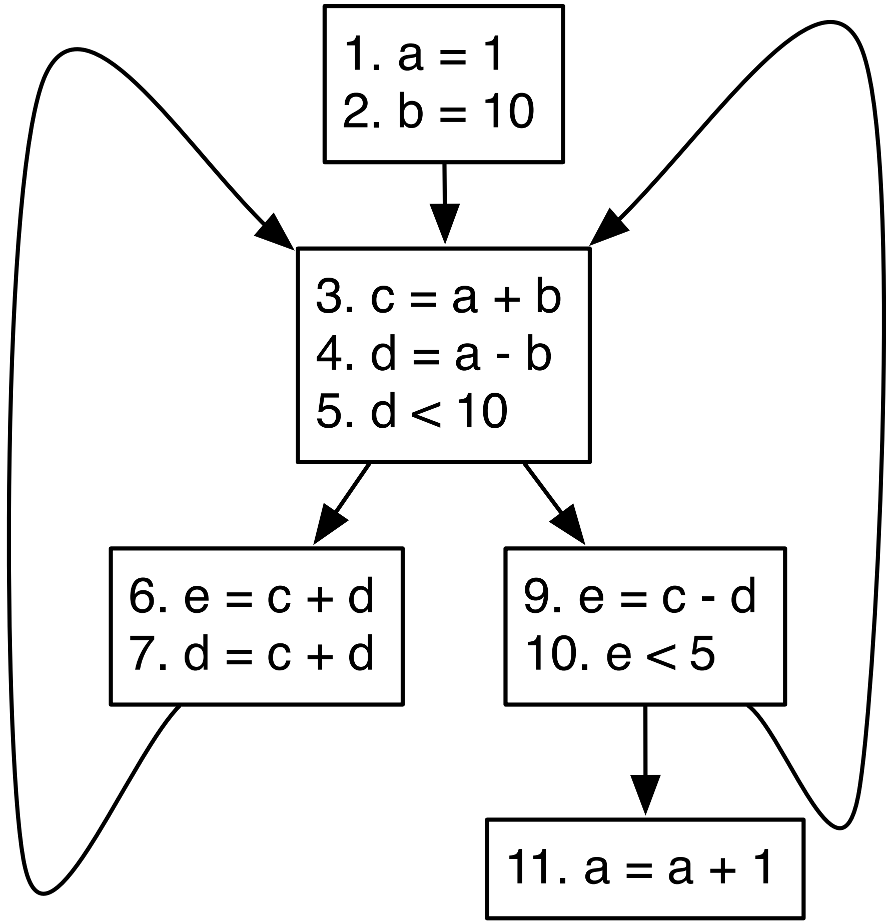
Basic Blocks

- A *basic block* is a sequence of three-addr code with
  - (a) no jumps from it except the last statement
  - (b) no jumps into the middle of the basic block

- A *control flow graph* (CFG) is a graphical representation of the basic blocks of a three-address program
  - Nodes are basic blocks
  - Edges represent jump from one basic block to another
    - Conditional branches identify true/false cases either by convention (e.g., all left branches true, all right branches false) or by labeling edges with true/false condition
  - Compiler may or may not create explicit CFG structure

Example

```
1. a = 1
2. b = 10
3. c = a + b
4. d = a - b
5. if (d < 10) goto 9
6. e = c + d
7. d = c + d
8. goto 3
9. e = c - d
10. if (e < 5) goto 3
11. a = a + 1
```



Levels of Abstraction

- Key design feature of IRs: what level of abstraction to represent
  - if x rop y goto l   with explicit relation, OR
  - t = x rop y; if t goto l   only booleans in guard
  - Which is preferable, under what circumstances?

- Representation of arrays
  - x = y[z]   high-level, OR
  - t = y + 4*z; x = *t;   low-level (ptr arith)
  - Which is preferable, under what circumstances?

Levels of Abstraction (cont'd)

- Function calls?
  - Should there be a function call instruction, or should the calling convention be made explicit?
    - Former is easier to work with, latter may enable some low-level optimizations, e.g.,passing parameters in registers
- Virtual method dispatch?
  - Same as above
- Object construction
  - Distinguished "new" call that invokes constructor, or separate object allocation and initialization?

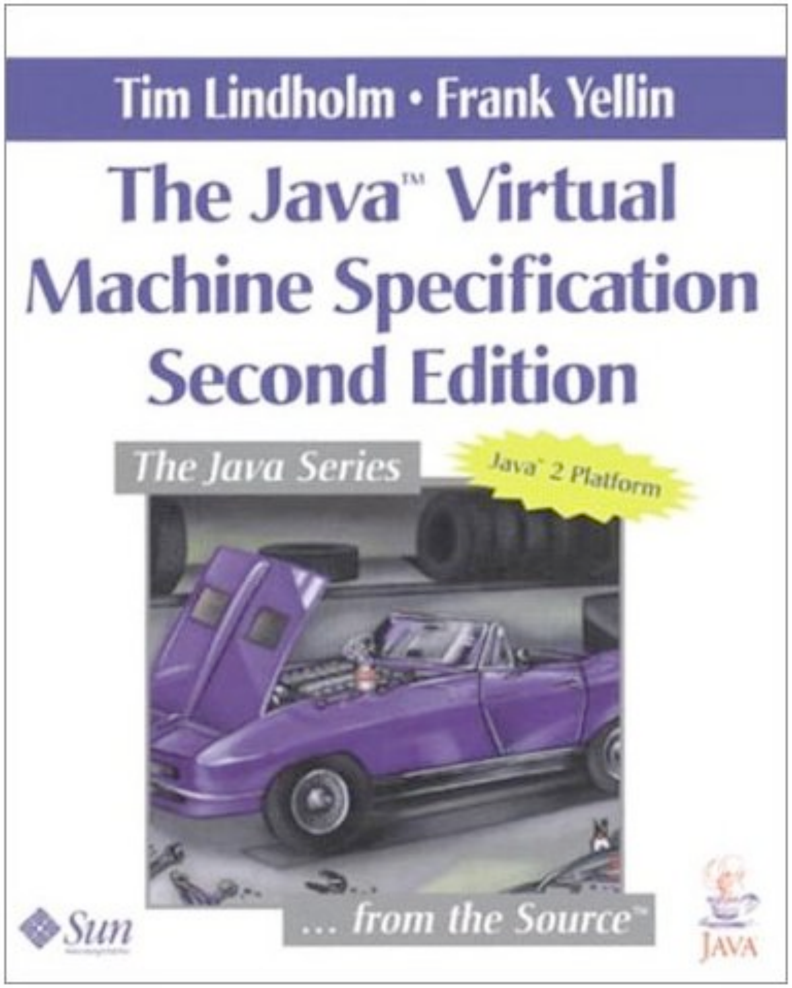
Virtual Machines

- An IR has a semantics
- Can interpret it using a *virtual machine*
  - Java virtual machine
  - Dalvik virutal machine
  - Lua virtual machine
  - “Virtual” just means implemented in software, rather than hardware, but even hardware uses some interpretation
    - E.g., x86 processor has complex instruction set that’s internally interpreted into much simpler form
- Tradeoffs?

Java Virtual Machine (JVM)

- JVM memory model
  - Stack (function call frames, with local variables)
  - Heap (dynamically allocated memory, garbage collected)
  - Constants
- Bytecode files contain
  - Constant pool (shared constant data)
  - Set of classes with fields and methods
    - Methods contain instructions in Java bytecode language
    - Use javap -c to disassemble Java programs so you can look at their bytecode

JVM Semantics



- Documented in the form of a 500 page, English language book
  - http://java.sun.com/docs/books/jvms/
- Many concerns
  - Binary format of bytecode files
    - Including constant pool
  - Description of execution model (running individual instructions)
  - Java bytecode verifier
  - Thread model

JVM Design Goals

- Type- and memory-safe language
  - Mobile code—need safety and security
- Small file size
  - Constant pool to share constants
  - Each instruction is a byte (only 256 possible instructions)
- Good performance
- Good match to Java source code

JVM Execution Model

- From the JVM book:
  - Virtual Machine Start-up
  - Loading
  - Linking: Verification, Preparation, and Resolution
  - Initialization
  - Detailed Initialization Procedure
  - Creation of New Class Instances
  - Finalization of Class Instances
  - Unloading of Classes and Interfaces
  - Virtual Machine Exit

JVM Instruction Set

- *Stack-based language*
  - All instructions take operands from the stack
- Categories of instructions
  - Load and store (e.g. aload_0,istore)
  - Arithmetic and logic (e.g. ladd,fcmpl)
  - Type conversion (e.g. i2b,d2i)
  - Object creation and manipulation (new,putfield)
  - Operand stack management (e.g. swap,dup2)
  - Control transfer (e.g. ifeq,goto)
  - Method invocation and return (e.g. invokespecial,areturn)

    - (from http://en.wikipedia.org/wiki/Java_bytecode)

Example

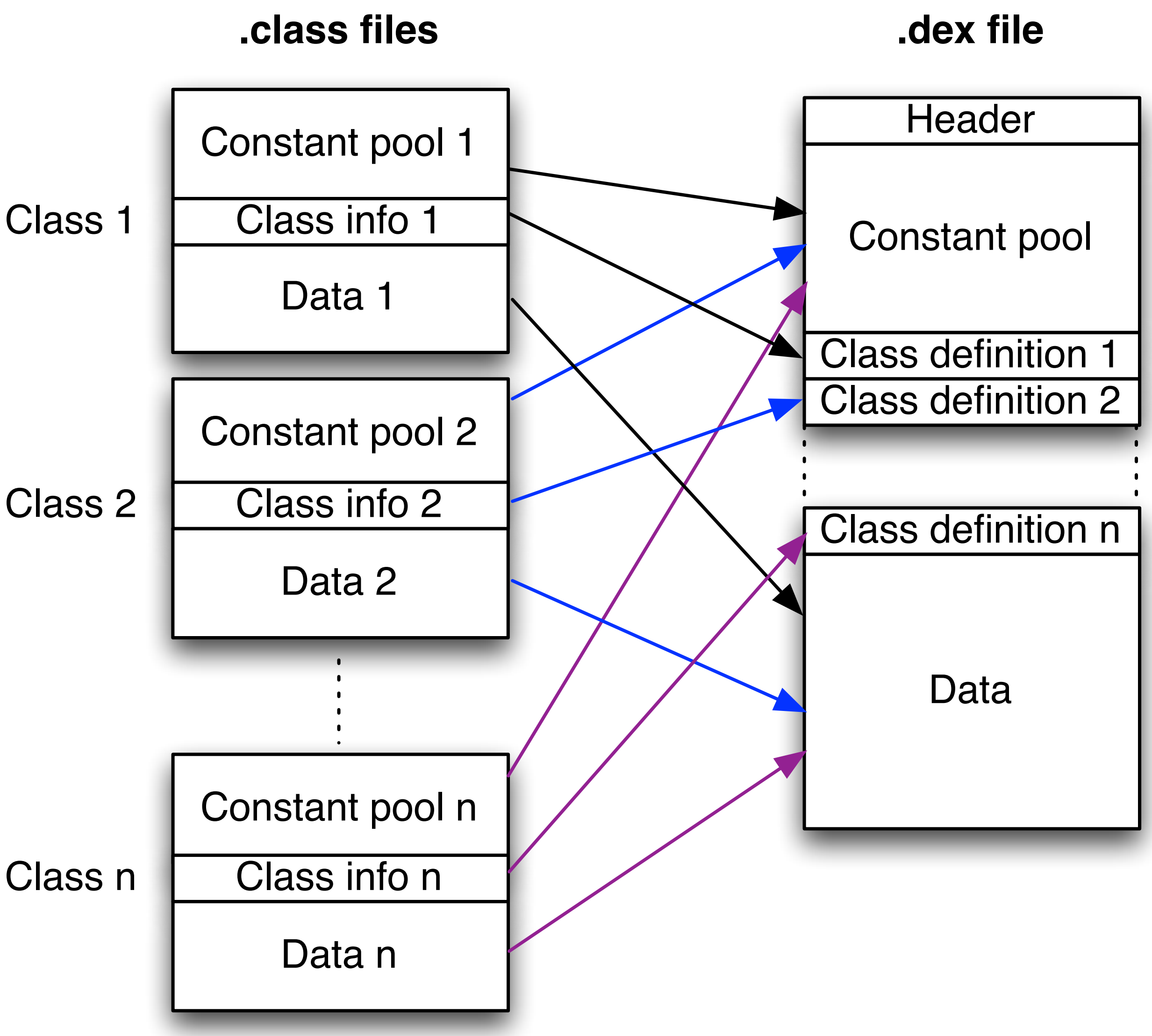
```
class A {
   public static void main(void) {
      System.out.println("Hello, world!");
   }
}
```

- Try compiling with javac, look at result using javap -c
- Things to look for:
  - Various instructions; references to classes, methods, and fields; exceptions; type information
- Things to think about:
  - File size really compact (Java → J)? Mapping onto machine instructions; performance; amount of abstraction in instructions

Dalvik Virtual Machine

- Alternative target for Java
- Developed by Google for Android phones
  - Register-, rather than stack-, based
  - Designed to be even more compact
- .dex (Dalvik) files are part of apk's that are installed on phones (apks are zip files, essentially)
  - All classes must be joined together in one big .dex file, contrast with Java where each class separate
  - .dex produced from .class files

Compiling to .dex



- Many .class files ⇒ one .dex file
- Enables more sharing

Source for this and several of the following slides:: Octeau, Enck, and McDaniel. The ded Decompiler. Networking and Security Research Center Tech Report NAS-TR-0140-2010, The Pennsylvania State University. May 2011. http://siis.cse.psu.edu/ded/papers/NAS-TR-0140-2010.pdf

Dalvik is Register-Based

```
public int add(int a, int b)
{
    return a + b;
}
```

(a) Source Code

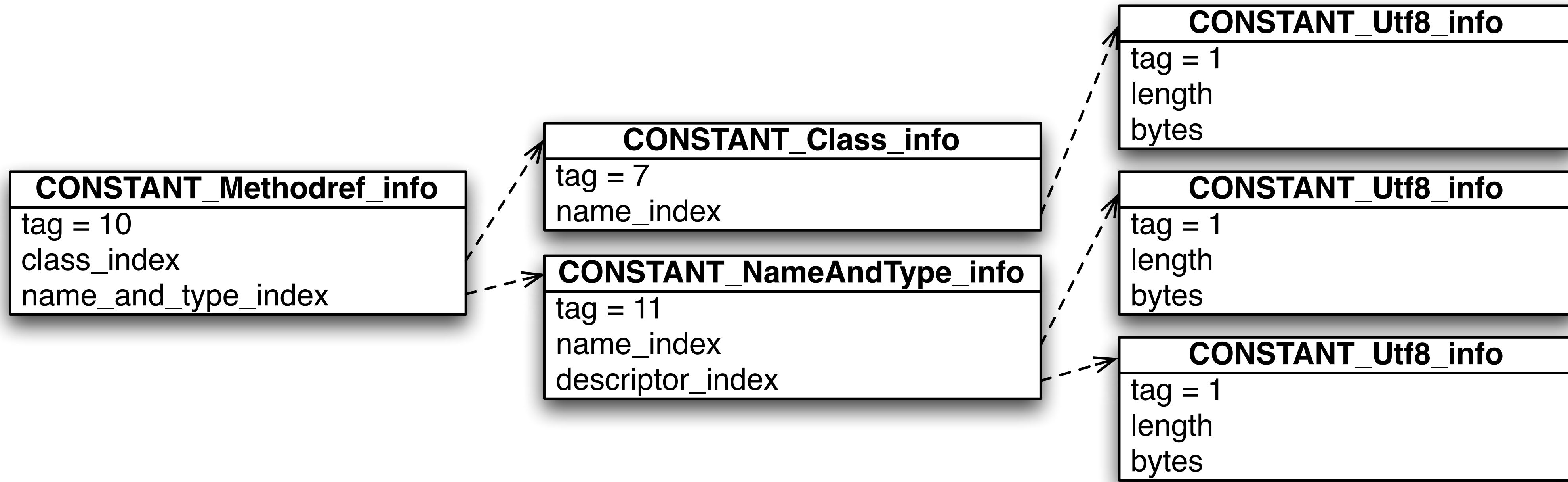
```
public int add(int, int)
   0:   iload_1
   1:   iload_2
   2:   iadd
   3:   ireturn
```

(b) Java (stack) bytecode

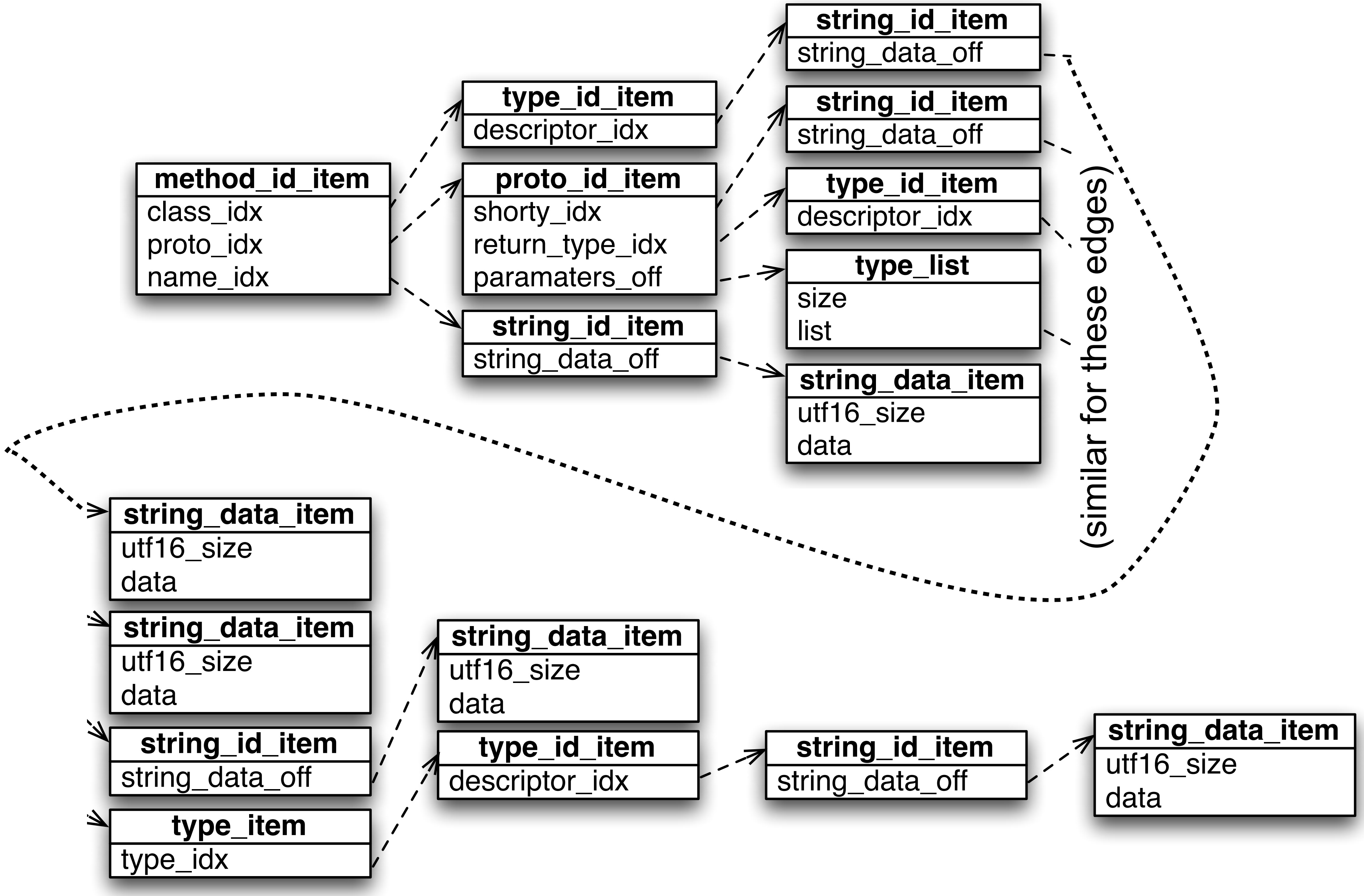
```
public int add(int, int)
   0:   add-int v0,v2,v3
   2:   return  v0
```

(c) Dalvik (register) bytecode

JVM Levels of Indirection



Dalvik Levels of Indirection



Discussion

- Why did Google invent its own VM?
  - Licensing fees? (C.f. current lawsuit between Oracle and Google)
  - Performance?
  - Code size?
  - Anything else?

Just-in-time Compilation (JIT)

- Virtual machine that compiles some bytecode all the way to machine code for improved performance
  - Begin interpreting IR
  - Find performance critical sections
  - Compile those to native code
  - Jump to native code for those regions
- Tradeoffs?
  - Compilation time becomes part of execution time

Trace-Based JIT

- Recently popular idea for Javascript interpreters
  - JS hard to compile efficiently, because of large distance between its semantics and machine semantics
    - Many unknowns sabotage optimizations, e.g., in e.m(...), what method will be called?
- Idea: find a critical (often used) trace of a section of the program's execution, and compile that
  - Jump into the compiled code when hit beginning of trace
  - Need to be able to back out in case conditions for taking trace are not actually met