Code generation

High level languages

- Java
  - stack code
  - allocate registers to top of stack
- object-oriented
  - method invocation
  - member layout
- functional
  - higher order functions
  - function calls

Code generator generators

- tree pattern matching
- tree parsing
- peephole

Compiling Java

Class files

- structure for describing program
- machine-independent stream of bytes
- verified when loaded

Issues

- stack reduces reordering
- virtual methods reduce inlining
- multiple threads limit transformations
- verify bytecodes to ensure safety

Converting into real code

- analyze stack to determine size
- represent stack as temporary variables
- try to avoid excessive copying
- allocate variables to registers

Compiling stack code

General algorithm

- determine local storage
  max locals + max stack + max temps
- form basic blocks
- find stack height for instruction
- translate instructions

Naive approach

- map each local/stack location to a frame location
- translate each instruction
- move locations between memory and registers

Register allocation approach

- map top of stack, first locals to registers
- *fixed* approach maps registers for entire method
- *basic block* approach maps registers for basic blocks

Object-oriented (OO) languages

Objects

- a collection of data
- functions (methods) for operating on data

Classes

- collection of objects with same attributes
- organizes space of objects
- allows shared implementation of objects

Implementation

- class record
  - pointers to methods (method table)
  - storage for class data
- object record
  - pointer to class type (tag)
  - storage for local data
- location → offset in object record/method table

Class hierarchy

Inheritance

- class may inherit data/methods from another class
- ancestor class bestows attributes (superclass)
- descendent class inherits attributes (subclass)
- subclass should work wherever superclass is expected
- subclass may override methods from superclass (dynamic methods)
- multiple ancestors → multiple inheritance

Impact

- class of object not completely known at compile-time
  (since object of type subclass is allowed wherever class is allowed)
- need to test tags at runtime
- could result in non-constant data/method pointer offset

Can we eliminate overhead of data/method lookups?

Data layout optimization

Single inheritance

- ensure constant offset for fields through *prefixing*
- when class B inherits from class A
  - lay out fields of A at beginning of B in same order
  - place new fields of B afterwards
- field accessed as constant offset from object record

Multiple inheritance

- ensure constant offset for fields
- assign slots for field via graph coloring
  (may leave gaps between slots)
- descriptor table
  - eliminate gaps through indirection
  - assign unique descriptor slot via coloring
  - descriptor stores offsets for field
- field accessed as constant offset plus indirection

Method lookup optimization

Single inheritance

- arrange method tables entries via prefixing
- override methods by overwriting slot
- ensure constant offset for methods
- method are executed through
  1. fetch pointer to class record from object
  2. get function pointer at offset in method table
  3. invoke method through function pointer

Multiple inheritance

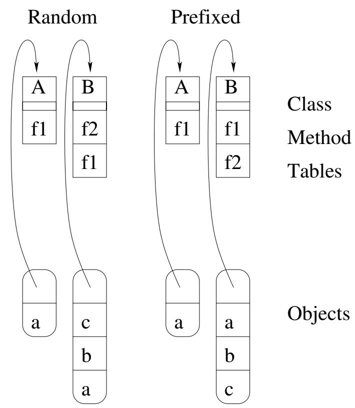
- assign slots via graph coloring
- overwrite slots as needed

Additional optimizations

- type propagation to prove class type - convert method lookup into function call
- inlining - merge code into call site, eliminates call overhead

Inheritance example

```
class A extends Obj { int a;    f1(); }
class B extends A   { int b,c;  f2(); }
A x;
x.a = x.f1();
```



Code for random

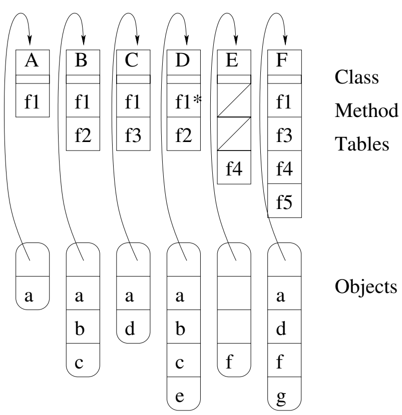
1. check x's pointer to class record
2. if (x→class == A)
   (a) call x→method[0]
   (b) assign value to x.field[0]
3. else if (x→class == B)
   (a) call x→method[1]
   (b) assign value to x.field[2]

Code for prefix

1. call x→method[0]
2. assign value to x.field[0]

Multiple inheritance example

```
class A extends Obj
  { int a;    f1(); }

class B extends A
  { int b,c;  f2(); }

class C extends A
  { int d;    f3(); }

class D extends B
  { int e;    f1*(); }

class E extends Obj
  { int f;    f4(); }

class F extends C,E
  { int g;    f5(); }
```



Functional programming languages

Functional programming

- trys to avoid side effects (e.g., assignment)
- encourages equational reasoning
- calculate solutions to equations (e.g., λ-calculus)

Features

- emphasis on function calls, recursion
- higher order functions
  (functions used as arguments, result)
- nested functions with lexical scope

Examples

```
(define FACT
 (lambda (n)
  (cond [(equal? n 1) 1]
   [t (mult n (FACT (sub n 1)))])))
```

```
(define ADDN
 (lambda (n)
  (lambda (x)
   (add n x))))
```


Compilation techniques

Higher order functions

- represent function pointers as *closures*
- record containing pointer to function and method to access nonlocal variables
- simple closure → function & static link
- must allocate activation records on heap
- analysis to determine when variables *escape*
  (may be refered to by inner-nested functions)

Function calls

- tail recursion → result of call is the return value of the parent procedure
- convert tail recursion from function call to goto
- can transform all function calls into tail recursion by adding argument for *continuation* (current state represented as closure)
- may also inline functions

Code generator generators

Automating the process

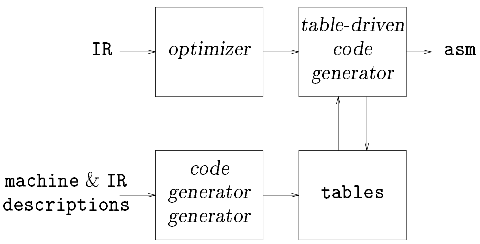
- would like a description-based tool
- machine description + IR description give code generator (cg)
- resulting cg should produce great code
- resulting cg should run quickly

Two major schools

- tree pattern matching
- instruction matching

Code generator generators

The big picture



This scheme should look familiar

Tree pattern matching

Assume that the program is represented as a set of trees.

Tree rewriting schemes (*BURS*)

- machine description is
  1. mapping of subtree into single node
  2. associated code (to be emitted)
- *example pattern:*
  - $\mathtt{r}_i \leftarrow$ `+ a b`
  - {`load r1,a; load r2,b; add r1,r1,r2`}
- paradigm is
  - find a pattern to match subtree
  - replace *rhs* pattern with *lhs* node
  - emit the associated code

Tree rewriting schemes

Several basic techniques

- work from a simple tree walk
  depth-first traversal
  simple local choice criterion
- adopt Aho & Corasick string matching (TWIG)
  matches multiple string patterns
  translate to/from linear form
- adopt Aho & Johnson (dynamic programming)
  run rewriting and cost computation concurrently
  choose low-cost alternative at each point
- use a real tree pattern matching algorithm
  generate all subtree matches concurrently
  pick the best overall match

Tree parsing schemes

Use LR parsers

- encode pattern matching into parsing problem
  — use well understood technology
  — write grammar to describe target machine
- reductions emit code
  — attributed-style specification
  — lots of contextual knowledge available
- grammars are *very* ambiguous
  — reduce/reduce ⇒ pick longer reduction
  — shift/reduce ⇒ shift
- linear time scheme!

Instruction matching

Assume program is represented in low-level intermediate representation (IR).

Peephole optimization

- find logically adjacent instructions that can be combined
  - use a very small context (3-10 instructions)
  - combining i_1 and i_2 ⇒ faster i_3
- work at register-transfer language (*rtl*) level
  - machine description in *rtl*
  - low-level IR description in *rtl*
- using pattern matching, synthesize more complex instructions
- useful for implementing many machine-dependent optimizations

Instruction matching

Generating "peephole" code generators

- provide a one-to-one translation for IR
- add patterns to improve code
  (more complex instructions and addressing modes)

Training generator

- feed a set of representative programs to the trainer and let it build a table by exhaustive search
- one time expense (*and it is expensive*)
- use a linear time pattern matcher run from the tables produced by the trainer

Typical machines

- RT/PC w/o floating point - 70-100 instructions
- MC68020 - millions of possible instructions