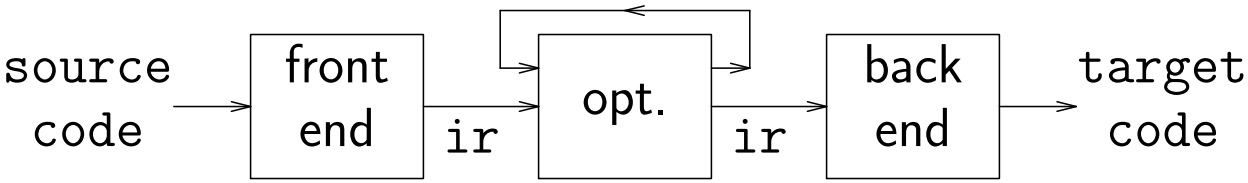
Intermediate representations



front end produces an intermediate representation (*IR*) for the program.

optimizer transforms the code in IR form into an equivalent program that may run more efficiently.

back end transforms the code in IR form into native code for the target machine

The IR encodes knowledge that the compiler has derived about the source program.

Intermediate representations

Advantages

- compiler can make multiple passes over program
- break the compiler into manageable pieces
- support multiple languages and architectures using multiple front & back ends
- enables machine-independent optimization

Desirable properties

- easy & inexpensive to generate and manipulate
- contains sufficient information

Examples

- abstract syntax tree (AST)
- directed acyclic graph (DAG)
- control flow graph (CFG)
- three address code
- stack code

Intermediate representations

Broadly speaking, IRs fall into three categories:

Structural

- structural IRs are graphically oriented
- examples: trees, directed acyclic graphs
- heavily used in source to source translators
- nodes, edges tend to be large

Linear

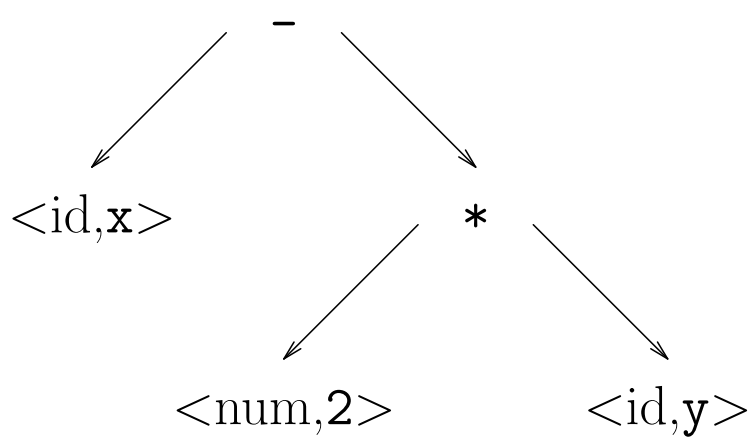
- pseudo-code for some abstract machine
- large variation in level of abstraction
- simple, compact data structures
- easier to rearrange

Hybrids

- combination of graphs and linear code
- attempt to take best of each
- examples: control-flow graph

Abstract syntax tree

An abstract syntax tree (AST) is the procedure's parse tree with the nodes for most non-terminal symbols removed.



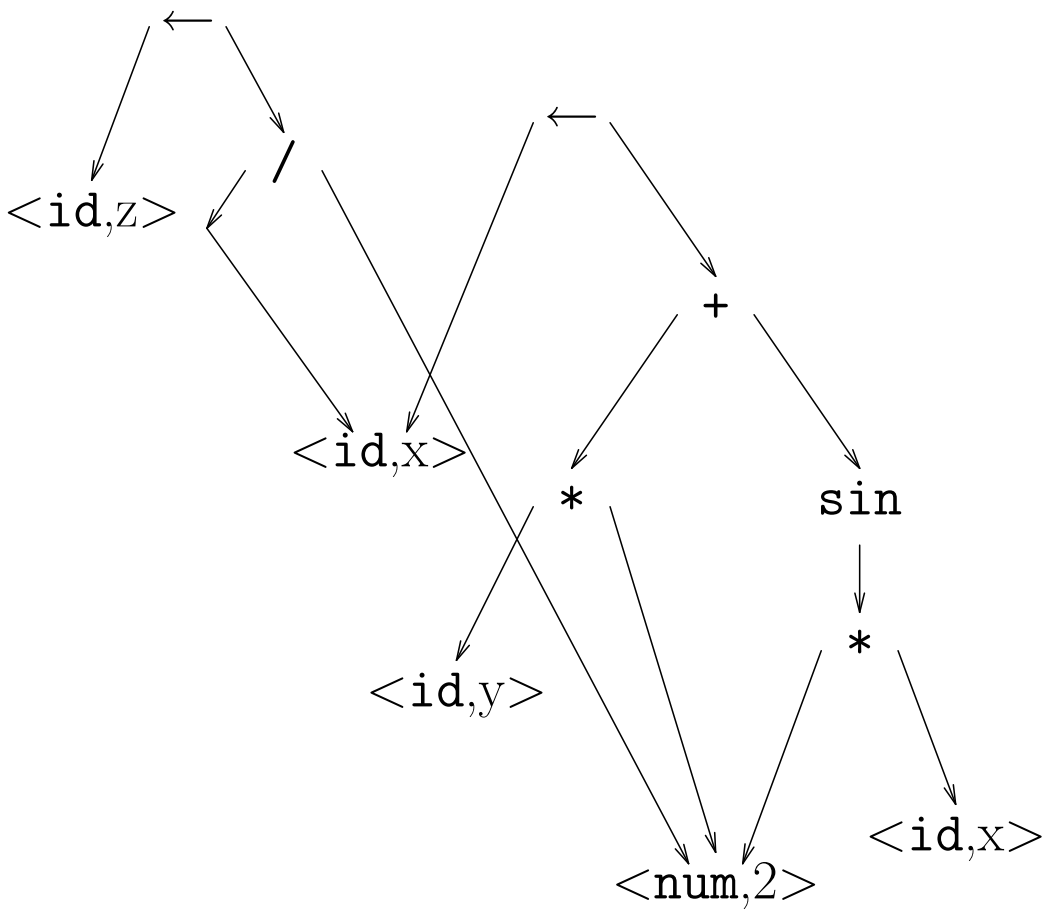
This represents "`x - 2 * y`".

For ease of manipulation, can use a linearized (operator) form of the tree.

`x 2 y * -` in postfix form.

Directed acyclic graph

A directed acyclic graph (DAG) is an AST with a unique node for each value.




```
x ← 2 * y + sin(2*x)
z ← x / 2
```

Control flow graph

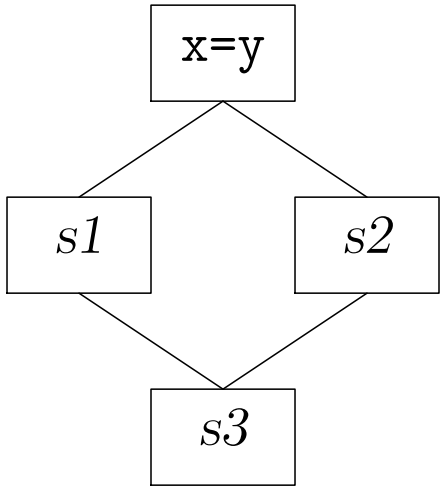
The control flow graph (CFG) models the transfers of control in the procedure.

- nodes in the graph are *basic blocks*
  maximal-length straight-line blocks of code
- edges in the graph represent control flow
  loops, if-then-else, case, goto

Example

```
if (x=y)
   then s1
   else s2
s3
```

becomes



Three address code

Three address code generally allow statements of the form:

$\texttt{x} \leftarrow \texttt{y}\ op\ \texttt{z}$

with a single operator and, at most, three names.

Complex expressions like

```
x - 2 * y
```

are simplified to

```
t1 ← 2 * y
t2 ← x - t1
```

Advantages

- compact form (direct naming)
- names for intermediate values

Register transfer language (RTL)

- only load/store instructions access memory
- all other operands are registers
- version of three address code for RISC

Three address code

Typical statement types

1. assignments — `x` ← `y` *op* `z`
2. assignments — `x` ← *op* `y`
3. assignments — `x` ← `y[i]`
4. assignments — `x` ← `y`
5. branches — `goto L`
6. conditional branches — `if x` *relop* `y goto L`
7. procedure calls — `param x` and `call p`
8. address and pointer assignments

Can represent three address code using *quadruples*

`x - 2 * y`

(1)	load	t1	y	
(2)	loadi	t2	2	
(3)	mult	t3	t2	t1
(4)	load	t4	x	
(5)	sub	t5	t4	t2

Stack machine code

Can simplify IR by assuming implicit stack

Example

```
z = x - 2 * y
```

becomes

```
push x
push 2
push y
multiply
subtract
store z
```

Advantages

- compact form
- introduced names are implicit, not explicit
- simple to generate and execute code

Disadvantages

- processors operate on registers, not stacks
- difficult to reuse values on stack

Intermediate representations

But this isn't the whole story

Symbol table:

- identifiers, procedures
- size, type, location
- lexical nesting depth

Constant table:

- representation, type
- storage class, offset(s)

Storage map:

- storage layout
- overlap information
- (virtual) register assignments

Virtual machines

Can interpret IR using "virtual machine"

Examples

- P-code for Pascal
- postscript for display devices
- Java byte code for everywhere

Result

- easy & portable
- much slower

Just-in-time compilation (JIT)

- begin interpreting IR
- find performance critical section(s)
- compile section(s) to native code
- ...or just compile entire program
- compilation time becomes execution time

Java virtual machine (JVM)

The JVM consists of four parts

Memory

- stack (for function call frames)
- heap (for dynamically allocated memory)
- constant pool (shared constant data)
- code segment (instructions of class files)

Registers

- stack pointer (SP), local stack pointer (LSP), program counter (PC)

Condition codes

- stores result of last conditional instruction

Execution unit

1. reads current JVM instruction
2. change state of virtual machine
3. increment PC (modify if call, branch)

Java byte codes

Arithmetic instructions

`ineg`	[...:i] → [...:-i]	
`iadd`	[...:i1,i2] → [...:i1+i2]	
`isub`	[...:i1,i2] → [...:i1-i2]	
`imul`	[...:i1,i2] → [...:i1*i2]	
`idiv`	[...:i1,i2] → [...:i1/i2]	

Direct instructions

`iinc k a`	[...] → [...]	local[k] ← local[k]+a

Branch instructions

`goto L`	[...] → [...]	branch to L
`ifeq L`	[...:i] → [...]	branch if i = 0
`ifne L`	[...:i] → [...]	branch if i != 0
`ifnull L`	[...:o] → [...]	branch if o = null
`ifnonnull L`	[...:o] → [...]	branch if o != null
`if_icmpeq L`	[...:i1:i2] → [...]	branch if i1 = i2
`if_icmpne L`	[...:i1:i2] → [...]	branch if i1 != i2
`if_icmpgt L`	[...:i1:i2] → [...]	branch if i1 > i2
`if_icmplt L`	[...:i1:i2] → [...]	branch if i1 < i2
`if_acmpeq L`	[...:o1:o2] → [...]	branch if o1 = o2
`if_acmpne L`	[...:o1:o2] → [...]	branch if o1 != o2

Java byte codes

Constant loading

`iconst_0`	[...] → [...:0]	
`iconst_1`	[...] → [...:1]	
`aconst_null`	[...] → [...:null]	
`ldc_int i`	[...] → [...:i]	
`ldc_string s`	[...] → [...:str(s)]	

Locals operations

`iload k`	[...] → [...:local[k]]	
`aload k`	[...] → [...:local[k]]	
`istore k`	[...:i] → [...]	local[k]←i
`astore k`	[...:o] → [...]	local[k]←o

Stack operations

`dup`	[...:v] → [...:v,v]	
`pop`	[...:v] → [...]	
`swap`	[...:v1,v2] → [...:v2,v1]	

Functions

`invoke`	[...:args] → [...]	push stack frame, ...
`ireturn`	[...:i] → [...]	ret i, pop stack frame
`areturn`	[...:o] → [...]	ret o, pop stack frame
`return`	[...] → [...]	pop stack frame

Java bytecode interpreter

```
pc = code.start
while (true) {
    new_pc = pc + inst_len(code[pc]);
    switch (opcode(code[pc])) {
        case iconst_1:
            push(1); break;
        case iload:
            push(local[code[pc+1]]); break;
        case istore:
            t ← pop();
            local[code[pc+1]] ← t; break;
        case iadd:
            t1 ← pop(); t2 ← pop();
            push(t1 + t2); break;
        case ifeq:
            t ← pop();
            if (t = 0) new_pc = code[pc+1]; break;
        ...
    }
    pc ← new_pc;
}
```