# Semantic Processing

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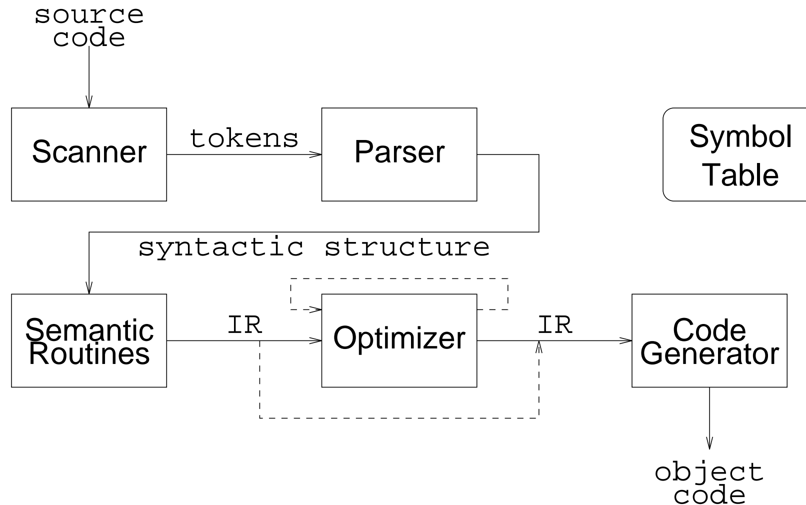
# Alternatives for semantic processing




- one-pass analysis and synthesis
- one-pass compiler plus peephole
- one-pass analysis & IR synthesis + code generation pass
- multipass analysis (gcc)
- multipass synthesis (gcc)
- language-independent and retargetable compilers (gcc)

# One-pass compilers

- interleave scanning, parsing, checking, and translation
- no explicit IR
- generates target machine code directly
  emit short sequences of instructions at a time on each parser action (symbol match for predictive parsing/LR reduction)
  $\Rightarrow$ little or no optimization possible (minimal context)

Can add a *peephole optimization pass*

- extra pass over generated code through window (*peephole*) of a few instructions
- smoothes "rough edges" between segments of code emitted by one call to the code generator

# One-pass analysis/synthesis + code generation

*Generate explicit IR as interface to code generator*

- linear – e.g., tuples
- code generator alternatives:
  - one tuple at a time
  - many tuples at a time for more context and better code

Advantages

- back-end independent from front-end
  $\Rightarrow$ easier retargetting
  IR must be expressive enough for different machines
- add optimization pass later (multipass synthesis)

# Multipass analysis

Historical motivation: constrained address spaces

Several passes, each writing output to a file

1. scan source file, generate tokens (place identifiers and constants directly into symbol table)
2. parse token file
   generate *semantic actions* or linearized parse tree
3. parser output drives:
   - declaration processing to symbol table file
   - semantic checking with synthesis of code/linear IR

# Multipass analysis

Other reasons for multipass analysis (omitting file I/O)

- language may require it – e.g., declarations after use:
  1. scan, parse and build symbol table
  2. semantic checks and code/IR synthesis
- take advantage of tree-structured IR for less restrictive analysis: scanning, parsing, tree generation combined, one or more subsequent passes over the tree perform semantic analysis and synthesis

# Multipass synthesis

Passes operate on linear or tree-structured IR

Options

- code generation and peephole optimization
- multipass transformation of IR: machine-independent and machine-dependent optimizations
- high-level machine-independent IR to lower-level IR prior to code generation
- language-independent front ends (first translate to high-level IR)
- retargettable back ends (first transform into low-level IR)

# Multipass synthesis: e.g., GNU C compiler (`gcc`)

- language-dependent parser builds language-independent trees
- trees drive generation of machine-independent low-level **R**egister **T**ransfer **L**anguage for machine-independent optimization
- thence to target machine code and peephole optimization

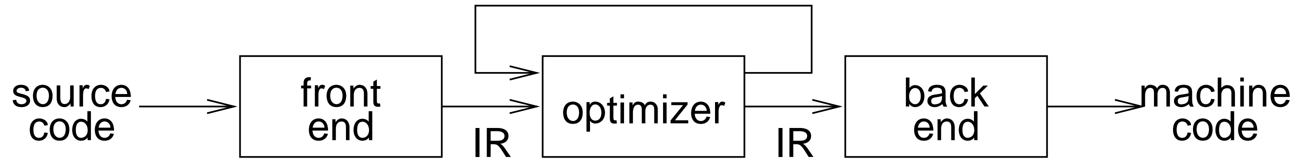
# Intermediate representations

*Why use an intermediate representation?*

1. break the compiler into manageable pieces
   good software engineering technique
2. allow a complete pass before code is emitted
   lets compiler consider more than one option
3. simplifies retargeting to new host
   isolates back end from front end
4. simplifies handling of “poly-architecture” problem
   $m$ lang’s, $n$ targets $\Rightarrow m+n$ components (*myth*)
5. enables machine-independent optimization
   general techniques, multiple passes

*An intermediate representation is a compile-time data structure*

# Intermediate representations




Generally speaking:

- front end produces IR
- optimizer transforms that representation into an equivalent program that may run more efficiently
- back end transforms IR into native code for the target machine

# Intermediate representations

*Representations talked about in the literature include:*

- abstract syntax trees (AST)
- linear (operator) form of tree
- directed acyclic graphs (DAG)
- control flow graphs
- program dependence graphs
- static single assignment form
- 3-address code
- hybrid combinations

# Intermediate representations

*Important IR Properties*

- ease of generation
- ease of manipulation
- cost of manipulation
- level of abstraction
- freedom of expression
- size of typical procedure
- original or derivative

Subtle design decisions in the IR have far reaching effects on the speed and effectiveness of the compiler.

Level of exposed detail is a crucial consideration.

# Intermediate representations

Broadly speaking, IRs fall into three categories:

Structural

- structural IRs are graphically oriented
- examples include trees, DAGs
- heavily used in source to source translators
- nodes, edges tend to be large

Linear

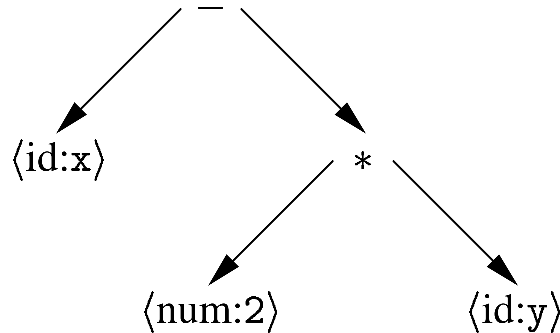
- pseudo-code for some abstract machine
- large variation in level of abstraction
- simple, compact data structures
- easier to rearrange

Hybrids

- combination of graphs and linear code
- attempt to take best of each
- e.g., control-flow graphs

# 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 "$\mathtt{x} - 2 * \mathtt{y}$".

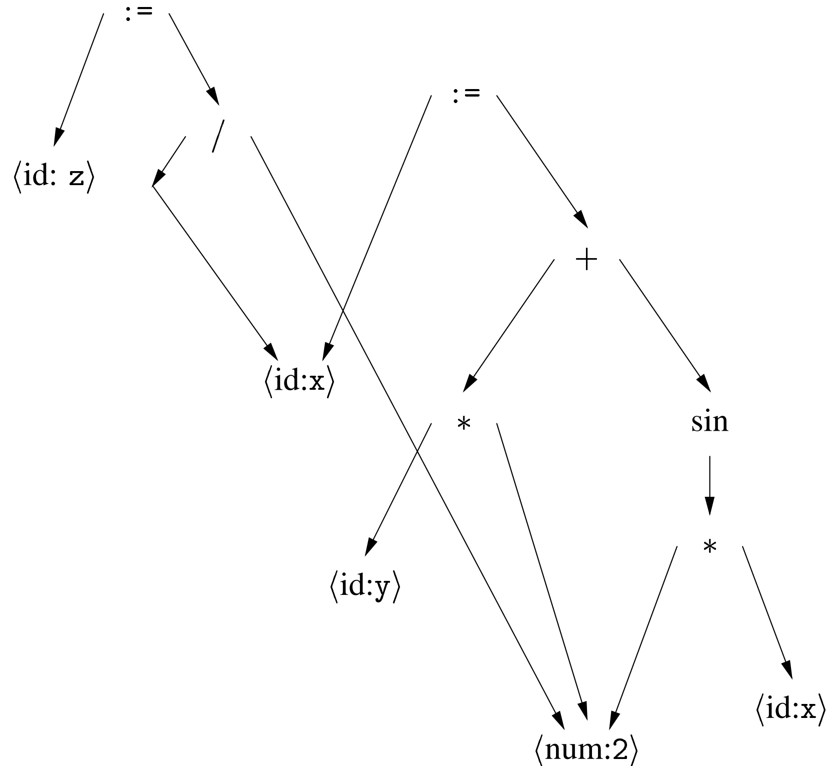
For ease of manipulation, can use a linearized (operator) form of the tree.

e.g., in postfix form: $\mathtt{x}\ 2\ \mathtt{y} * -$

# Directed acyclic graph

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

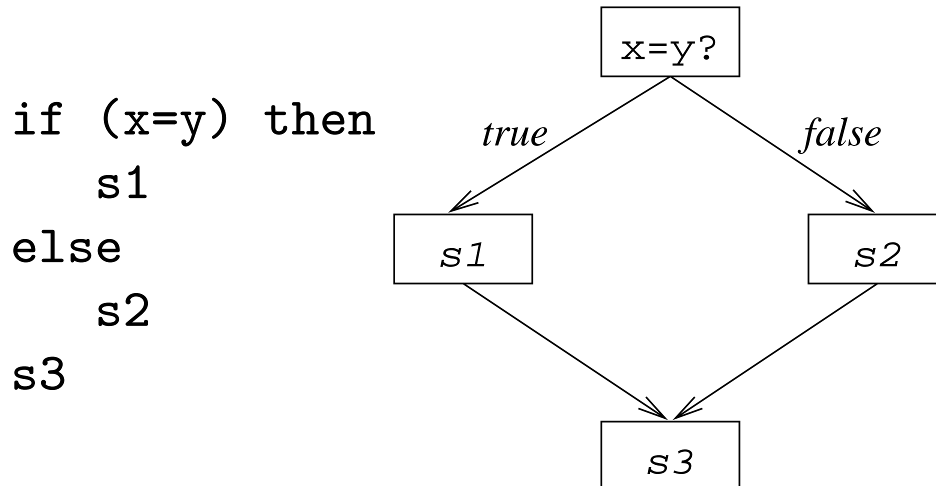
```
x := 2 * y + sin(2*x)
z := x / 2
```



# Control flow graph

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

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



# 3-address code

3-address code can mean a variety of representations.

In general, it allow statements of the form:

```
x ← y op z
```

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

Simpler form of expression:

```
x - 2 * y
```

becomes

```
t1 ← 2 * y
t2 ← x - t1
```

*Advantages*

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

Can include forms of prefix or postfix code

# 3-address code

Typical statement types include:

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

# 3-address code

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 | t3 |

- simple record structure with four fields
- easy to reorder
- explicit names

# 3-address code

Triples

```
x - 2 * y
```

| | | | |
|---|---|---|---|
| (1) | load | y | |
| (2) | loadi | 2 | |
| (3) | mult | (1) | (2) |
| (4) | load | x | |
| (5) | sub | (4) | (3) |

- use table index as implicit name
- require only three fields in record
- harder to reorder

# 3-address code

Indirect Triples

`x - 2 * y`

| | stmt | | op | arg1 | arg2 |
|---|---|---|---|---|---|
| (1) | (100) | (100) | load | y | |
| (2) | (101) | (101) | loadi | 2 | |
| (3) | (102) | (102) | mult | (100) | (101) |
| (4) | (103) | (103) | load | x | |
| (5) | (104) | (104) | sub | (103) | (102) |

- list of 1st triple in statement
- simplifies moving statements
- more space than triples
- implicit name space management

# Other hybrids

An attempt to get the best of both worlds.

- graphs where they work
- linear codes where it pays off

Unfortunately, there appears to be little agreement about where to use each kind of IR to best advantage.

For example:

- PCC and FORTRAN 77 directly emit assembly code for control flow, but build and pass around expression trees for expressions.
- Many people have tried using a control flow graph with low-level, three address code for each basic block.

# 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

# Advice

- Many kinds of IR are used in practice.
- There is no widespread agreement on this subject.
- A compiler may need several different IRs
- Choose IR with right level of detail
- Keep manipulation costs in mind

# Semantic actions

Parser must do more than accept/reject input; must also initiate translation.

*Semantic actions* are routines executed by parser for each syntactic symbol recognized.

Each symbol has associated *semantic value* (e.g., parse tree node).

Recursive descent parser:

- one routine for each non-terminal
- routine returns semantic value for the non-terminal
- store semantic values for RHS symbols in local variables

What about a table-driven LL(1) parser?

- maintain explicit *semantic stack* distinct from parse stack
- actions push results and pop arguments

# LL parsers and actions

How does an LL parser handle actions?

Expand productions *before* scanning `RHS` symbols, so:

- push actions onto parse stack like other grammar symbols
- pop and perform action when it comes to top of parse stack

# LL parsers and actions

```
push EOF
push Start Symbol
token ← next_token()
repeat
    pop X
    if X is a terminal or EOF then
        if X = token then
            token ← next_token()
        else error()
    else if X is an action
        perform X
    else /* X is a non-terminal */
        if M[X,token] = X → Y1Y2 ··· Yk then
            push Yk, Yk−1, ··· , Y1
        else error()
until X = EOF
```

# LR parsers and action symbols

What about LR parsers?

Scan entire RHS before applying production, so:

- cannot perform actions until entire RHS scanned
- can only place actions at very end of RHS of production
- introduce new marker non-terminals and corresponding productions to get around this restriction[†]

$$A \to w \textit{ action } \beta$$

becomes

$$A \to M\beta$$

$$M \to w \textit{ action}$$

[†]yacc, bison, CUP do this automatically