CSE 401 – Compilers

Intermediate Representations

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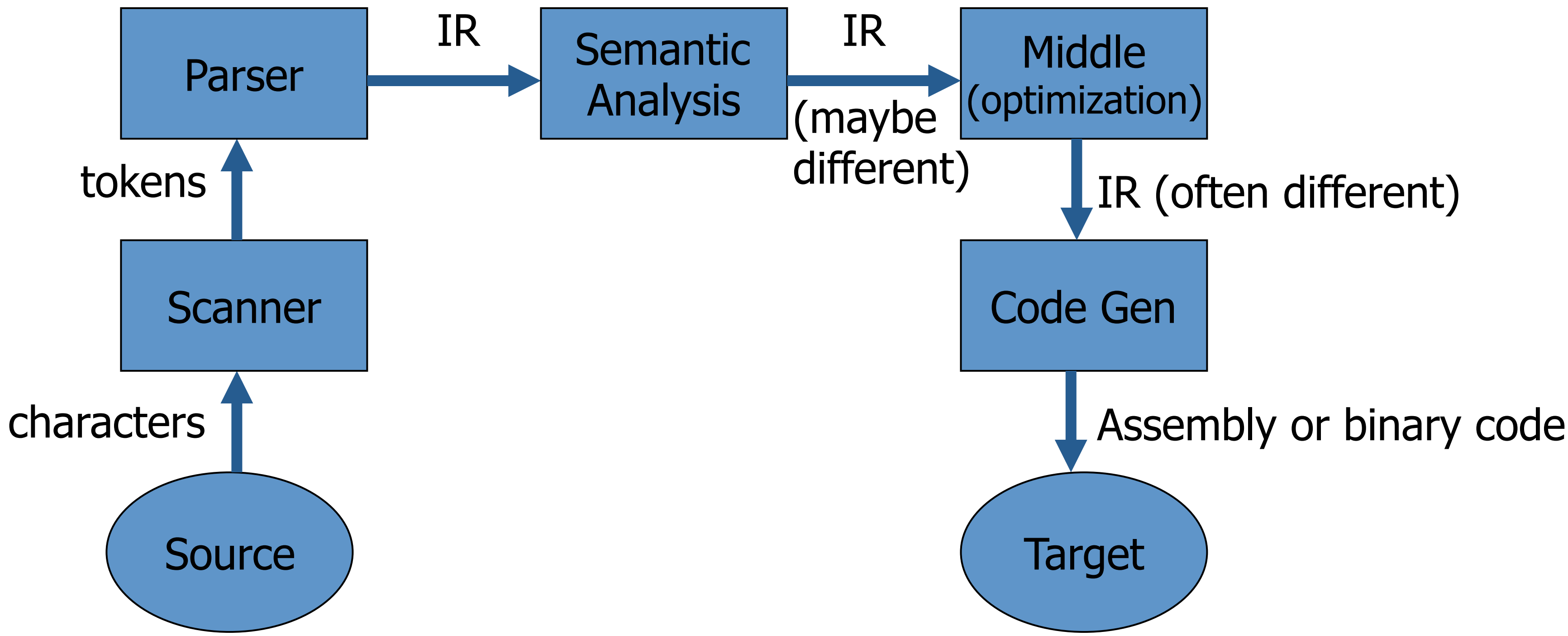
Administrivia

- No sections this week – not far enough along with newer material, so extra time for project
  - TAs will be in 006 lab during section times
  - Reminder: gdb can be useful for debugging compiled code
- Parsers back later than we wanted; will avoid penalizing errors twice on semantics grading
  - Let us know if we miss something
- Extra written hw before final exams covering optimization, back-end?
  - Or are review questions on old exams + section problems enough?

Agenda

- Survey of Intermediate Representations
  - Graphical
    - Concrete/Abstract Syntax Trees (ASTs)
    - Control Flow Graph
    - Dependence Graph
  - Linear Representations
    - Stack Based
    - 3-Address
- Several of these will show up as we explore program analysis and optimization

Compiler Structure (review)



Intermediate Representations

- In most compilers, the parser builds an intermediate representation of the program
  - Typically an AST, as in the MiniJava project
- Rest of the compiler transforms the IR to improve ("optimize") it and eventually translate to final code
  - Typically will transform initial IR to one or more different IRs along the way
- Some high-level examples now; more specifics later as needed

IR Design

- Decisions affect speed and efficiency of the rest of the compiler
  - General rule: compile time is important, but performance of generated code often more important
  - Typical case for production code: compile a few times, run many times
    - Although the reverse is true during development
  - So make choices that improve compile time as long as they don't compromise the result

IR Design

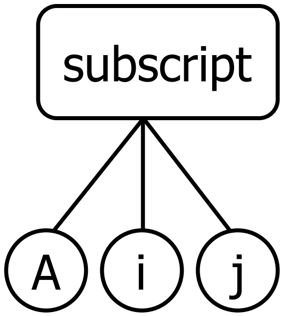
- Desirable properties
  - Easy to generate
  - Easy to manipulate
  - Expressive
  - Appropriate level of abstraction
- Different tradeoffs depending on compiler goals
- Different tradeoffs in different parts of the same compiler
  - So often different IRs in different parts

IR Design Taxonomy

- Structure
  - Graphical (trees, graphs, etc.)
  - Linear (code for some abstract machine)
  - Hybrids are common (e.g., control-flow graphs whose nodes are basic blocks of linear code)
- Abstraction Level
  - High-level, near to source language
  - Low-level, closer to machine (exposes more details to compiler)

Examples: Array Reference

A[i,j]



or

t1 ← A[i,j]

```
loadI   1   => r1
sub  rj,r1  => r2
loadI  10  => r3
mult r2,r3 => r4
sub  ri,r1  => r5
add  r4,r5 => r6
loadI @A  => r7
add  r7,r6 => r8
load r8     => r9
```

Levels of Abstraction

- Key design decision: how much detail to expose
  - Affects possibility and profitability of various optimizations
    - Depends on compiler phase: some semantic analysis & optimizations are easier with high-level IRs close to the source code. Low-level usually preferred for other optimizations, register allocation, code generation, etc.
  - Structural (graphical) IRs are typically fairly high-level – but are also used for low-level
  - Linear IRs are typically low-level
  - But these generalizations don't always hold

Graphical IRs

- IRs represented as a graph (or tree)
- Nodes and edges typically reflect some structure of the program
  - E.g., source code, control flow, data dependence
- May be large (especially syntax trees)
- High-level examples: syntax trees, DAGs
  - Generally used in early phases of compilers
- Other examples: control flow graphs and data dependency graphs
  - Often used in optimization and code generation

Concrete Syntax Trees

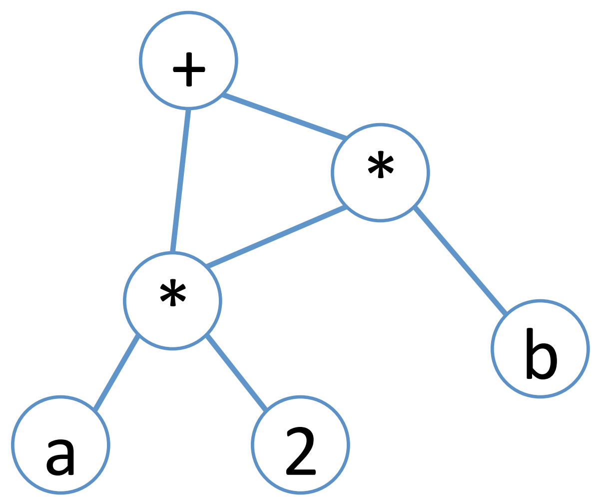
- The full grammar is needed to guide the parser, but contains many extraneous details
  - Chain productions
  - Rules that control precedence and associativity
- Typically the full syntax tree does not need to be used explicitly

Abstract Syntax Trees

- Want only essential structural information
  – Omit extra junk
- Can be represented explicitly as a tree or in a linear form
  – Example: LISP/Scheme/Racket S-expressions are essentially ASTs
- Common output from parser; used for static semantics (type checking, etc.) and sometimes high-level optimizations

DAGs (Directed Acyclic Graphs)

- Variation on ASTs with shared substructures
- Pro: saves space, exposes redundant sub-expressions
- Con: less flexibility if part needs to be changed



Basic Blocks

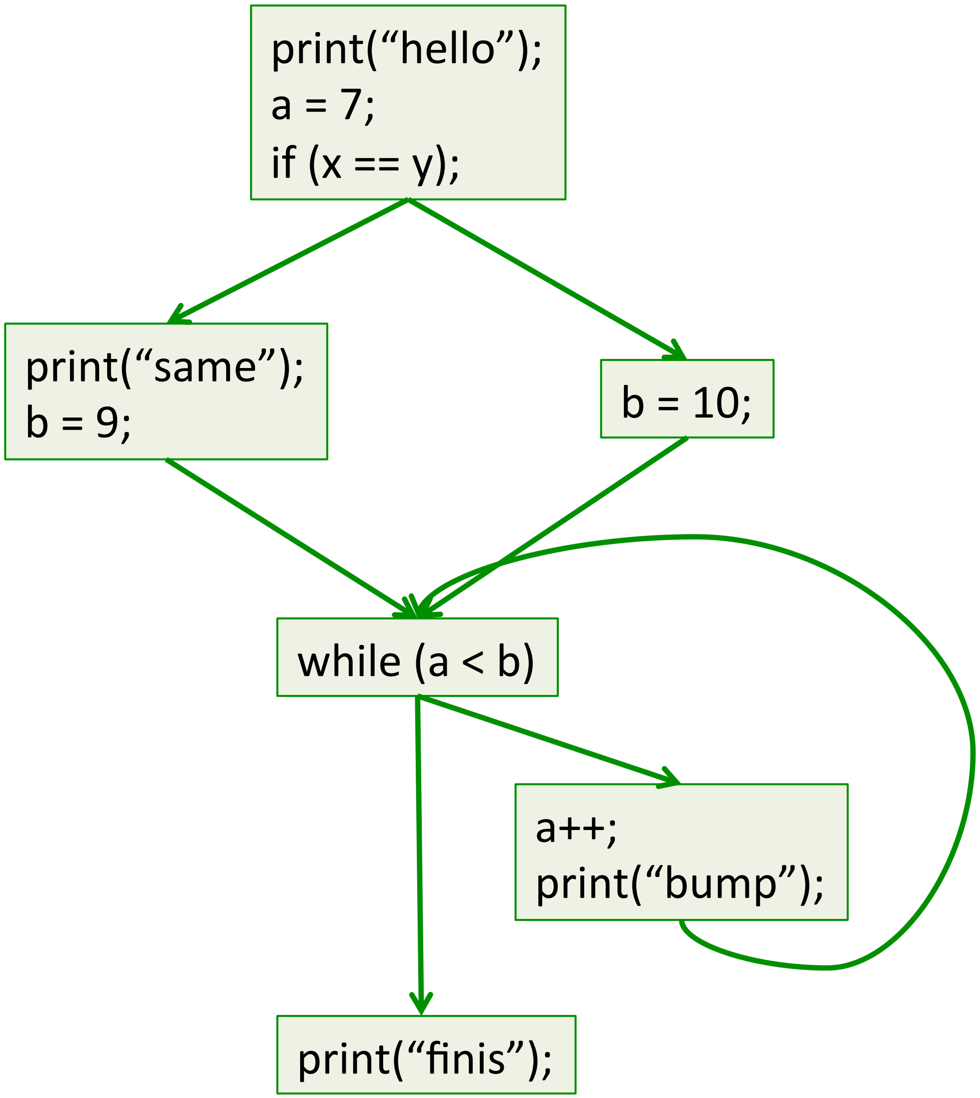
- Fundamental concept in analysis/optimization
- A *basic block* is:
  - A sequence of code
  - One entry, one exit
  - Always executes as a single unit (“straightline code”) – so it can be treated as an indivisible block
- Usually represented as some sort of a list although Trees/DAGs are possible

Control Flow Graph (CFG)

- Nodes: *basic blocks*
- Edges: represent possible flow of control from one block to another, i.e., possible execution orderings
  - Edge from A to B if B could execute immediately after A in some possible execution
- Required for much of the analysis done during optimization phases

CFG Example

```
print("hello");
a=7;
if (x == y) {
  print("same");
  b = 9;
} else {
  b = 10;
}
while (a < b) {
  a++;
  print("bump");
}
print("finis");
```



Dependency Graphs

- Often used in conjunction with another IR
- Data dependency: edges between nodes that reference common data
- Examples
  - Block A defines x then B reads it (RAW – read after write)
  - Block A reads x then B writes it (WAR – "anti-dependence)
  - Blocks A and B both write x (WAW) – order of blocks must reflect original program semantics
- These restrict reorderings the compiler can do

Linear IRs

- Pseudo-code for some abstract machine
- Level of abstraction varies
- Simple, compact data structures
  - Commonly used: arrays, linked structures
- Examples: 3-address code, stack machine code

```
t1 ← 2
t2 ← b
t3 ← t1 * t2
t4 ← a
t5 ← t4 – t3
```

- Fairly compact
- Compiler can control reuse of names – clever choice can reveal optimizations
- ILOC & similar code

```
push 2
push b
multiply
push a
subtract
```

- Each instruction consumes top of stack & pushes result
- Very compact
- Easy to create and interpret
- Java bytecode, MSIL

Abstraction Levels in Linear IR

- Linear IRs can also be close to the source language, very low-level, or somewhere in between.
- Example: Linear IRs for C array reference a[i][j+2]

  – High-level: $t1 \leftarrow a[i,j+2]$

IRs for a[i][j+2], cont.

- Medium-level

  t1 ← j + 2

  t2 ← i * 20

  t3 ← t1 + t2

  t4 ← 4 * t3

  t5 ← addr a

  t6 ← t5 + t4

  t7 ← *t6

- Low-level

  r1 ← [fp-4]

  r2 ← r1 + 2

  r3 ← [fp-8]

  r4 ← r3 * 20

  r5 ← r4 + r2

  r6 ← 4 * r5

  r7 ← fp – 216

  f1 ← [r7+r6]

Abstraction Level Tradeoffs

- High-level: good for some high-level optimizations, semantic checking; but can't optimize things that are hidden – like address arithmetic for array subscripting
- Low-level: need for good code generation and resource utilization in back end but loses some semantic knowledge (e.g., variables, data aggregates, source relationships)
- Medium-level: more detail but keeps more higher-level semantic information
- Many compilers use all 3 in different phases

Hybrid IRs

- Combination of structural and linear
- Level of abstraction varies
- Control-flow graph is often an example of this
  - Basic IR is a graph
  - Nodes in the graph can be linear lists of IR instructions

What IR to Use?

- Common choice: all(!)
  - AST or other structural representation built by parser and used in early stages of the compiler
    - Closer to source code
    - Good for semantic analysis
    - Facilitates some higher-level optimizations
  - Hybrid IR for optimization phases
  - Transform to low-level IR for later stages of compiler
    - Closer to machine code
    - Exposes machine-related optimizations
    - Use to build control-flow graph

Coming Attractions

- Survey of compiler “optimizations”
  - Analysis and transformations (including SSA)
- Back-end organization in production compilers
  - Instruction selection and scheduling, register allocation
- Other topics depending on time
  - Dynamic languages? JVM? Memory management (garbage collection)? Any preferences?