

CSE P 501 – Compilers

Intermediate Representations

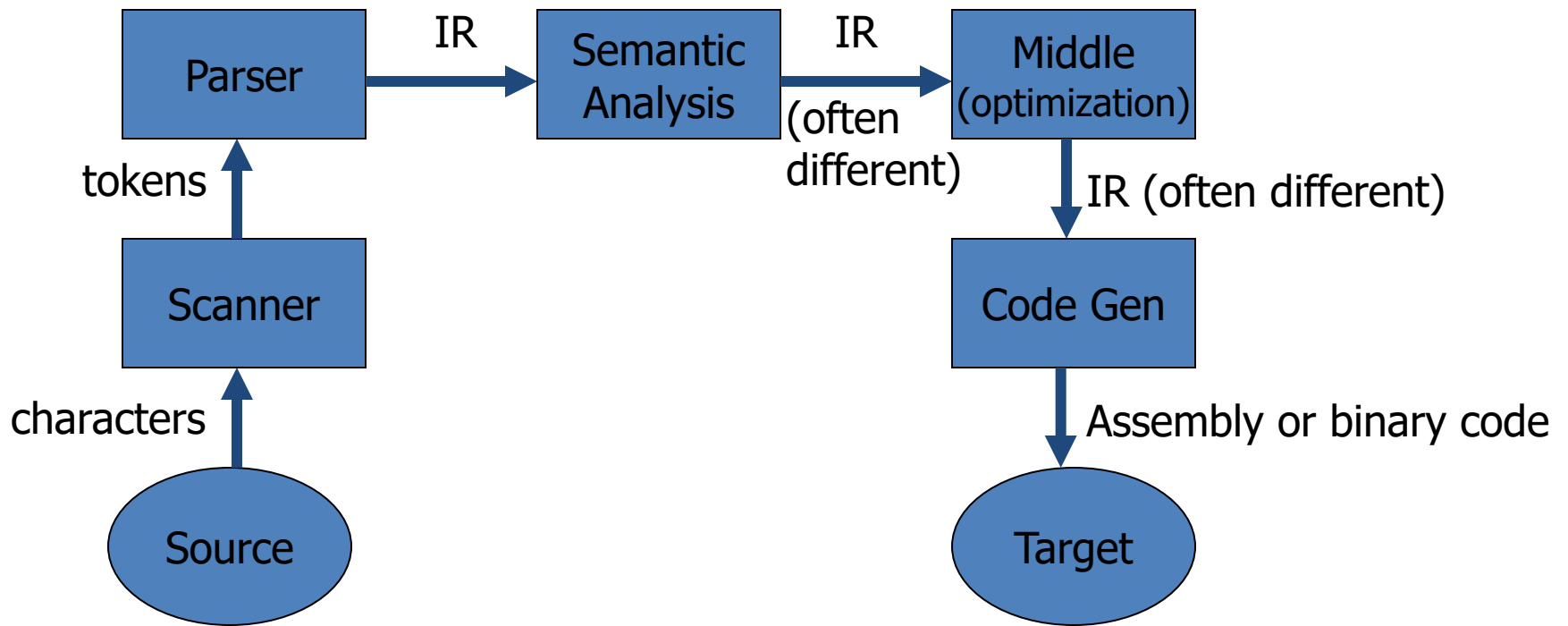
Hal Perkins

Autumn 2019

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 target code
 - Typically will transform initial IR to one or more different IRs along the way
- Some general 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/quality 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 compiler speed as long as they don't compromise the result

IR Design

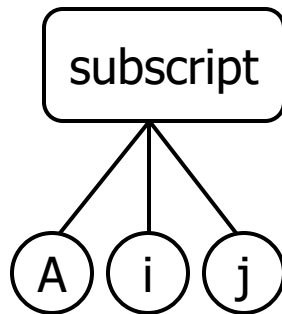
- Desirable properties
 - Easy to generate
 - Easy to manipulate
 - Expressive
 - Appropriate level of abstraction
- Different tradeoffs depending on compiler goals
- Different tradeoffs in different parts of the same compiler
 - So often different IRs in different parts

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

source: $A[i,j]$



$t1 \leftarrow A[i,j]$

```
loadl 1 => r1
sub rj,r1 => r2
loadl 10 => r3
mult r2,r3 => r4
sub ri,r1 => r5
add r4,r5 => r6
loadl @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

- IR 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

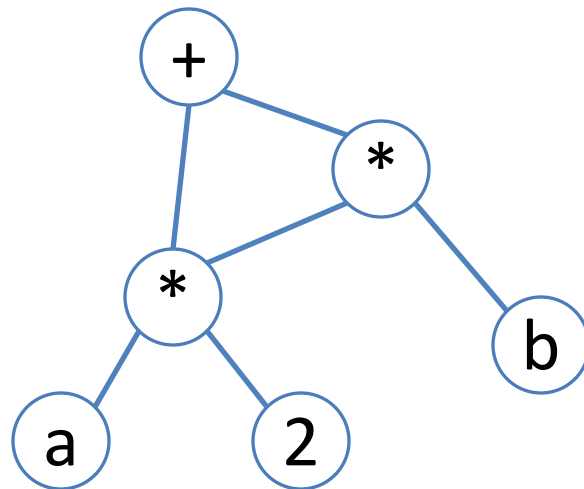
- The full grammar is needed to guide the parser, but contains many extraneous details
 - Chain productions
 - Rules that control precedence and associativity
- Typically the full syntax tree (parse tree) is not used explicitly, but sometimes we want it (structured source code editors or transformations, ...)

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 S-expressions are essentially ASTs (e.g., `(* 2 (+ 3 4))`)
- Common output from parser; used for static semantics (type checking, etc.) and sometimes high-level optimizations

DAGs (Directed Acyclic Graphs)

- Variation on ASTs to capture shared substructures
- Pro: saves space, exposes redundant sub-expressions
- Con: less flexibility if part of tree should be changed
- Example: $(a * 2) + ((a * 2) * b)$



Linear IRs

- Pseudo-code for some abstract machine
- Level of abstraction varies
- Simple, compact data structures
 - Commonly used: arrays, linked lists
- 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.
- Examples: Linear IRs for C array reference $a[i][j+2]$
 - High-level: $t1 \leftarrow a[i,j+2]$

More IRs for $a[i][j+2]$

- Medium-level

$t1 \leftarrow j + 2$

$t2 \leftarrow i * 20$

$t3 \leftarrow t1 + t2$

$t4 \leftarrow 4 * t3$

$t5 \leftarrow \text{addr } a$

$t6 \leftarrow t5 + t4$

$t7 \leftarrow *t6$

- Low-level

$r1 \leftarrow [\text{fp}-4]$

$r2 \leftarrow r1 + 2$

$r3 \leftarrow [\text{fp}-8]$

$r4 \leftarrow r3 * 20$

$r5 \leftarrow r4 + r2$

$r6 \leftarrow 4 * r5$

$r7 \leftarrow \text{fp} - 216$

$f1 \leftarrow [r7+r6]$

Abstraction Level Tradeoffs

- High-level: good for some source-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 are usually missing)
- Medium-level: more detail but keeps more higher-level semantic information – great for machine-independent optimizations. Many (all?) optimizing compilers work at this level
- Many compilers use all 3 in different phases

Three-Address Code (TAC)

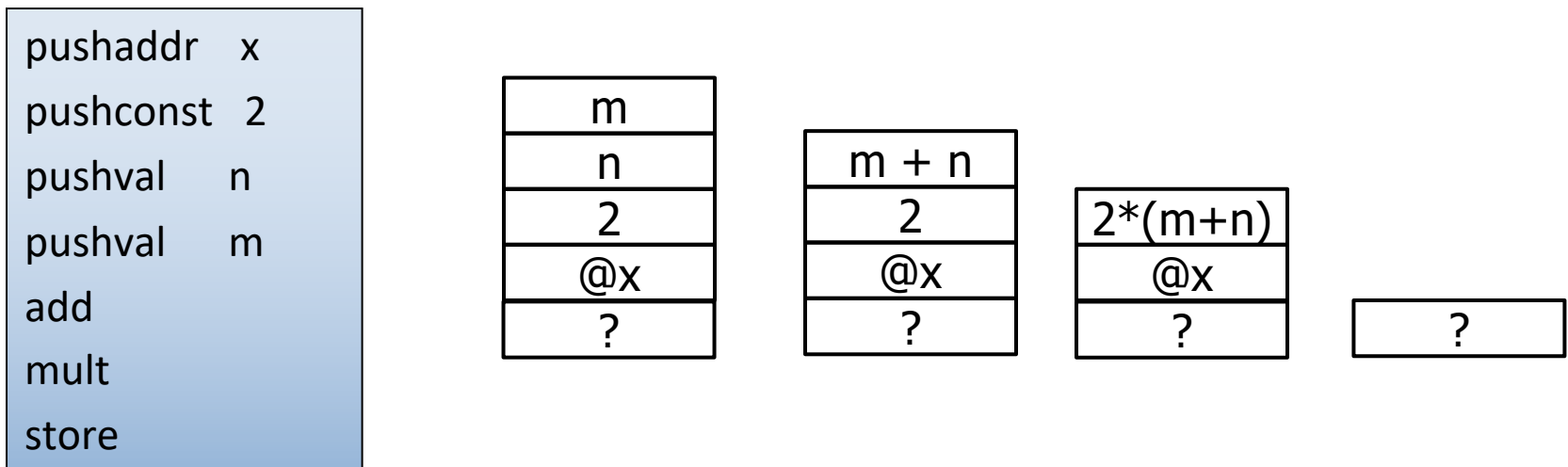
- Usual form: $x \leftarrow y \text{ op } z$
 - One operator
 - Maximum of 3 names
 - (Copes with: nullary $x \leftarrow y$ and unary $x \leftarrow \text{op } y$)
- Eg: $x = 2 * (m + n)$ becomes
 - $t1 \leftarrow m + n; \quad t2 \leftarrow 2 * t1; \quad x \leftarrow t2$
 - You may prefer: `add t1, m, n; mul t2, 2, t1; mov x, t2`
 - Invent as many new temp names as needed. “expression temps” – don’t correspond to any user variables; de-anonymize expressions
- Store in a quad(ruple)
 - $\langle \text{lhs}, \text{rhs1}, \text{op}, \text{rhs2} \rangle$

Three Address Code

- Advantages
 - Resembles code for actual machines
 - Explicitly names intermediate results
 - Compact
 - Often easy to rearrange
- Various representations
 - Quadruples, triples, SSA (Static Single Assignment)
 - We will see much more of this...

Stack Machine Code Example

Hypothetical code for $x = 2 * (m + n)$



Compact: common opcodes just 1 byte wide; instructions have 0 or 1 operand

Stack Machine Code

- Originally used for stack-based computers (famous example: B5000, ~1961)
- Often used for virtual machines:
 - Pascal – pcode
 - Forth
 - Java bytecode in a .class files (generated by Java compiler)
 - MSIL in a .dll or .exe assembly (generated by C#/F#/VB compiler)
- Advantages
 - Compact; mostly 0-address opcodes (fast download over slow network)
 - Easy to generate; easy to write a front-end compiler, leaving the 'heavy lifting' and optimizations to the JIT
 - Simple to interpret or compile to machine code
- Disadvantages
 - Somewhat inconvenient/difficult to optimize directly
 - Does not match up with modern chip architectures

Hybrid IRs

- Combination of structural and linear
- Level of abstraction varies
- Most common example: control-flow graph (CFG)

Control Flow Graph (CFG)

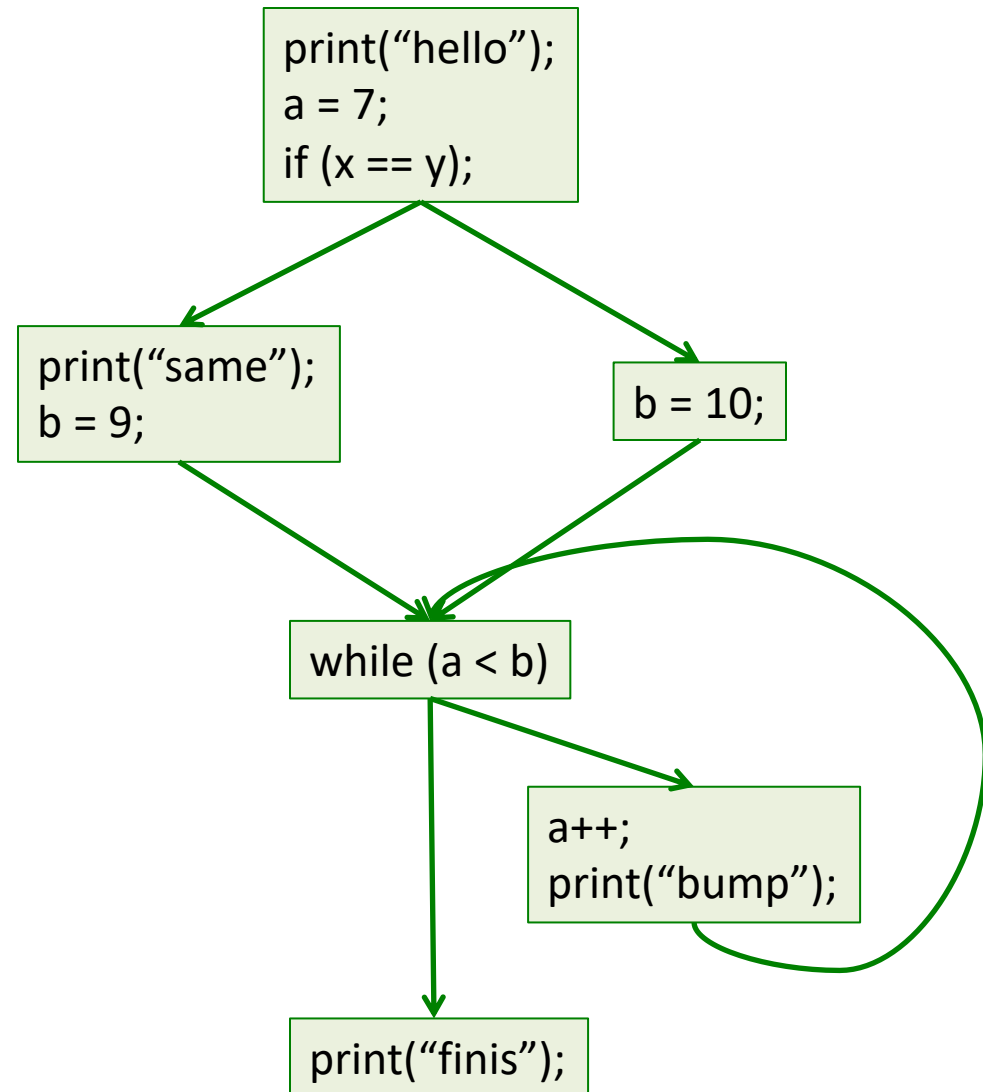
- Nodes: *basic blocks*
- Edges: represent possible flow of control from one block to another, i.e., possible execution orderings
 - Edge from A to B if B could execute immediately after A in some possible execution
- Required for much of the analysis done during optimization phases

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 unit
 - We’ll ignore exceptions, at least for now
- Usually represented as some sort of a list although Trees/DAGs are possible

CFG Example

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



Basic Blocks: Start with Tuples

```
1 i = 1
2 j = 1
3 t1 = 10 * i
4 t2 = t1 + j
5 t3 = 8 * t2
6 t4 = t3 - 88
7 a[t4] = 0
8 j = j + 1
9 if j <= 10 goto #3
10 i = i + 1
11 if i <= 10 goto #2
12 i = 1
13 t5 = i - 1
14 t6 = 88 * t5
15 a[t6] = 1
16 i = i + 1
17 if i <= 10 goto #13
```

Typical "tuple stew" - IR generated by traversing an AST

Partition into **Basic Blocks**:

- Sequence of consecutive instructions
- No jumps into the middle of a BB
- No jumps out of the middles of a BB
- "I've started, so I'll finish"
- (Ignore exceptions)

Basic Blocks: Leaders

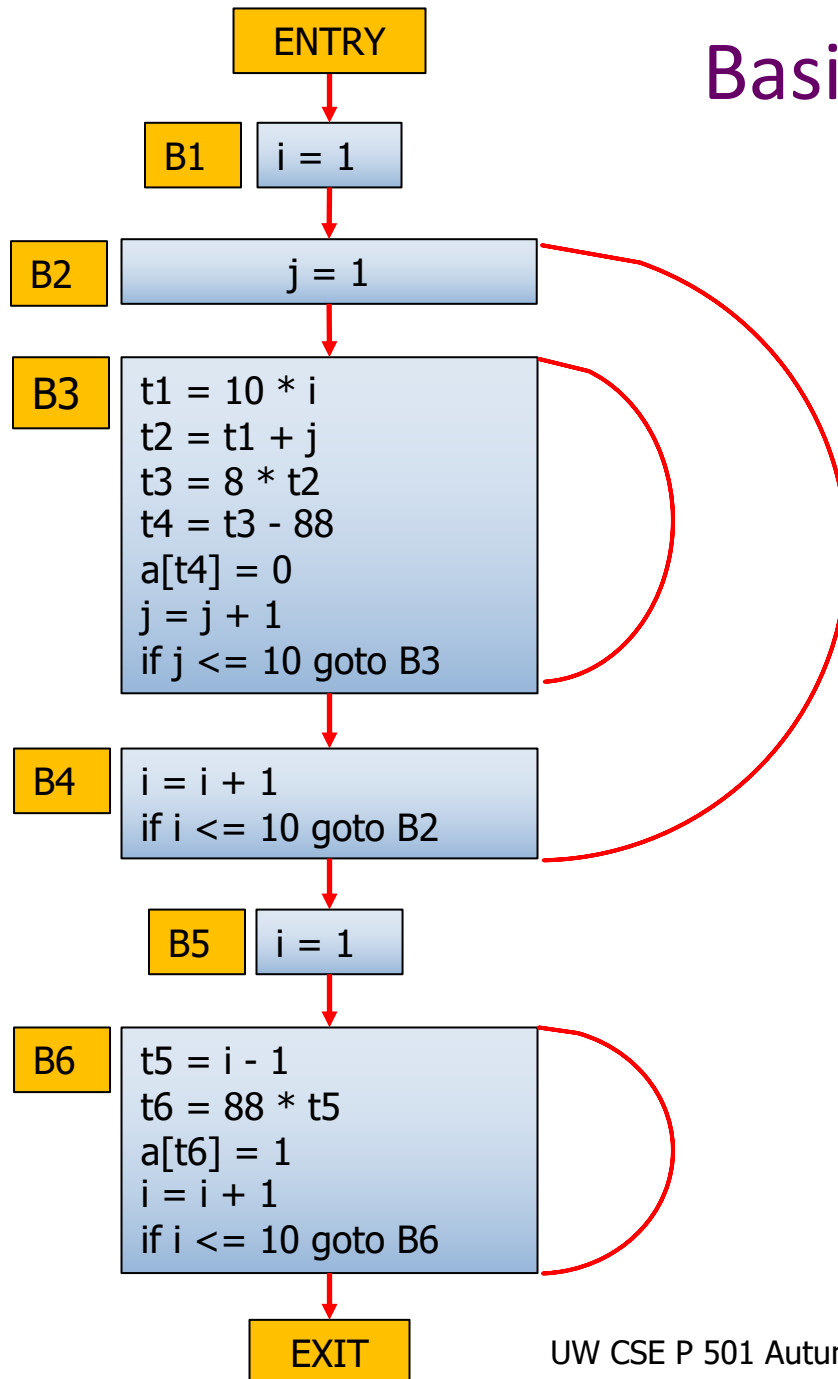
```
1 i = 1
2 j = 1
3 t1 = 10 * i
4 t2 = t1 + j
5 t3 = 8 * t2
6 t4 = t3 - 88
7 a[t4] = 0
8 j = j + 1
9 if j <= 10 goto #3
10 i = i + 1
11 if i <= 10 goto #2
12 i = 1
13 t5 = i - 1
14 t6 = 88 * t5
15 a[t6] = 1
16 i = i + 1
17 if i <= 10 goto #13
```

Identify **Leaders** (first instruction in a basic block):

- First instruction is a leader
- Any target of a branch/jump/goto
- Any instruction immediately after a branch/jump/goto

Leaders in **red**. Why is each leader a leader?

Basic Blocks: Flowgraph



Control Flow Graph ("CFG", again!)

- 3 loops total
- 2 of the loops are nested

Most of the executions likely spent in loop bodies; that's where to focus efforts at optimization

Identifying Basic Blocks: Recap

- Perform linear scan of instruction stream
- A basic blocks begins at each instruction that is:
 - The beginning of a method
 - The target of a branch
 - Immediately follows a branch or return

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

What IR to Use?

- Common choice: all(!)
 - AST used in early stages of the compiler
 - Closer to source code
 - Good for semantic analysis
 - Facilitates some higher-level optimizations
 - Lower to linear IR for optimization and codegen
 - Closer to machine code
 - Use to build control-flow graph
 - Exposes machine-related optimizations
 - Hybrid (graph + linear IR = CFG) for dataflow & opt

Coming Attractions

- Survey of compiler “optimizations”
- Analysis and transformation algorithms for optimizations (including SSA IR)
- Back-end organization in production compilers
 - Instruction selection and scheduling, register allocation
- Other topics depending on time