CS 335: Intermediate Representations

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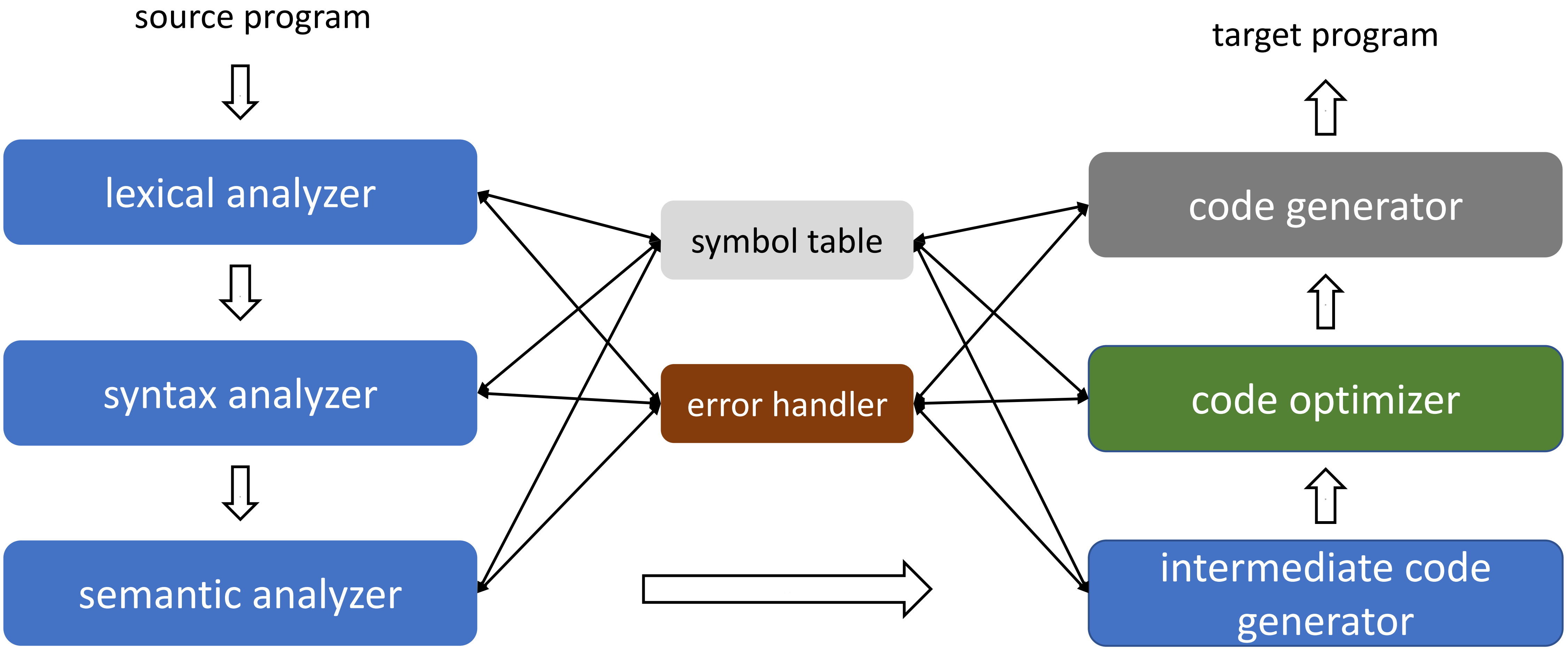
Content influenced by many excellent references, see References slide for acknowledgements.

An Overview of Compilation



source program

lexical analyzer

syntax analyzer

semantic analyzer

symbol table

error handler

intermediate code generator

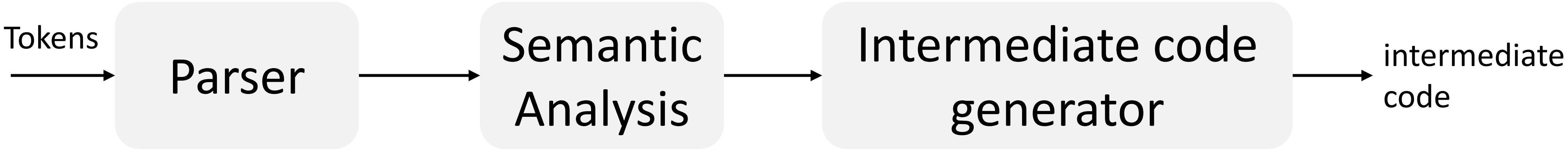
code optimizer

code generator

target program

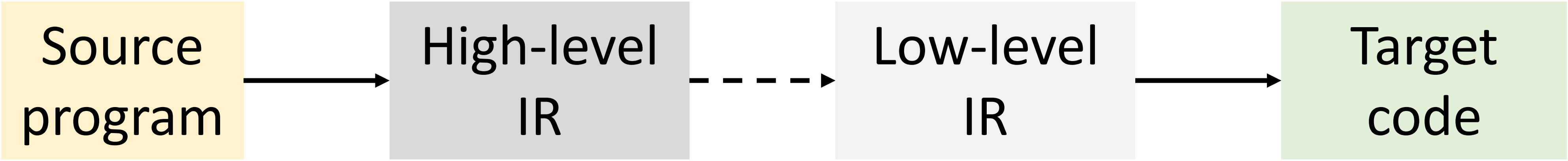
Intermediate Representation (IR)

- IR is a data structure used internally by a compiler or virtual machine (VM) while translating a source program
  - Front end analyses a source program and creates an IR
  - Back end analyses the IR and generates target code
- An well-designed IR helps ease compiler development
  - Plug in m front ends with n back ends to come up with $m \times n$ compilers



Intermediate Representation (IR)

- Compilers may create a number of IRs during the translation process



- High-level IRs (e.g., syntax trees) are closer to the source and are well-suited for tasks like static type checking
- Low-level IRs are closer to the target ISA and are suitable for tasks like register allocation and instruction selection

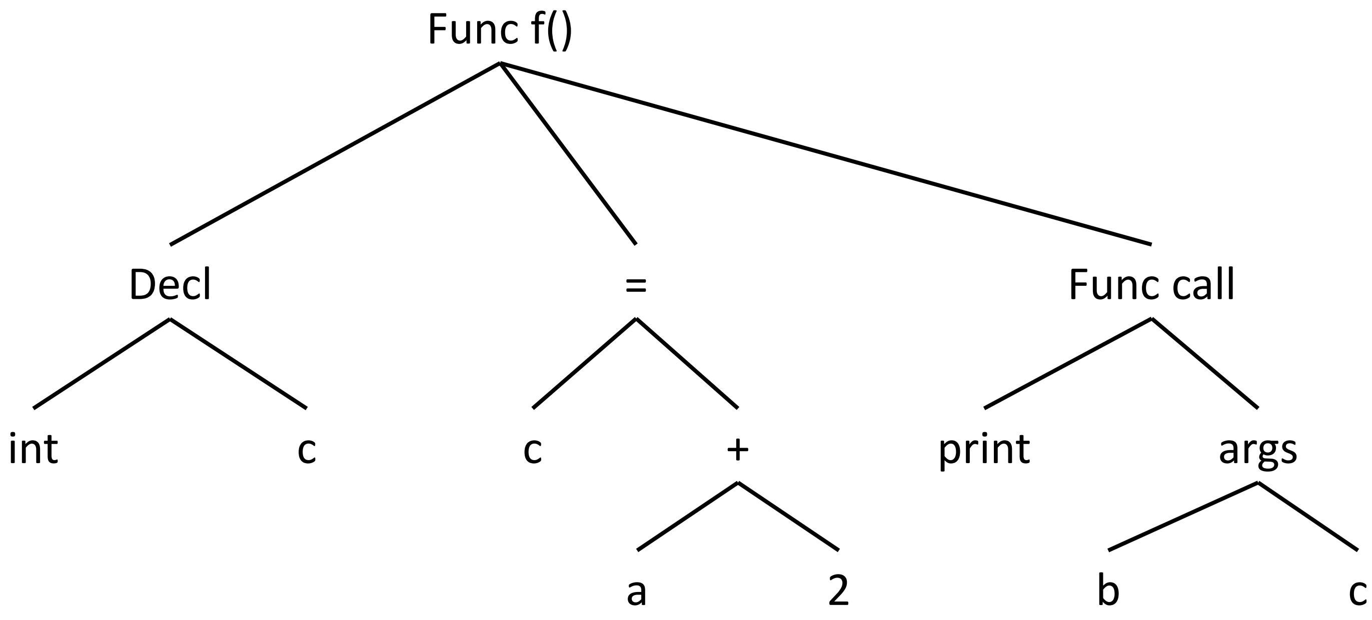
Types of IRs

- **Abstraction**-based classification
    - High-level IR – preserves many source structures like loops and array bounds
    - Medium-level IR – often independent of the source language
        - Chosen to be suitable to represent language features and to generate code
    - Low-level IR – similar to the target ISA
- **Structural** classification
    - Graphical, or linear, or hybrid
    - Hybrid combines features of both graphical and linear IR
        - E.g., CFG + 3AC or AST+3AC

High-Level IR

- Maintains enough information to reconstruct source code (e.g., AST)
  - Structured control flow, variable names, method names
  - Allows high-level optimizations like inlining

```
int f(int a, int b) {
    int c;
    c = a + 2;
    print(b, c);
}
```



Medium-Level and Low-Level IR

- Medium-level IR (MIR) (e.g., three-address code)
  - Independent of source language
  - Amenable to code optimizations (e.g., manipulating list of instructions)
  - Amenable for code generation for a variety of architectures

- Low-level IR (LIR)
  - Similar to assembly code with extra pseudo-instructions plus infinite registers
  - Close correspondence to the target ISA and is often architecture-dependent
  - Allows low-level optimizations (e.g., instruction scheduling)

Points about IR Design

- IR needs to be amenable to analysis and modifications
- Issues to consider in IR design
  - Decide on the appropriate level of abstraction to cover many language and architecture features
    - For example, LLVM IR and Java bytecode are IRs that have been used successfully for a number of source languages
  - Suitability for code optimization and code generation
  - Other factors like space overhead
- Difficult to come up with a general IR that meets all objectives

Graphical IRs

Derivation of an input

CFG

$Start \rightarrow Expr$

$Expr \rightarrow Expr + Term$

$Expr \rightarrow Expr - Term$

$Expr \rightarrow Term$

$Term \rightarrow Term \times Factor$

$Term \rightarrow Term \div Factor$

$Term \rightarrow Factor$

$Factor \rightarrow (\ Expr\ )$

$Factor \rightarrow \mathbf{num} \mid \mathbf{name}$

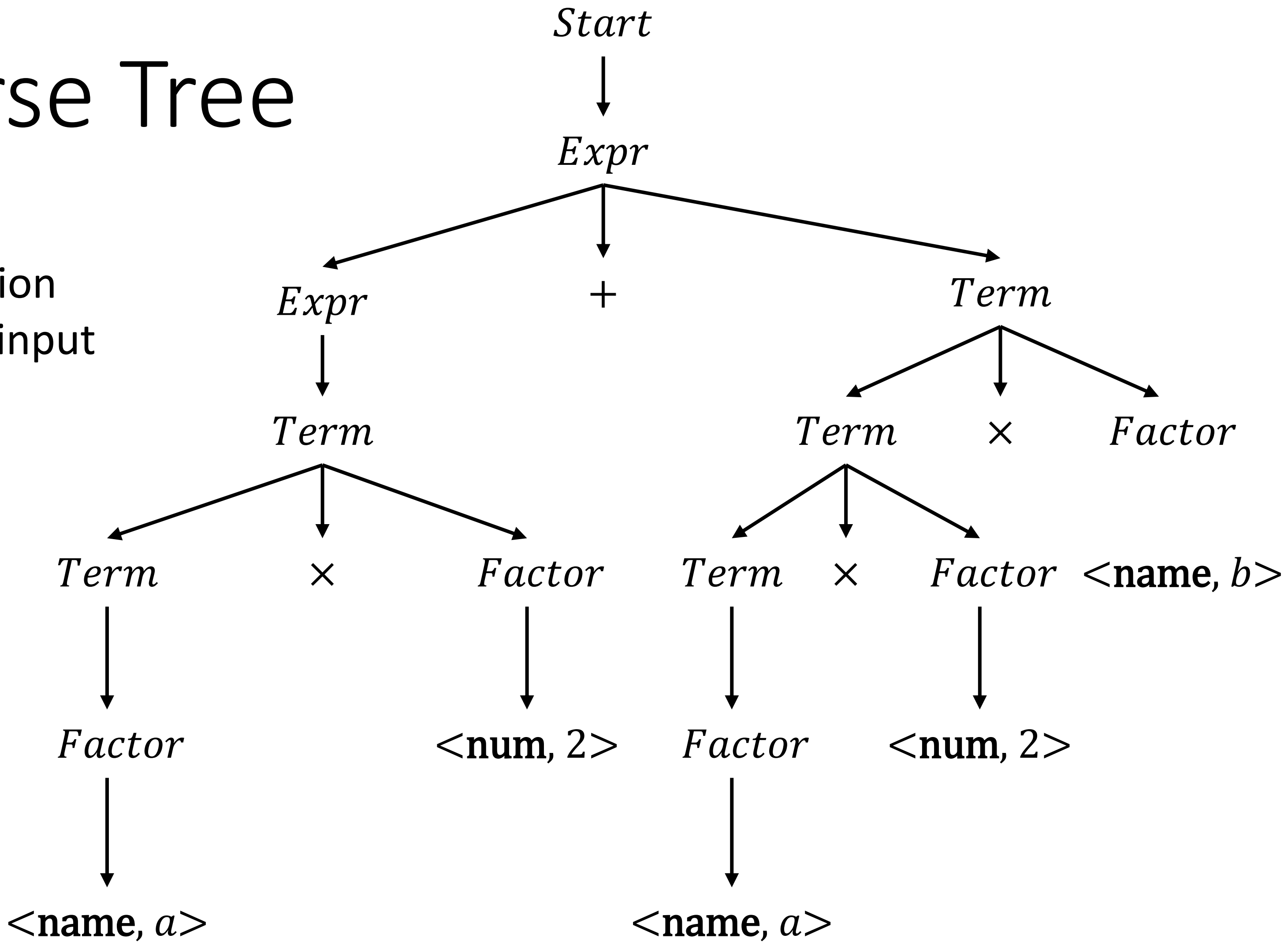
$\boldsymbol{a \times 2 + a \times 2 \times b}$

$$
\begin{aligned}
Start \rightarrow Expr &\rightarrow Expr + Term \\
&\rightarrow Term + Term \\
&\rightarrow Term \times Factor + Term \\
&\ldots
\end{aligned}
$$

Example of a Parse Tree

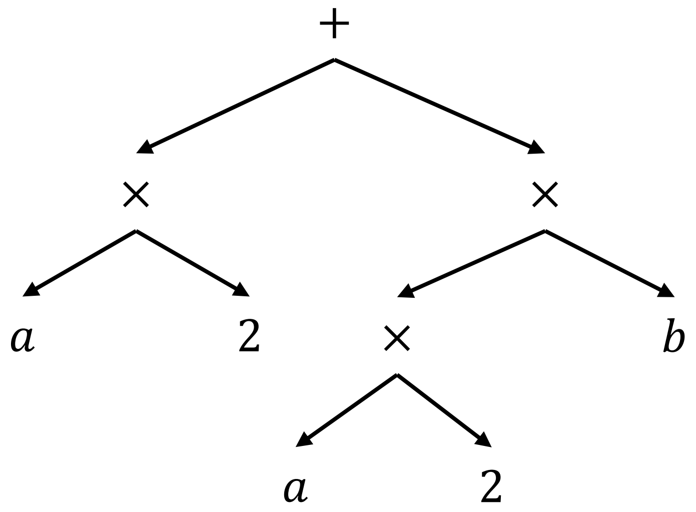
Parse tree is a graphical representation of a derivation corresponding to an input

Used in parsing and attribute grammar frameworks



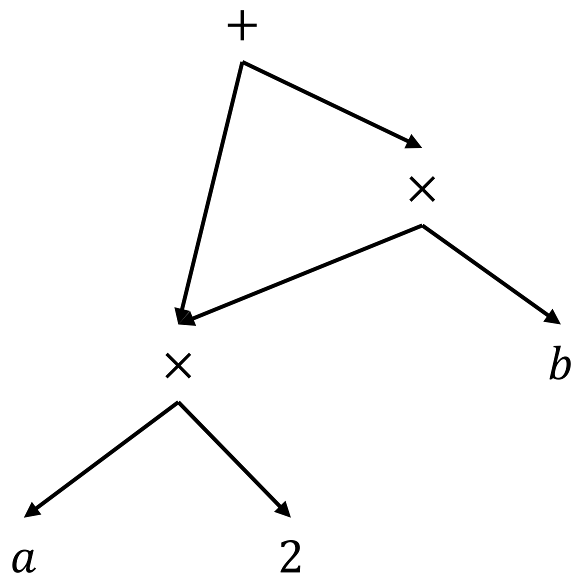
Abstract Syntax Tree (AST)

- An AST compresses the parse tree by omitting **many** internal nodes corresponding to nonterminal symbols
    - Leaf nodes represent operands
- AST is a near-source-level representation that retains precedence and meaning of the expression



Directed Acyclic Graph (DAG)

- DAGs compress ASTs and **can avoid duplicate** subtrees
  - Reduces memory footprint
  - Nodes in a DAG can have multiple parents



- DAGs encode hints for evaluating the expression
  - If a does not change between the two uses, then the compiler can generate code to evaluate $a \times 2$ only once

SDD to Construct Syntax Trees

Production	Semantic Rules
$E \rightarrow E_1 + T$	$E.node = \textbf{new}\ Node("+", E_1.node, T.node)$
$E \rightarrow E_1 - T$	$E.node = \textbf{new}\ Node("-", E_1.node, T.node)$
$E \rightarrow T$	$E.node = T.node$
$T \rightarrow (E)$	$T.node = E.node$
$T \rightarrow \textbf{id}$	$T.node = \textbf{new}\ Leaf(\textbf{id}, \textbf{id}.entry)$
$T \rightarrow \textbf{num}$	$T.node = \textbf{new}\ Leaf(\textbf{num}, \textbf{num}.val)$

Constructing a DAG using the SDD

$p_1 = Leaf(\textbf{id}, entry\text{–}a)$

$p_2 = Leaf(\textbf{id}, entry\text{–}a) = p_1$

$p_3 = Leaf(\textbf{id}, entry\text{–}b)$

$p_4 = Leaf(\textbf{id}, entry\text{–}c)$

$p_5 = Node(" - ", p_3, p_4)$

$p_6 = Node(" * ", p_1, p_5)$

$p_7 = Node(" + ", p_1, p_6)$

$p_8 = Leaf(\textbf{id}, entry\text{–}b) = p_3$

$p_9 = Leaf(\textbf{id}, entry\text{–}c) = p_4$

$p_{10} = Node(" - ", p_3, p_4) = p_5$

$p_{11} = Leaf(\textbf{id}, entry\text{–}d)$

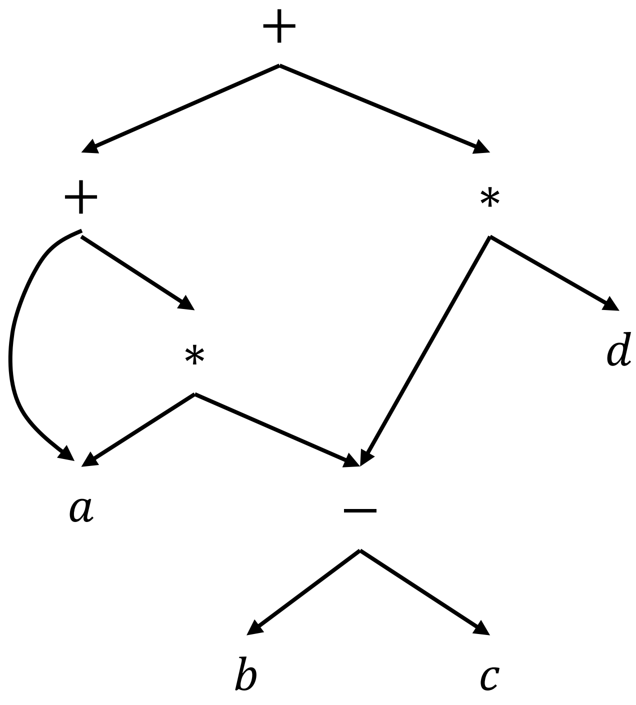
$p_{12} = Node(" * ", p_5, p_{11})$

$p_{13} = Node(" + ", p_7, p_{12})$

return existing node if it exits

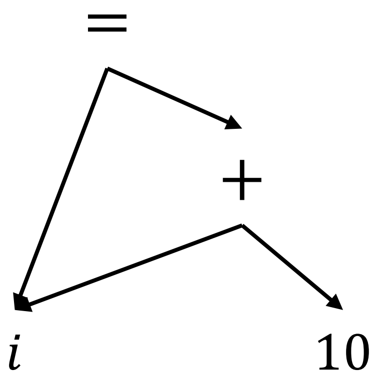
DAG for expression

$a \ + \ a * (b - c) \ + (b - c) * d$



Value-Number Method for DAGs

Often DAG nodes are stored in an array data structure



1	**id**		
2	**num**	10	
3	+	1	2
4	=	1	3

value number

symbol table entry for i

can also use pointers

signature

Sigature of an interior node is the triple $<\text{op}, l, r>$

Basic Block (BB)

- A BB is a maximal sequence of instructions with only one entry and one exit point
  - Entry is to the start of the BB, and exit is from the end of the BB
  - Only the start/leader instruction can be the target of a JUMP instruction
- There are no jumps in or out of the middle of a BB
- Identifying BBs
  1. The first instruction of the input code is a leader
  2. Instructions that are targets of conditional/unconditional jumps are leaders
  3. Instructions that immediately follow conditional/unconditional jumps are leaders

Identifying BBs

```
(1)  $i = 1$
(2)  $j = 1$
(3)  $t_1 = 10 \times i$
(4)  $t_2 = t_1 + j$
(5)  $t_3 = 8 \times t_2$
(6)  $t_4 = t_3 - 88$
(7)  $a[t_4] = 0.0$
(8)  $j = j + 1$
(9)  if $j \leq 10$ goto (3)
(10) $i = i + 1$
(11) if $i \leq 10$ goto (2)
(12) $i = 1$
(13) $t_5 = i - 1$
(14) $t_6 = 88 \times t_5$
(15) $a[t_6] = 1.0$
(16) $i = i + 1$
(17) if $i \leq 10$ goto (13)
```

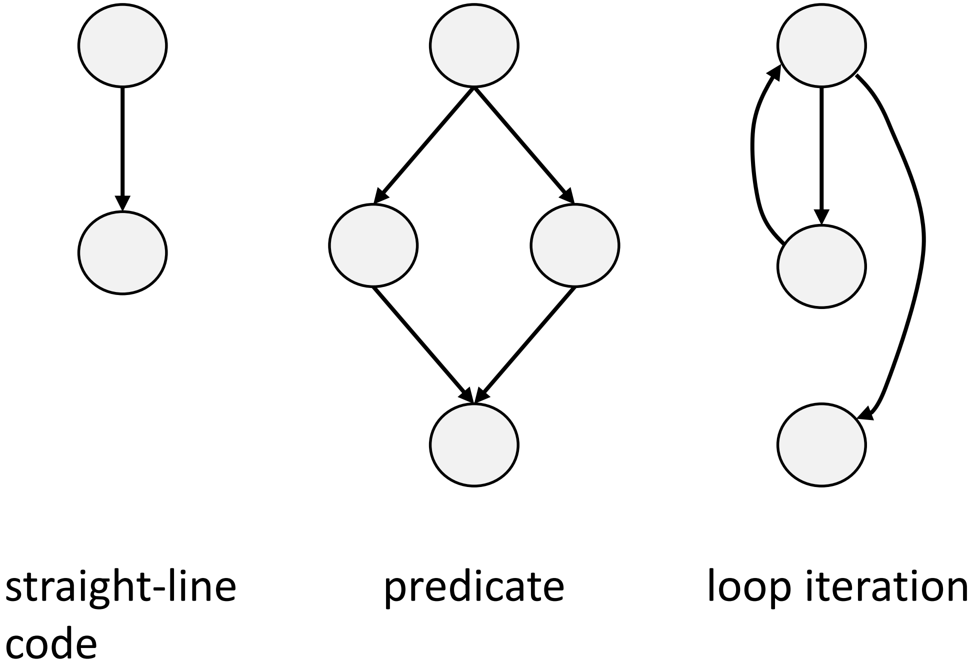
target

follows a conditional

- Statements `(1)`, `(2)`, `(3)`, `(10)`, `(12)`, and `(13)` are leaders
- There are six BBs: `(1)`, `(2)`, `(3)-(9)`, `(10)-(11)`, `(12)`, `(13)-(17)`

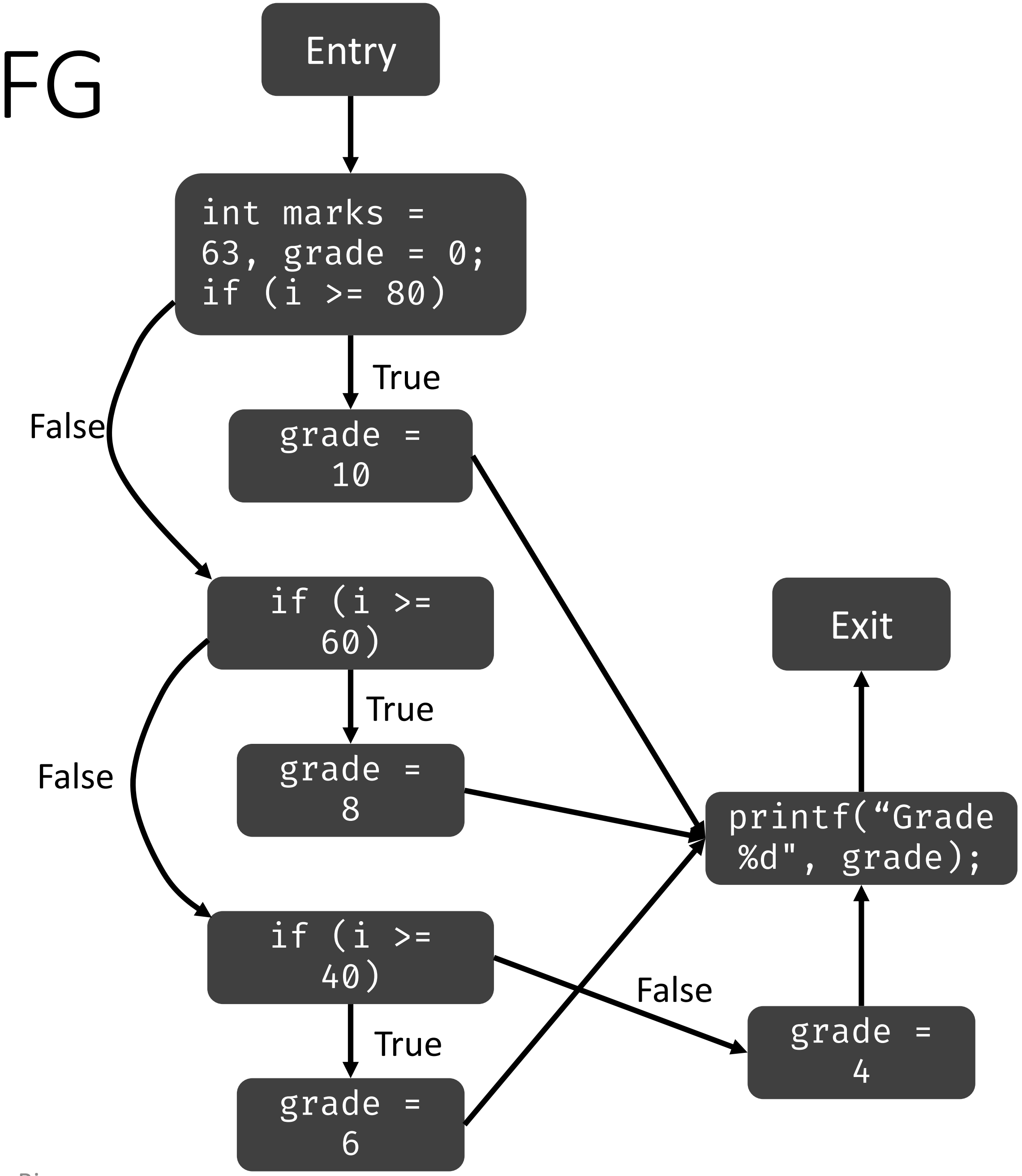
Control Flow Graph (CFG)

- Graphical representation of control flow during execution
  - Each node represents a statement or a BB
  - An entry and an exit node are often added to a CFG for a function
  - An edge represents possible transfer of control between nodes
- Used for compiler optimizations and static analysis (e.g., instruction scheduling and global register allocation)



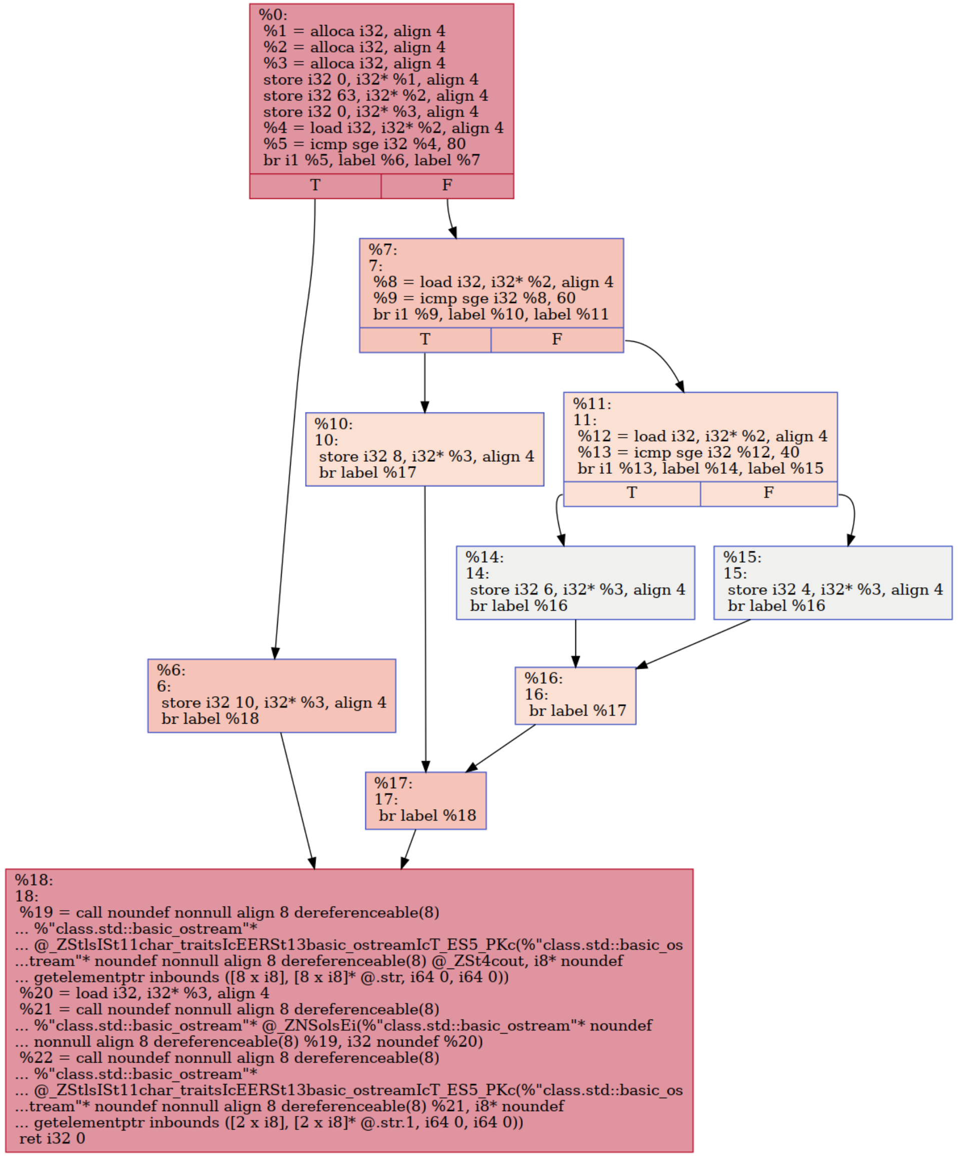
Example of BBs and a CFG

```
int main() {
    int marks = 63, grade = 0;
    if (marks >= 80)
      grade = 10;
    else if (marks >= 60)
      grade = 8;
    else if (marks >= 40)
      grade = 6;
    else
      grade = 4;
    printf("Grade %d", grade);
    return 0;
}
```



Example CFG Generated with LLVM

```
int main() {
    int marks = 63, grade = 0;
    if (marks >= 80)
      grade = 10;
    else if (marks >= 60)
      grade = 8;
    else if (marks >= 40)
      grade = 6;
    else
      grade = 4;
    printf(“Grade %d", grade);
    return 0;
}
```



```
%0:
 %1 = alloca i32, align 4
 %2 = alloca i32, align 4
 %3 = alloca i32, align 4
 store i32 0, i32* %1, align 4
 store i32 63, i32* %2, align 4
 store i32 0, i32* %3, align 4
 %4 = load i32, i32* %2, align 4
 %5 = icmp sge i32 %4, 80
 br i1 %5, label %6, label %7
```

```
%7:
7:
 %8 = load i32, i32* %2, align 4
 %9 = icmp sge i32 %8, 60
 br i1 %9, label %10, label %11
```

```
%10:
10:
 store i32 8, i32* %3, align 4
 br label %17
```

```
%11:
11:
 %12 = load i32, i32* %2, align 4
 %13 = icmp sge i32 %12, 40
 br i1 %13, label %14, label %15
```

```
%14:
14:
 store i32 6, i32* %3, align 4
 br label %16
```

```
%15:
15:
 store i32 4, i32* %3, align 4
 br label %16
```

```
%6:
6:
 store i32 10, i32* %3, align 4
 br label %18
```

```
%16:
16:
 br label %17
```

```
%17:
17:
 br label %18
```

```
%18:
18:
 %19 = call noundef nonnull align 8 dereferenceable(8)
... %"class.std::basic_ostream"*
... @_ZStlsISt11char_traitsIcEERSt13basic_ostreamIcT_ES5_PKc(%"class.std::basic_os
...tream"* noundef nonnull align 8 dereferenceable(8) @_ZSt4cout, i8* noundef
... getelementptr inbounds ([8 x i8], [8 x i8]* @.str, i64 0, i64 0))
 %20 = load i32, i32* %3, align 4
 %21 = call noundef nonnull align 8 dereferenceable(8)
... %"class.std::basic_ostream"* @_ZNSolsEi(%"class.std::basic_ostream"* noundef
... nonnull align 8 dereferenceable(8) %19, i32 noundef %20)
 %22 = call noundef nonnull align 8 dereferenceable(8)
... %"class.std::basic_ostream"*
... @_ZStlsISt11char_traitsIcEERSt13basic_ostreamIcT_ES5_PKc(%"class.std::basic_os
...tream"* noundef nonnull align 8 dereferenceable(8) %21, i8* noundef
... getelementptr inbounds ([2 x i8], [2 x i8]* @.str.1, i64 0, i64 0))
 ret i32 0
```

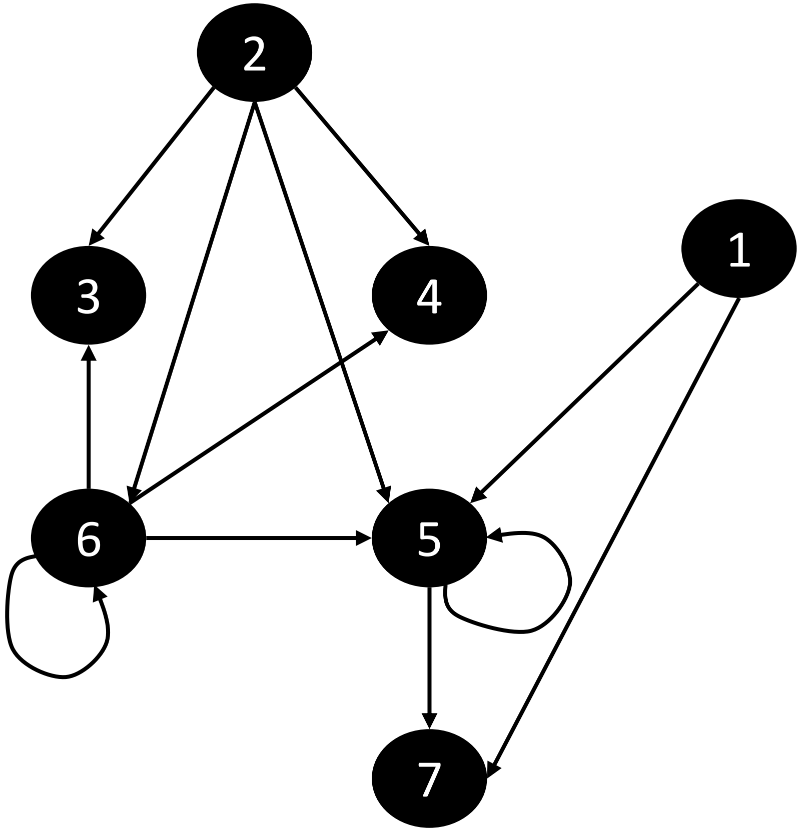
CFG for 'main' function

[Control Flow Graph generator for code in C++]

Data Dependence Graph (DDG)

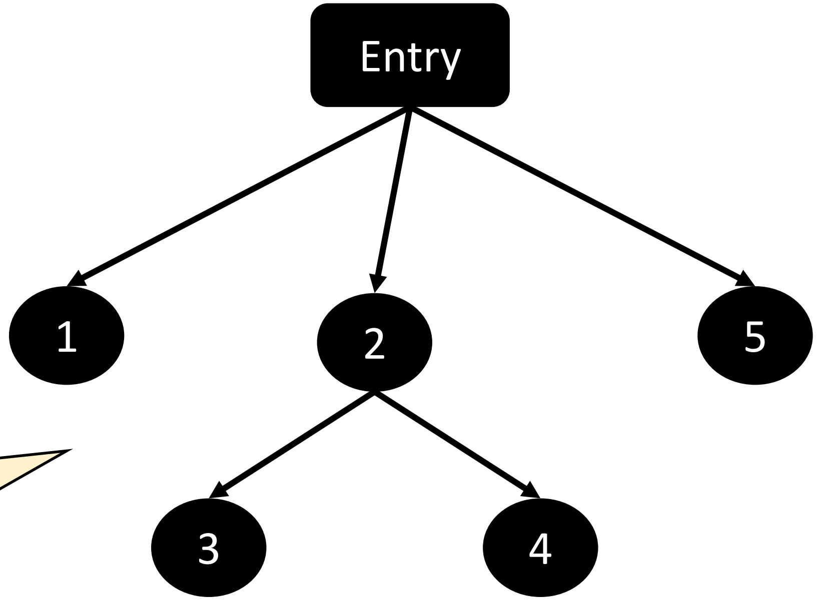
- A graph that models **flow of values** from definitions to uses in a code fragment
  - Nodes represent operations
  - DDG does not capture the control flow
  - E.g., used in instruction scheduling

```
1.   x = 0
2.   i = 1
3.   while (i < 100)
4.     if (a[i] > 0)
5.       x = x + a[i]
6.     i = i + 1
7.   print(x)
```



Control Dependence Graph (CDG)

```
1.   read i
2.   if i == 1
3.     print “true”
      else
4.     print “false”
5.   print “done”
```



- Vertices represent executable statements
- A dummy entry node represents the start of execution

- If statement X determines whether statement Y is executed, then Y is control dependent on X
- Statements that are guaranteed to execute are control dependent on entry to the program

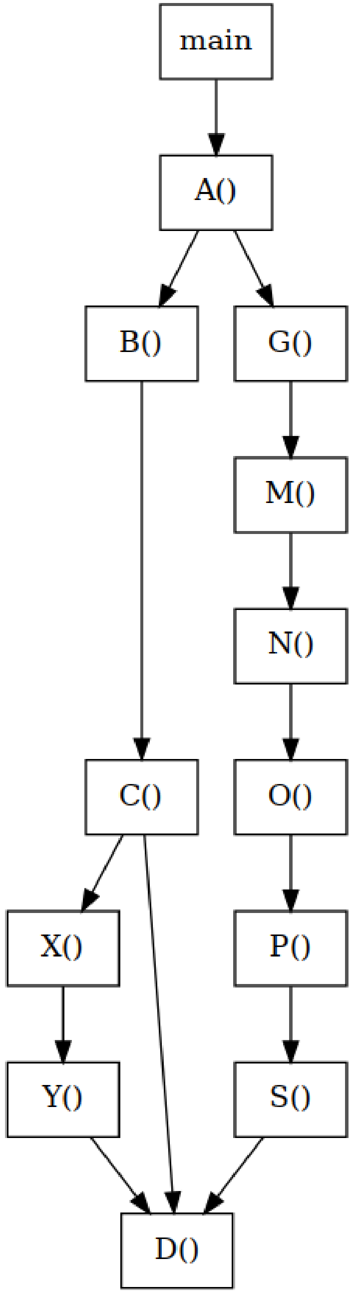
Call Graph

- A graph that represents the calling relationships among the procedures in a program
    - Represents run-time transfer of control among procedures
- The call graph has a node for each procedure and an edge for each call site
    - A function p calls another function q from three places
    - The call graph will have three (p, q) edges, one for each call site

Call Graph Example

```
static void D() { }
static void Y() { D(); }
static void X() { Y(); }
static void C() { D(); X(); }
static void B() { C(); }
static void S() { D(); }
static void P() { S(); }
static void O() { P(); }
static void N() { O(); }
static void M() { N(); }
static void G() { M(); }
static void A() { B(); G(); }
int main() { A(); }
```

[How to Generate a calling graph for C++ code]



Call graph: <stdin>

Linear IRs

Types of Linear IRs

- One-address code
  - Models behavior of stack machines and accumulator machines
  - Makes use of implicit names
  - Useful where storage efficiency is important (e.g., transmission over a network)
- Two-address code
  - The result of one address is often **redefined** with the result (destructive operation)
  - Not very popular currently
- Three-address code
  - Most operations take two operands and produce a result
  - Resembles a simple RISC machine

Stack Machine Code

- Assumes the presence of a stack with operands
- Operations take their operands from the stack and push the result onto the stack
    - Operands are addressed implicitly with the stack pointer
- JVM is a stack-based VM

$a - 2 \times b$ →

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

Three-Address Code (3AC)

- At most one operator in the RHS

$$x + y * z$$

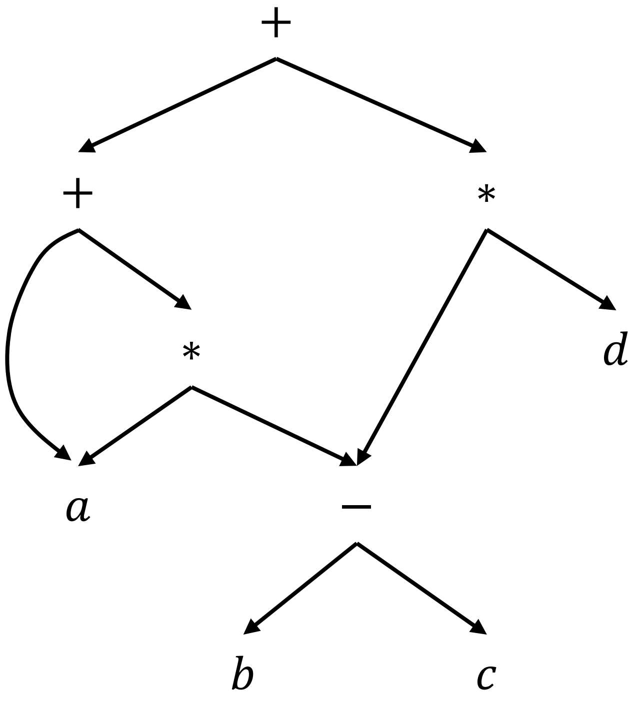
$$\begin{aligned} t_1 &= y * z \\ t_2 &= x + t_1 \end{aligned}$$

t_1 and t_2 are compiler-generated temporary variables

- 3AC is a linearized representation of a syntax tree where explicit names correspond to interior graph nodes
- Popularly used in code optimization and code generation
  - Use of names for intermediate values allows 3AC to be easily rearranged

DAG and Corresponding 3AC

DAG for expression
$a\ +\ a*(b-c)\ +(b-c)*d$



$\boldsymbol{t_1 = b - c}$
$t_2 = a * t_1$
$t_3 = a + t_2$
$t_4 = \boldsymbol{t_1} * d$
$t_5 = t_3 + t_4$

Forms of 3AC

- Composed of two concepts: addresses and instructions
- Addresses can be program variables, constants, and temporaries
  - Variables can be pointers to the symbol table entries
  - Distinct names for each temporary helps in optimization analyses

```
do
  i = i + 1;
while (a[i] < v);
```

Suppose each array element takes 8 units of space

Using symbolic labels	Using position numbers
L: $t_1 = i + 1$	100: $t_1 = i + 1$
$i = t_1$	101: $i = t_1$
$t_2 = i * 8$	102: $t_2 = i * 8$
$t_3 = a[t_2]$	103: $t_3 = a[t_2]$
if $t_3 < v$ goto L	104: if $t_3 < v$ goto 100

arbitrary starting point

Forms of 3AC

i. Assignments of the form $x = y \textbf{ op } z$, $x = \textbf{op } y$, or $x = y$

i. Unconditional jump goto L

ii. Conditional jumps of the form if x goto L, if x **relop** y goto L

iii. Procedure calls and returns of the form "param x", "call p, n", "$y =$ call p, n", and "return y“

v. Indexed copy instructions of the form $x = y[i]$ and $x[i] = y$

vi. Address and pointer assignments of the form $x = \&y$, $x = *y$, and $*x = y$

param x_1	$p(x_1, x_2, \dots, x_n)$
param x_2	
…	
param x_n	
call p, n	

Example Java Code and its 3AC

```
public class Example1 {
  int x;
  double y;
  Example1(int x, double y) {
    this.x = x;
    this.y = y;
  }
  public static void main(String[]
args) {
    /* Using argument args so that
we can compile with javac */
    Example1 a = new
Example1(2,3.14);
    System.out.println(a.x);
    System.out.println(a.y);
  }
}
```

```
Example1.ctor:
  beginfunc
  // get object reference, implicit
  // this pointer
  t1 = popparam
  // get offset for x
  t2 = symtable(Example1, x)
  t3 = popparam // get x’s value
  *(t1+t2) = t3
  // get offset for y
  t4 = symtable(Example1, y)
  t5 = popparam // get y’s value
  *(t1+t4) = t5
  return
  endfunc
```

Example Java Code and its 3AC

```
Example1.main:
  beginfunc
  // size of Example1() object in
  t1 = 12 // bytes
  param t1
  // manipulate stack pointer
  stackpointer +xxx
  call allocmem 1 // 1 param
  stackpointer -yyy
  // Save object reference
  t2 = popparam
  t3 = 2
  t4 = 3.14
  param t2 // object reference
  param t3
  param t4
  call Example1.ctor
  ... // other lines
```

```
  // get offset for x
  t5 = symtable(Example1, x)
  t6 = *(t2+t5) // read a.x
  param t6
  // manipulate stack pointer
  stackpointer +xxx
  call print 1
  stackpointer -yyy
  // get offset for y
  t7 = symtable(Example1, y)
  t8 = *(t2+t7) // read a.y
  param t8
  stackpointer +xxx
  call print 1
  stackpointer -yyy
  ...
  return
  endfunc
```

Implementing 3AC

- We can use data structures like quadruples, triples, and indirect triples
- Quadruple (or quad) have four fields op, arg_1, arg_2, and $result$
  - Instructions with unary operators will not use arg_2
  - Operators like param do not use both arg_2 and $result$
  - Conditional and unconditional jumps put the target label in $result$
- Triples have three fields op, arg_1, and arg_2, and refer to the result of an operation by its position

Implementing 3AC with Quadruples and Triples

Consider the expression
$a = b * -c + b * -c$

$t_1 = -\, c$
$t_2 = b * t_1$
$t_3 = -\, c$
$t_4 = b * t_3$
$t_5 = t_2 + t_4$
$a = t_5$

	op	arg_1	arg_2	$result$
0	$-$	c		t_1
1	$*$	b	t_1	t_2
2	$-$	c		t_3
3	$*$	b	t_3	t_4
4	$+$	t_2	t_4	t_5
5	$=$	t_5		a

pointer to symbol table entries

	op	arg_1	arg_2
0	$-$	c	
1	$*$	b	(0)
2	$-$	c	
3	$*$	b	(2)
4	$+$	(1)	(3)
5	$=$	a	(4)

refer by position

Representations in Triples

- How do you represent $x[i] = y$ and $x = y[i]$ with triples?

		op	$\boldsymbol{arg_1}$	$\boldsymbol{arg_2}$
$x[i] = y$	0	[ ]	x	i
	1	$=$	(0)	y

		op	$\boldsymbol{arg_1}$	$\boldsymbol{arg_2}$
$x = y[i]$	0	[ ]	y	i
	1	$=$	x	(0)

Quadruples vs Triples

Quadruples	**Triples**
• Requires many temporaries	• Requires fewer temporaries, temporaries are implicit
• Easy to move around instructions, does not impact instructions that use results	• Implicit references need to be updated if instructions are moved around

Reordering Instructions with Triples

Quadruples

Op	Arg$_1$	Arg$_2$	Result
$+$	t_2	t_3	t_1
$+$	t_5	t_6	t_4
$+$	t_2	t_8	t_7
$+$	t_8	t_5	t_9
…	…	…	…
$*$	…	t_1	…
$+$	…	t_1	…
$-$	…	t_1	…

Triples

	Op	Arg$_1$	Arg$_2$
0	$+$	t_2	t_3
1	$+$	t_5	t_6
2	$+$	t_2	t_8
3	$+$	t_8	t_5
…	…	…	…
	$*$	…	(0)
	$+$	…	(0)
	$-$	…	(0)

How to fix this?

Indirect Triples Representation of 3AC

Consider the expression
$a = b * -c + b * -c$

$t_1 = -\, c$
$t_2 = b * t_1$
$t_3 = -\, c$
$t_4 = b * t_3$
$t_5 = t_2 + t_4$
$a = t_5$

list of instructions

simplifies reordering instructions

(0)
(1)
(2)
(3)
(4)
(5)
…

	op	arg_1	arg_2
0	$-$	c	
1	$*$	b	(0)
2	$-$	c	
3	$*$	b	(2)
4	$+$	(1)	(3)
5	$=$	a	(4)

Importance of Naming

$$\begin{aligned}
&a \leftarrow b + c\\
&b \leftarrow a - d\\
&c \leftarrow b + c\\
&d \leftarrow a - d
\end{aligned}$$

- Value of a and c **may** be different
- Value of b and d **are** the same

$$\begin{aligned}
&\boldsymbol{t_1 \leftarrow b}\\
&\boldsymbol{t_2 \leftarrow c}\\
&t_3 \leftarrow t_1 + t_2\\
&a \leftarrow t_3\\
&\boldsymbol{t_4 \leftarrow d}\\
&t_1 \leftarrow t_3 - t_4\\
&\boldsymbol{b \leftarrow t_1}\\
&t_2 \leftarrow t_1 + t_2\\
&c \leftarrow t_2\\
&t_4 \leftarrow t_3 - t_4\\
&\boldsymbol{d \leftarrow t_4}
\end{aligned}$$

Assigns names to source variables, uses fewer names, but difficult to identify that b and d have the same value

$$\begin{aligned}
&t_1 \leftarrow b\\
&t_2 \leftarrow c\\
&t_3 \leftarrow t_1 + t_2\\
&a \leftarrow t_3\\
&t_4 \leftarrow d\\
&t_5 \leftarrow t_3 - t_4\\
&\boldsymbol{b \leftarrow t_5}\\
&t_6 \leftarrow t_5 + t_2\\
&c \leftarrow t_6\\
&t_5 \leftarrow t_3 - t_4\\
&\boldsymbol{d \leftarrow t_5}
\end{aligned}$$

Assigns names to destination values, uses more names, makes it explicit that b and d have the same value

Static Single Assignment (SSA) Form

- All assignments in SSA are to variables with different names
  - Every variable is defined before it is used
- SSA encodes information about both control and data flow

3AC	SSA
$p = a + b$	$p_1 = a + b$
$q = p - c$	$q_1 = p_1 - c$
$p = q * d$	$p_2 = q_1 * d$
$p = e - p$	$p_3 = e - p_2$
$q = p + q$	$q_2 = p_3 + q_1$

Static Single Assignment Book

Static Single Assignment (SSA) Form

How about variables defined in multiple control flow paths?

```
if ($flag$) {
    $x_1 = -1$
} else {
    $x_2 = 1$
}

$y = \cdots * a$
```

```
if ($flag$) {
    $x_1 = -1$
} else {
    $x_2 = 1$
}
$x_3 = \phi(x_1, x_2)$
$y = x_3 * a$
```

A ϕ function takes several names and merges them defining a new name

Example of a Loop in SSA Form

```
x = …
y = …
while (x < 100)
    x = x + 1
    y = y + x
```

```
       x0 = …
       y0 = …
       if (x0 >= 100) goto next
loop:  …
       …
       x2 = x1 + 1
       y2 = y1 + 1
       if (x2 < 100) goto loop
next:  x3 = …
       y3 = …
```

What to fill in?

What to fill in?

Example of a Loop in SSA Form

```
x = …
y = …
while (x < 100)
    x = x + 1
    y = y + x
```

```
       $x_0$ = …
       $y_0$ = …
       if ($x_0$ >= 100) goto next
loop:  $x_1$ = $\phi$($x_0$, $x_2$)
       $y_1$ = $\phi$($y_0$, $y_2$)
       $x_2$ = $x_1$ + 1
       $y_2$ = $y_1$ + $x_2$
       if ($x_2$ < 100) goto loop
next:  $x_3$ = $\phi$($x_0$, $x_2$)
       $y_3$ = $\phi$($y_0$, $y_2$)
```

Importance of SSA Form

- A program is in SSA form if (i) each definition has a new name, and (ii) each use refers to a single definition
- SSA helps code optimizations since no names are killed
  - Makes use-def chains explicit, otherwise Reaching Definitions analysis would be required in absence of SSA

```
y = 1
y = 2
x = y
```

$y_1 = 1$
$y_2 = 2$
$x = y_2$

- SSA form has had a huge impact on compiler design
  - Simplifies and improves many optimizations (e.g., constant propagation, dead-code elimination, and register allocation)
- Most modern production compilers use SSA form (e.g., GCC, LLVM, Hotspot)

Static single-assignment form

Other Linear IRs

- Fully-typed 3AC IR
- Scalars are in SSA form
- Supports SIMD/vector operations

Java Bytecode

```
0:    iconst_2
1:    istore_1
2:    iload_1
3:    sipush  1000
6:    if_icmpge       44
9:    iconst_2
10:   istore_2
11:   iload_2
12:   iload_1
13:   if_icmpge       31
16:   iload_1
17:   iload_2
```

LLVM IR

```
define i32 @f(i32 %a, i32 %b) {
; <label>:0
    %1 = mul i32 2, %b
    %2 = add i32 %a, %1
    ret i32 %2
}
define i32 @main() {
; <label>:0
    %1 = call i32 @f(i32 10, i32 20)
    ret i32 %1
}
```

What are the differences between LLVM and java bytecode?

Symbol Table

Need for a Symbol Table

- Compilers generate meta-information during translation
    - For example, type of a variable, lexeme, line number for the declaration, and scope
- Information is saved in a **data structure** called symbol table
    - Alternate is to maintain meta-information in AST nodes and recompute the information when needed by AST traversal
        - Repeated AST traversals can be expensive
    - Saves all declarations, helps check if a variable is declared, helps with type checking, and determining scope of a variable
- Symbol table needs to be updated whenever
    i. A new name is discovered
    ii. New information about an existing name is discovered

Desired Properties of Symbol Table

- Symbol table is accessed across several compiler phases
- Interface
  - `lookup(name)` – Return the data stored against `name`
  - `insert(name, record)` – Add information about the variable `name`

- Efficiency is paramount
  - Unordered lists vs Ordered lists vs Hash tables
  - Should be efficient to grow/shrink the symbol table since number of variables may vary across programs

Symbol Table Entries

- Each entry corresponds to a declaration of a **name**
- Entry format need not be uniform because information depends upon the type of the name
- Symbol table information is filled in at various times
  - Keywords can be entered initially
  - Identifier lexemes are added by the scanner
  - Attributes are filled in as information becomes available

Nested Scopes

```
static int w = 1; /* level 0 */
int x = 0;
void example(int a, int b) { /* level 1 */
  int c = 1;
  {
    int b = 2, z = 3; /* level 2a */
    …
  }
  {
    int a = 4, x = 5; /* level 2b */
    …
    {
      int c = 6, x = 7; /* level 3 */
      b = a + b + c + w;
    } } }

int main() { example(10, 20); }
```

Level	Names
0	`w, x, example`
1	`a, b, c`
2a	`b, z`
2b	`a, x`
3	`c, x`

names declared in each scope

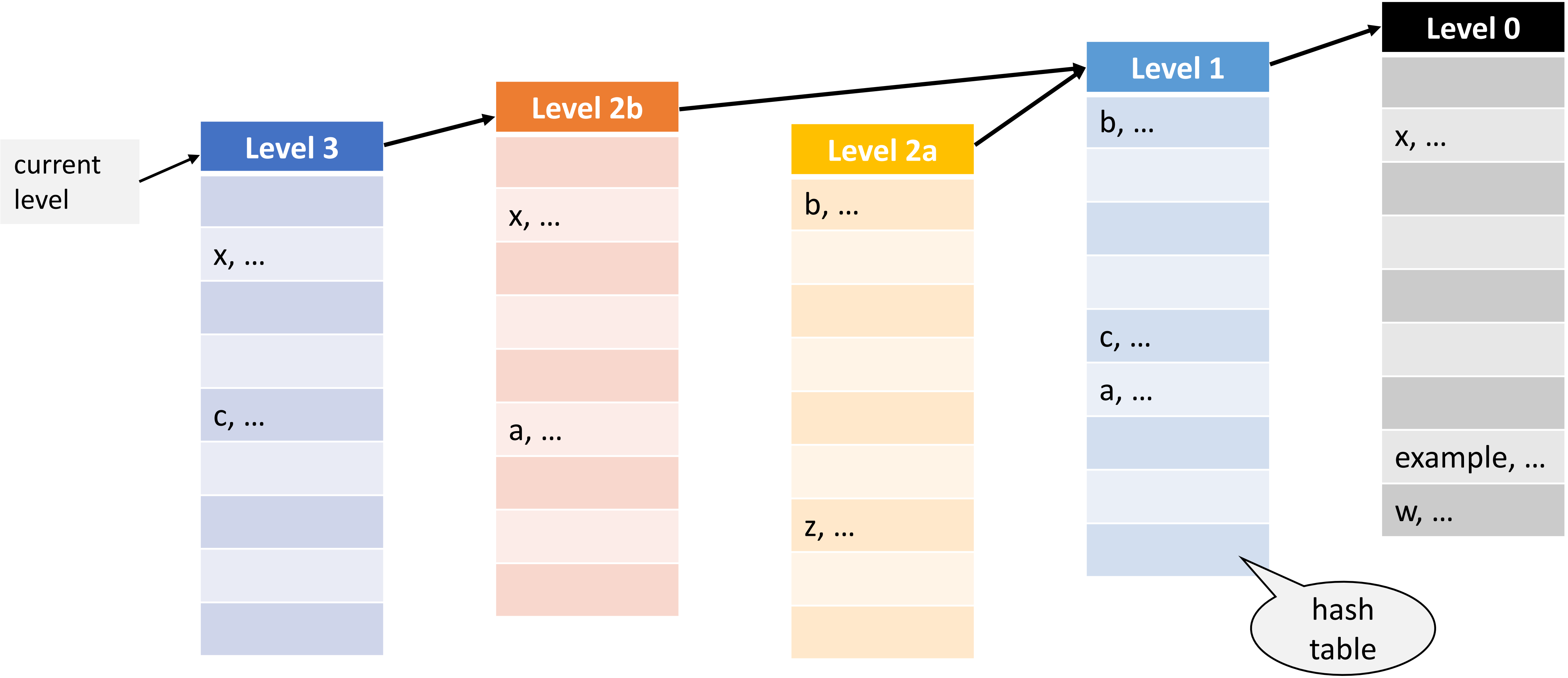
$$b_1 = a_{2b} + b_1 + c_3 + w_0$$

Dealing with Nested Scopes

- Name resolution – resolve a name reference to its specific declaration

- Possible idea
  - Create a new symbol table with each new lexical scope
  - `insert()` operates on the current symbol table
  - `lookup()` checks symbol tables in order
    - Start with current scope and go up the hierarchy
    - Report an error only if `lookup()` fails across all levels
  - Structure is also called a “sheaf of tables”

Symbol Table Structure for Nested Scope



Maintaining Namespace of Structure Fields

- Separate tables
  - Maintain a separate table for each structure
- Selector table
  - Maintain a separate table for structure fields
  - Need to maintain fully-qualified field names
- Unified table
  - Club all information in a single global symbol table
  - Maintain fully-qualified field names

Name Resolution for Object-Oriented Languages

- Resolution rules are slightly more involved
  - Scoped symbol tables for a method, a class, and other classes in the package and package-level variables

- Consider resolving a name `foo` in a method `m()` in class `Klass`
  - First check the lexically scoped symbol table corresponding to `m()`
  - If not found, then search the symbol table according to the inheritance hierarchy, starting from `Klass`
  - If not found, then search the global symbol table for that name

Name Mangling in C++

- C++ linker supports a global namespace
  - Compiler has to pass more information about names to the linker for name resolution
- **Name mangling** facilitates function overloading and visibility within different scopes by constructing a unique string for every source-language name
- Mangled names in C++ start with _Z, followed by attributes that encode information about the name

`int f() {}`	`_Z1fv`
`int f(int) {}`	`_Z1fi`
`void g() {}`	`_Z1gv`

`namespace a {`
`  int bar;`
`}`
	`_ZN1a3barE`

```
$ c++filt _ZN5cs3355Outer5InnerC1ERKi
cs335::Outer::Inner::Inner(int const&)
```

Itanium C++ ABI   The Secret Life of C++: Symbol Mangling   GCC CPP Mangling Documentation

Practical Concern: Linking C and C++ Code

add.c

```c
int add(int a, int b) {
  return a + b;
}
```

sub.c

```c
int sub(int a, int b) {
  return a - b;
}
```

demo.h

```c
#ifndef __LIBRARY_H__
#define __LIBRARY_H__
/*#ifdef __cplusplus
  extern "C" {
#endif */
int add(int a, int b);
int sub(int a, int b);
/*#ifdef __cplusplus
  }
#endif */
#endif // __LIBRARY_H__
```

main.cpp

```cpp
#include "demo.h"
#include <cstdlib>
#include <iostream>
using std::cout;
int main() {
  int a = 0, b = 1, c = 2;
  cout << add(a, b) << "\t"
       << sub(c, b) << "\n";
  return EXIT_SUCCESS;
}
```

```
gcc -fPIC -c -o add.o add.c
gcc -fPIC -c -o sub.o sub.c
# Creating a static library
ar rcs libdemo.a add.o sub.o

g++ -c -I. -o main.o main.cpp
g++ main.o -L. -l:libdemo.a –o main
```

```
❯ g++ main.o -L. -l:libdemo.a -o main
/usr/bin/ld: main.o: in function `main’:
main.cpp:(.text+0x2d): undefined reference to `add(int, int)’
/usr/bin/ld: main.cpp:(.text+0x65): undefined reference to `sub(int, int)’
collect2: error: ld returned 1 exit status
```

```
❯ readelf -s main.o
Num:    Value             Size Type    Bind   Vis      Ndx Name
 8: 0000000000000000   196 FUNC    GLOBAL DEFAULT    1 main
 9: 0000000000000000     0 NOTYPE  GLOBAL DEFAULT  UND _Z3addii
13: 0000000000000000     0 NOTYPE  GLOBAL DEFAULT  UND _Z3subii
```

Generating IR

Translate expressions, array references, declarations, Boolean expressions, and control flow statements

Intermediate Code Generation

- Code generation needs to map source language abstractions to target machine abstractions

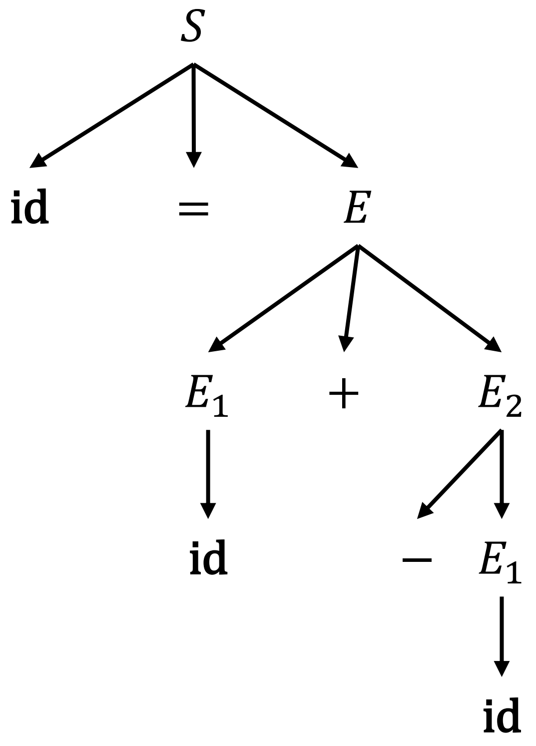
- Example of language-level abstractions
  - Identifiers, operators, expressions, statements, conditionals, iterations, functions (user-defined or libraries)
- Example of target-level abstractions
  - Memory locations, registers, stack, opcodes, addressing modes, system libraries, interface with the operating systems

Examples of 3AC Generation

$a = b + -c$

$\Rightarrow$

$t_1 = -c$
$t_2 = b + t_1$
$a = t_2$



$a = b * -c + b * -c$

$\Rightarrow$

$t_1 = -c$
$t_2 = b * t_1$
$t_3 = -c$
$t_4 = b * t_3$
$t_5 = t_2 + t_4$
$a = t_5$

SDD for Translating Expressions to 3AC

Production
$S \rightarrow \textbf{id} = E$
$E \rightarrow E_1 + E_2$
$E \rightarrow E_1 * E_2$
$E \rightarrow -E_1$
$E \rightarrow (E_1)$
$E \rightarrow \textbf{id}$

- $E.addr$ – Holds the value of expression E
  - Can be a name, a constant, or a temporary
- $E.code$ – Sequence of 3AC that evaluates E
- $S.code$ – Stores the 3AC for statement S
- gen – Helper function to create a 3AC instruction

SDD for Translating Expressions to 3AC

Production	Semantic Rules
$S \rightarrow \textbf{id} = E$	$S.code = E.code \mid\mid gen(symtop.get(\textbf{id}.lexeme)\ \text{"="}\ E.addr)$
$E \rightarrow E_1 + E_2$	$E.addr = \text{new}\ Temp()$ $E.code = E_1.code \mid\mid E_2.code \mid\mid gen(E.addr\ \text{"="}\ E_1.addr\ \text{" + "}\ E_2.addr)$
$E \rightarrow E_1 * E_2$	$E.addr = \text{new}\ Temp()$ $E.code = E_1.code \mid\mid E_2.code \mid\mid gen(E.addr\ \text{"="}\ E_1.addr\ \text{" * "}\ E_2.addr)$
$E \rightarrow -E_1$	$E.addr = \text{new}\ Temp()$ $E.code = E_1.code \mid\mid gen(E.addr\ \text{"="}\ \text{" - "}E_1.addr)$
$E \rightarrow (\ E_1\ )$	$E.addr = E_1.addr$ $E.code = E_1.code$
$E \rightarrow \textbf{id}$	$E.addr = symtop.get(\textbf{id}.lexeme)$ $E.code = \text{""}$

$symtop$ points to the current symbol table

Incremental Translation

Production	Semantic Rules
$S \rightarrow \textbf{id} = E$	$gen(symtop.get(\textbf{id}.lexeme)\ "="\ E.addr)$
$E \rightarrow E_1 + E_2$	$E.addr = \text{new } Temp()$ $gen(E.addr\ "="\ E_1.addr\ " + "\ E_2.addr)$
$E \rightarrow E_1 * E_2$	$E.addr = \text{new } Temp()$ $gen(E.addr\ "="\ E_1.addr\ " * "\ E_2.addr)$
$E \rightarrow -E_1$	$E.addr = \text{new } Temp()$ $gen(E.addr\ "="\ \ " - "E_1.addr)$
$E \rightarrow (\ E_1\ )$	$E.addr = E_1.addr$
$E \rightarrow \textbf{id}$	$E.addr = symtop.get(\textbf{id}.lexeme)$

gen creates a 3AC instruction and appends it to an instruction stream

Translating Array References

- Grammar can generate expressions like $c + a[i][j]$
- Challenge is in computing addresses of array references like $A[i][j]$
- Suppose w_r and w_e are the widths of a row and an element of an array respectively
- Address of array reference $A[i][j]$ is $base + i \times w_r + j \times w_e$

Production
$S \rightarrow$ **id** $= E$
$S \rightarrow L = E$
$E \rightarrow E_1 + E_2$
$E \rightarrow$ **id**
$E \rightarrow L$
$L \rightarrow$ **id** $[\ E\ ]$
$L \rightarrow L_1\ [\ E\ ]$

Translating Array References

- L has three synthesized attributes
  - $addr$ is used for computing the offset for array reference
  - $array$ points to the symbol table entry for the array name
    - $L.array.base$ gives the base address of the array
  - $type$ is the type of the array generated by L
    - For array of type t, $t.width$ is the width of type t and $t.elem$ gives the element type

Production
$S \rightarrow$ **id** $= E$
$S \rightarrow L = E$
$E \rightarrow E_1 + E_2$
$E \rightarrow$ **id**
$E \rightarrow L$
$L \rightarrow$ **id** $[\ E\ ]$
$L \rightarrow L_1\ [\ E\ ]$

Translating Array References

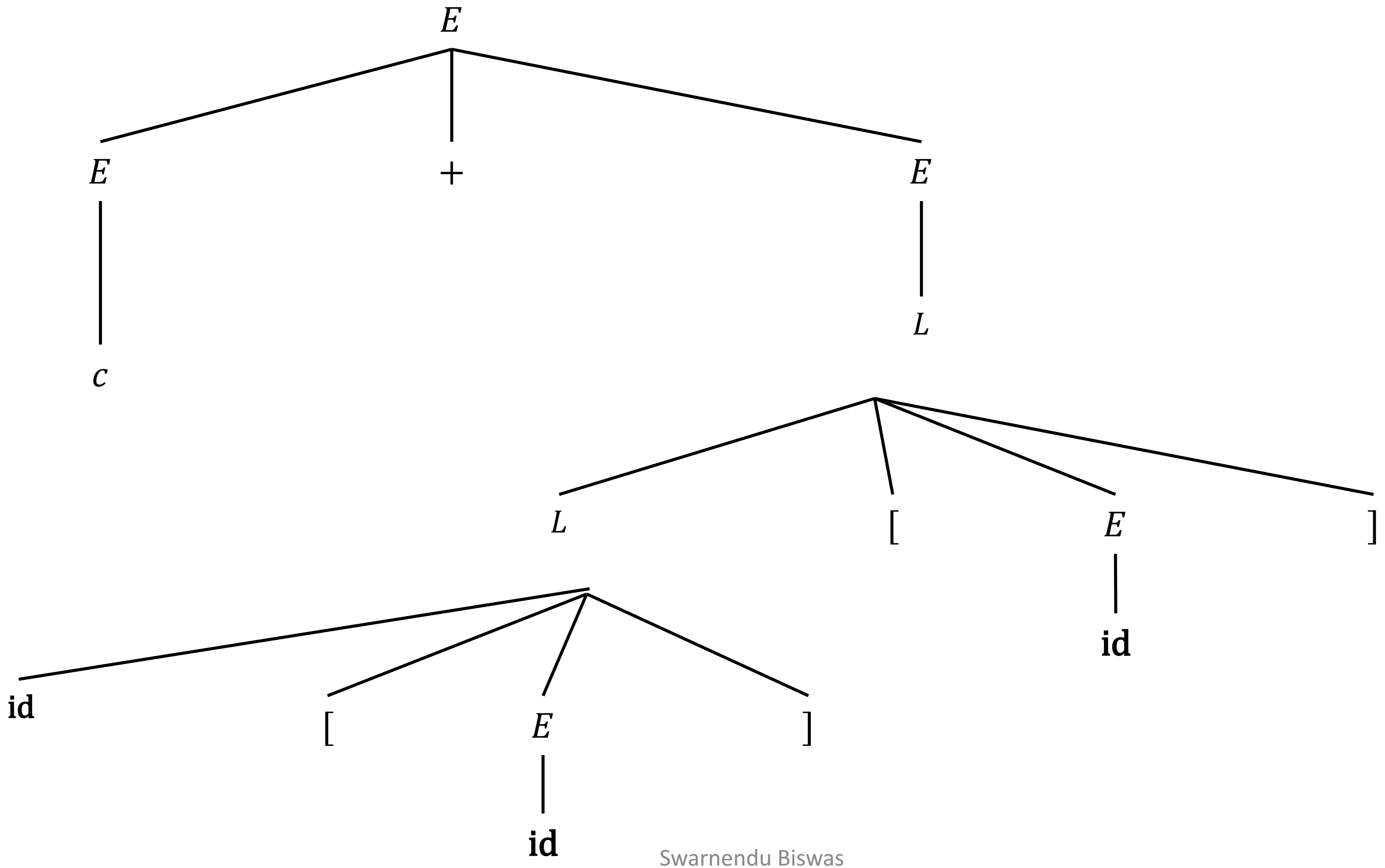
Production	Semantic Rules
$S \rightarrow \textbf{id} = E$	$gen(symtop.get(\textbf{id}.lexeme)\ "="\ E.addr)$
$S \rightarrow L = E$	$gen(L.array.base\ "["\ L.addr\ "]"\ " = "\ E.addr)$
$E \rightarrow E_1 + E_2$	$E.addr = \text{new}\ Temp()$ $gen(E.addr\ "="\ E_1.addr\ "+"\ E_2.addr)$
$E \rightarrow \textbf{id}$	$E.addr = symtop.get(\textbf{id}.lexeme)$
$E \rightarrow L$	$E.addr = \text{new}\ Temp()$ $gen(E.addr\ " = "\ L.array.base\ "["\ L.addr\ "]")$
$L \rightarrow \textbf{id}\ [\ E\ ]$	$L.array = symtop.get(\textbf{id}.lexeme);\ L.type = L.array.type.elem;$ $L.addr = \text{new}\ Temp();\ gen(L.addr\ "="\ E.addr\ "*"\ L.type.width)$
$L \rightarrow L_1\ [\ E\ ]$	$L.array = L_1.array;\ L.type = L_1.type.elem;\ t = \text{new}\ Temp();$ $gen(t\ "="\ E.addr\ "*"\ L.type.width)$ $gen(L.addr\ "="\ L_1.addr\ "+"\ t)$

Translating Expression $c + a[i][j]$

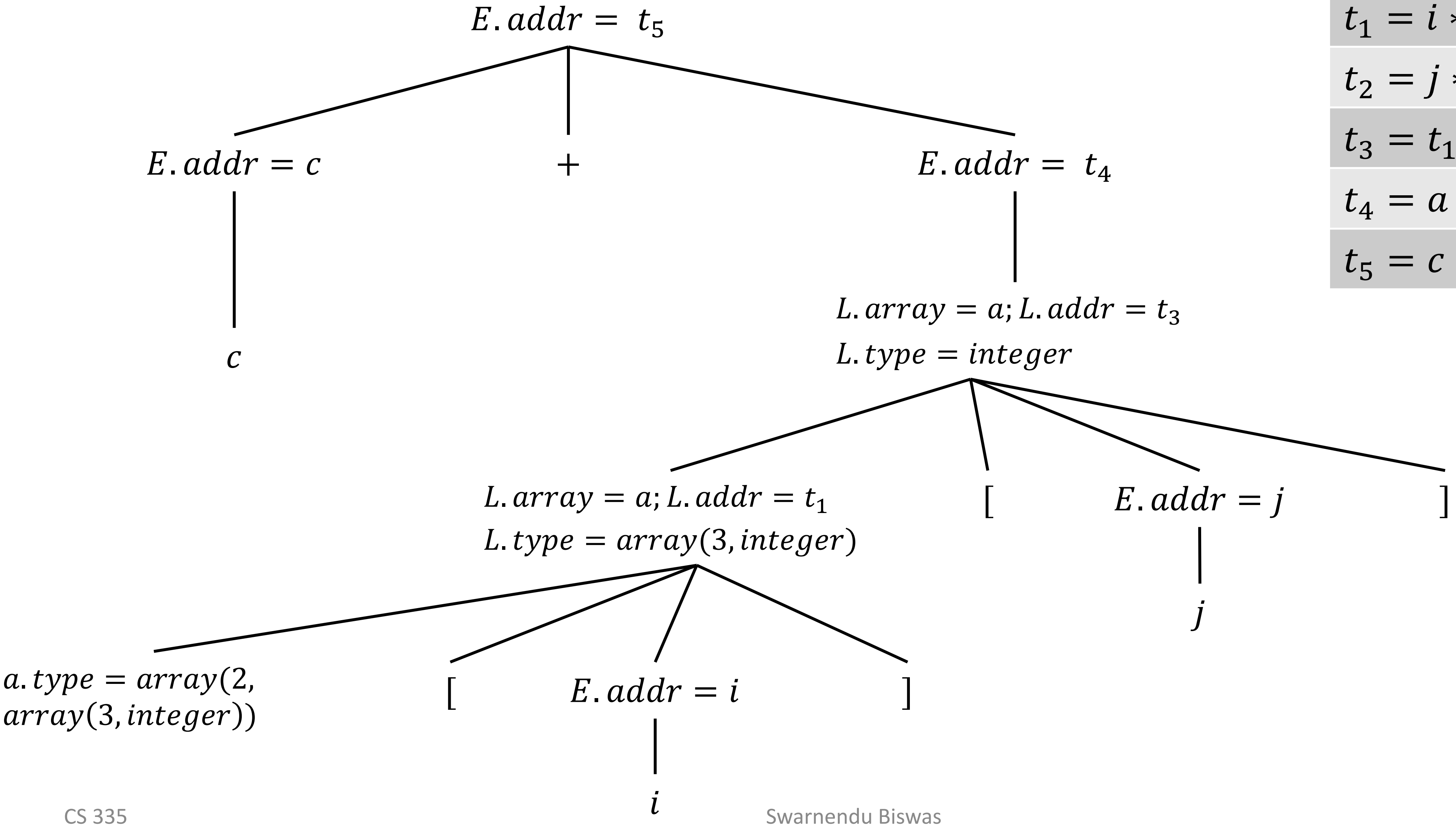
- Let a denote a 2×3 array of integers
  - Type of a is integer
  - Type of $a[i]$ is $array(3, integer)$, and $w_r = 12$ B
  - Type of $a[i][j]$ is $array(2, array(3, integer))$

3AC for $c + a[i][j]$
$t_1 = i * 12$
$t_2 = j * 4$
$t_3 = t_1 + t_2$
$t_4 = a\ [\ t_3\ ]$
$t_5 = c + t_4$

Parse Tree for $c + a[i][j]$



Annotated Parse Tree for $c + a[i][j]$



$E.addr = t_5$

$E.addr = c$

$+$

$E.addr = t_4$

c

$L.array = a; L.addr = t_3$

$L.type = integer$

$L.array = a; L.addr = t_1$

$L.type = array(3, integer)$

$[$

$E.addr = j$

$]$

j

$a.type = array(2, array(3, integer))$

$[$

$E.addr = i$

$]$

i

3AC for $c + a[i][j]$
$t_1 = i * 12$
$t_2 = j * 4$
$t_3 = t_1 + t_2$
$t_4 = a\ [\ t_3\ ]$
$t_5 = c + t_4$

Declarations

Goal: Layout storage for local variables as declarations are processed

$P \rightarrow D$

$D \rightarrow D; D$

$D \rightarrow$ **id**: T

$T \rightarrow$ **int**

$T \rightarrow$ **real**

$T \rightarrow$ array [num] of T_1

$T \rightarrow \uparrow T_1$

pointer type

For each name, create symbol table entry with information like type and relative address

The relative address is an offset from the base of the static data area or the field for local data in an activation record

Declarations

$P \rightarrow \{ offset = 0; \} D$	
$D \rightarrow D; D$	
$D \rightarrow$ **id**$: T$	$\{ enter(\text{id}.name, T.type, offset);\ \ offset = offset + T.width; \}$
$T \rightarrow$ **int**	$\{ T.type\ =\ \text{integer};\ T.width = 4; \}$
$T \rightarrow$ **real**	$\{ T.type\ =\ \text{real};\ T.width = 8;\ \}$
$T \rightarrow$ array [num] of T_1	$\{ T.type = array(num.val, T_1.type);\ T.width = num.val \times T_1.width;\ \}$
$T \rightarrow \uparrow T_1$	$\{ T.type = pointer(T_1.type);\ T.width = 4;\ \}$

- Global variable $offset$ keeps track of the next available relative address
- Function $enter$ creates a symbol table entry for $name$

Nested Procedures

- Invisible outside of its immediately enclosing procedure
- Can access local data of its enclosing procedures
- Used in languages like Pascal and functional languages like Haskell

```
function E(x: real): real;
    function F(y: real): real;
    begin
        F := x + y
    end;
begin
    E := F(3) + F(4)
end;
```

Nested Functions in GNU C

```
double foo(double a, double b) {
  double square(double z) { return z*z; }
  return square(a) + square(b);
}
```

```
void bar(int *array, int offset, int size) {
  int access(int *array, int index) { return array[index+offset]; }
  /* … */
  for (int i=0; i < size; i++)
    access(array, i);
  /* … */
}
```

---

https://gcc.gnu.org/onlinedocs/gcc/Nested-Functions.html

Keeping Track of Scope Information

$$P \rightarrow D$$
$$D \rightarrow D; D \mid \mathbf{id}: T \mid \mathbf{proc\ id}; D; S$$

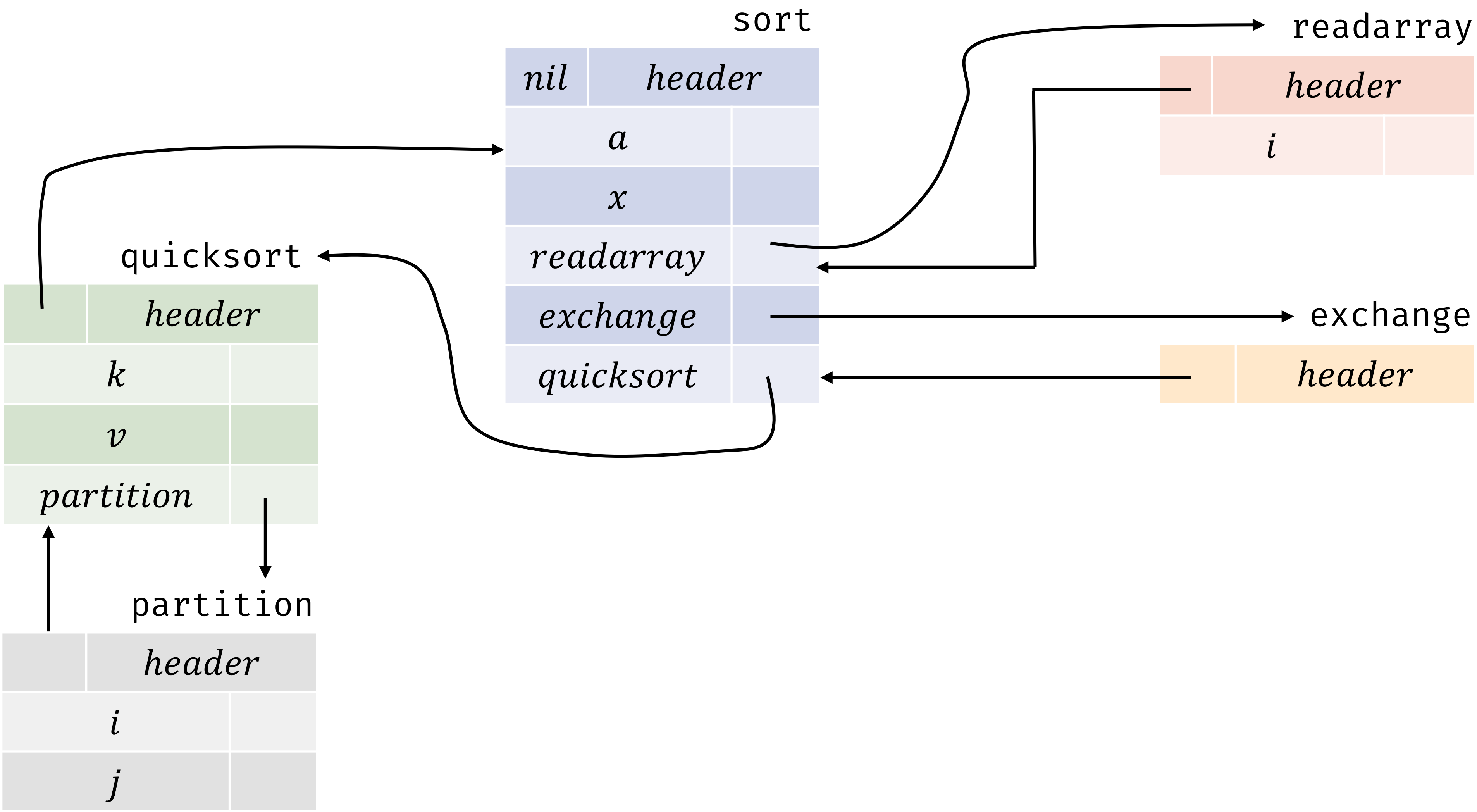
- A simple idea
  - When a nested procedure is seen, processing of declarations in enclosing procedure is temporarily suspended
  - A new symbol table is created for every procedure declaration $D \rightarrow \mathbf{proc\ id;}\ D_1 S$
    - Entries for D_1 are made in the new symbol table
  - Name represented by $\mathbf{id}$ is local to the enclosing procedure

Example Program with Nested Procedures

```
program sort;
  var a : array[1..n] of integer;
      x : integer;

  procedure readarray;
    var i : integer;
    ……

  procedure exchange(i,j : integers);
  ……
```

```
  procedure quicksort(m,n : integer);
    var k,v : integer;
    function partition(x,y : integer): integer;
      var i,j: integer;
      ……
    ……

  begin
    a[1-10]:= 0;
    readarray;
    quicksort(1,n);
  end
```

Symbol Tables for Nested Procedures



Helper Functions to Manipulate Symbol Table

- $mktable(previous)$
  - Create a new symbol table and returns a pointer to the new table
- $enter(table, name, type, offset)$
  - Creates a new entry for name $name$ in the symbol table pointed by $table$
- $addwidth(table, width)$
  - Records the cumulative width of all the entries in $table$ in the header
- $enterproc(table, name, newtable)$
  - Creates a new entry for procedure $name$ in $table$
  - Argument $newtable$ points to the symbol table for procedure $name$

Constructing Nested Symbol Tables

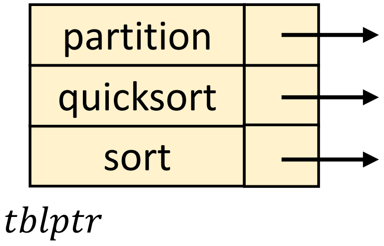
$$P \rightarrow \{\, t = mktable(nil);\ push(t, tblptr);\ push(0, offset);\, \}$$
$$\qquad D\ \{\, addwidth\big(top(tblptr), top(offset)\big);\ pop(tblptr);\ pop(offset);\, \}$$

$$D \rightarrow D_1\ D_2$$

$$D \rightarrow \textbf{proc id};\ \{\, t = mktable\big(top(tblptr)\big);\ push(t, tblptr);\ push(0, offset);\, \}$$
$$\qquad D_1; S \quad \{\, t = top(tblptr);\ addwidth\big(t, top(offset)\big);\ pop(tblptr);\ pop(offset);$$
$$\qquad\qquad enterproc(top(tblptr), \text{id}.name, t);\, \}$$

$$D \rightarrow \textbf{id} : T \quad \{\, enter\big(top(tblptr), \text{id}.name, T.type, top(offset)\big);$$
$$\qquad\qquad top(offset) = top(offset) + T.width\, \}$$

- $tblptr$ is a stack to hold pointers to symbol tables of enclosing procedures
- $offset$ is a stack to maintain relative offsets



Boolean Expressions

- Used to compute logical values (e.g., `x=true`) and influence flow of control (e.g., `if E then S`)

$$
\begin{aligned}
B &\rightarrow B \mid\mid B \\
&\rightarrow B \;\&\&\; B \\
&\rightarrow \,!\, B \\
&\rightarrow (\, B \,) \\
&\rightarrow E \; relop \; E \\
&\rightarrow \textbf{true} \\
&\rightarrow \textbf{false}
\end{aligned}
$$

$$relop \rightarrow < \,|\, \leq \,|\, = \,|\, \neq \,|\, > \,|\, \geq$$

Represent value of Boolean expressions:

i. Evaluate similar to arithmetic expressions
   - True can be 1 (or any nonzero value) and False can be 0

ii. Implement using flow of control, value is given by the position reached
   - Given expression $E_1 \; or \; E_2$, if E_1 is true, then the entire expression evaluates to true without evaluating E_2

Translating Boolean Expressions Using Numerical Representation

a **or** b **and not** c →

$t_1 = \textbf{not } c$
$t_2 = b \textbf{ and } t_1$
$t_3 = a \textbf{ or } t_2$

$a < b$ → **if** $a < b$ **then** 1 **else** 0 →

100: **if** $a < b$ **then** goto 103
101: $t = 0$
102: goto 104
103: $t = 1$

Short Circuit Code

- Short circuit code translates to conditional and unconditional jumps
  - $B.true$ if B is true and $B.false$ if B is false

ifFalse x goto L	if x is false, execute the instruction labeled L next
ifTrue x goto L	if x is true, execute the instruction labeled L next

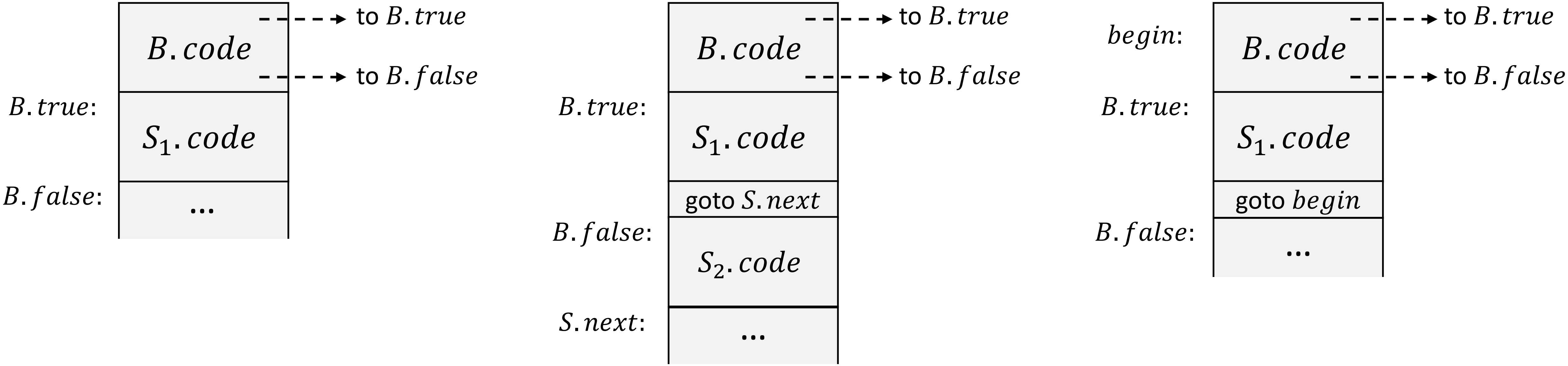
```
if ( $x < 100$ || $x > 200$ && $x \neq y$)
    $x = 0$;
```

```
        if $x < 100$ goto $L_2$
        ifFalse $x > 200$ goto $L_1$
        ifFalse x $\neq y$ goto $L_1$
$L_2$:  $x = 0$
$L_1$:
```

Control Flow

$S \rightarrow \textbf{if } (B)\ S_1 \mid \textbf{if } (B)\ S_1 \textbf{ else } S_2 \mid \textbf{while } (B)\ S_1$

Synthesized attributes $S.code$ and $B.code$ store 3AC
Inheritded attributes $S.next$, $B.true$, and $B.false$ are for jumps



$B.code$ — to $B.true$, to $B.false$
$B.true$: $S_1.code$
$B.false$: …

$B.code$ — to $B.true$, to $B.false$
$B.true$: $S_1.code$
goto $S.next$
$B.false$: $S_2.code$
$S.next$: …

$begin$: $B.code$ — to $B.true$, to $B.false$
$B.true$: $S_1.code$
goto $begin$
$B.false$: …

Generating 3AC for Boolean Expressions

Production	Semantic Rules
$B \rightarrow B_1 \mid\mid B_2$	$B_1.true = B.true;\ B_1.false = newlabel();$ $B_2.true = B.true;\ B_2.false = B.false;$ $B.code = B_1.code \mid\mid label(B_1.false) \mid\mid B_2.code$
$B \rightarrow B_1\ \&\&\ B_2$	$B_1.true = newlabel();\ B_1.false = B.false;$ $B_2.true = B.true;\ B_2.false = B.false;$ $B.code = B_1.code \mid\mid label(B_1.true) \mid\mid B_2.code$
$B \rightarrow\ !\,B_1$	$B_1.true = B.false;\ B_1.false = B.true; B.code = B_1.code$
$B \rightarrow E_1\ relop\ E_2$	$B.code = E_1.code \mid\mid E_2.code \mid\mid$ $gen($if $E_1.addr\ relop.op\ E_2.addr$ goto $B.true)$ $gen($"goto" $B.false)$
$B \rightarrow$ **true**	$B.code = gen($"goto" $B.true\ )$
$B \rightarrow$ **false**	$B.code = gen($"goto" $B.false)$

SDD for Control Flow Statements

Production	Semantic Rules
$P \rightarrow S$	$S.next = newlabel(); P.code = S.code \mid\mid label(S.next)$
S → **assign**	$S.code =$ **assign**$.code$
$S \rightarrow$ **if** $(B)\ S_1$	$B.true = newlabel(); B.false = S_1.next = S.next;$ $S.code = B.code \mid\mid label(B.true) \mid\mid S_1.code;$
$S \rightarrow$ **if** $(B)\ S_1$ **else** S_2	$B.true = newlabel(); B.false = newlabel();$ $S_1.next = S_2.next = S.next;$ $S.code = B.code \mid\mid label(B.true) \mid\mid S_1.code \mid\mid gen(\text{"goto"}\ S.next) \mid\mid$ $label(B.false) \mid\mid S_2.code$
$S \rightarrow$ **while** $(B)\ S_1$	$begin = newlabel(); B.true = newlabel(); B.false = S.next;$ $S_1.next = begin;$ $S.code = label(begin) \mid\mid B.code \mid\mid label(B.true) \mid\mid S_1.code \mid\mid$ $gen(\text{"goto"}\ begin)$
$S \rightarrow S_1\ S_2$	$S_1.next = newlabel();\ S_2.next = S.next;$ $S.code = S_1.code \mid\mid label(S_1.next) \mid\mid S_2.code$

Example of Control Flow Translation

$P \Rightarrow S$

$\Rightarrow$ **if** $(B)\ S$

$\Rightarrow$ **if** $(B_1 || B_2)\ S$

$\Rightarrow$ **if** $(B_1 || B_2 \&\& B_3)\ S$

$\Rightarrow$ **if** $(B_1 || B_2 \&\& B_3)\ S$

```
if ( $x < 100$ || $x > 200$  && $x \neq y$)
   $x = 0$;
```

```
        if $x < 100$ goto $L_2$
        goto $L_3$
$L_3$:  if $x > 200$ goto $L_4$
        goto $L_1$
$L_4$:  if $x \neq y$ goto $L_2$
        goto $L_1$
$L_2$:  $x = 0$
$L_1$:
```

Example of Control Flow Translation

```
if ( $x < 100 \,||\, x > 200 \;\&\&\; x \neq y$ )
   $x = 0$;
```

```
        if $x < 100$ goto $L_2$
        goto $L_3$
$L_3$:  if $x > 200$ goto $L_4$
        goto $L_1$
$L_4$:  if $x \neq y$ goto $L_2$
        goto $L_1$
$L_2$:  $x = 0$
$L_1$:
```

```
if ( $x < 100 \,||\, x > 200 \;\&\&\; x \neq y$ )
   $x = 0$;
```

```
        if $x < 100$ goto $L_2$
        ifFalse $x > 200$ goto $L_1$
        ifFalse $\mathrm{x} \neq y$ goto $L_1$
$L_2$:  $x = 0$
$L_1$:
```

Avoiding Redundant Gotos

3AC generation strategy can lead to redundant `gotos`

ifFalse x goto L	if x is false, execute the instruction labeled L next
ifTrue x goto L	if x is true, execute the instruction labeled L next

L_3: **if** $x > 200$ goto L_4
goto L_1
L_4: **…**

$\Downarrow$

L_3: **ifFalse** $x > 200$ goto L_1
L_4: **…**

avoids a jump

Avoiding Redundant Gotos

- Natural way is to let the control fall through, avoiding a jump
  - $fall$ is a special label indicating no jump

$S \rightarrow$ **if** $(B)\ S_1$	$B.true = fall;$ $B.false = S_1.next = S.next;$ $S.code = B.code \mid\mid S_1.code;$
$B \rightarrow E_1\ relop\ E_2$	$test = E_1.addr\ relop.op\ E_2.addr$ $s =$ **if** $B.true\ \neq fall\ and\ B.false\ \neq fall\ then$ $gen($"if" $test$ "goto" $B.true)\ \mid\mid\ gen($"goto" $B.false)$ **else if** $B.true\ \neq fall\ then\ gen($"if" $test$ "goto" $B.true)$ **else if** $B.false\ \neq fall\ then\ gen($"ifFalse" $test$ "goto" $B.false)$ **else** "" $B.code = E_1.code \mid\mid E_2.code \mid\mid s$

Challenge in Generating Code

- How do you associate labels to instruction addresses?
  - Consider the statement **if** $(B)\ S_1$
  - B is translated before S_1 in a pass, so then how do we set the target of $B.false$?
  - A separate pass is needed to bind labels to addresses of instructions (forward jumps)

$S \rightarrow$ **if** $(B)\ S_1$	$B.true = fall;$ $B.false = S_1.next = S.next;$ $S.code = B.code \mid\mid S_1.code;$

One-Pass Code Generation using Backpatching

- Backpatching generates code in one pass
  - Jump labels are synthesized attributes
  - Target of a jump is temporarily left unspecified when a jump is generated
  - Labels are filled when the proper target address can be determined
- Nonterminal B has two synthesized attributes
  - $truelist$ and $falselist$ – List of jump instructions to which control goes if B is true or false
- S has a synthesized attribute $nextlist$ denoting a list of jumps to the instruction immediately following S

$$
\begin{aligned}
B &\rightarrow B_1 \mid\mid M B_2 \\
&\rightarrow B_1 \,\&\&\, M B_2 \\
&\rightarrow\, ! B_1 \\
&\rightarrow (B_1) \\
&\rightarrow E_1\ rel\ E_2 \\
&\rightarrow \textbf{true} \\
&\rightarrow \textbf{false} \\
M &\rightarrow \epsilon
\end{aligned}
$$

Instructions will require a label

One-Pass Code Generation using Backpatching

- Assume instructions are stored in an array (say using quadruples)
- Labels represent array indices

- $makelist(i)$
  - Create a new list containing only i, return a pointer to the list
- $merge(p_1, p_2)$
  - Merge lists pointed to by p_1 and p_2 and return a pointer to the concatenated list
- $backpatch(p, i)$
  - Insert i as the target label for the instructions in the list pointed to by p

Translation Scheme with Backpatching

- We insert a marker nonterminal M in the grammar to pick up index of next quadruple

$M \rightarrow \epsilon$	$\{ M.instr = nextinstr; \}$

$B \rightarrow B_1 \;||\; MB_2$

$\rightarrow B_1 \;\&\&\; MB_2$

$\rightarrow \;! B_1$

$\rightarrow (B_1)$

$\rightarrow E_1 \; rel \; E_2$

$\rightarrow$ **true**

$\rightarrow$ **false**

$M \rightarrow \epsilon$

Translation Scheme with Backpatching

- Example translation scheme that can be used with bottom-up parsing

$B \rightarrow B_1 \text{ \&\& } M B_2$	$\{\ backpatch(B_1.truelist, M.instr);$ $B.truelist\ =\ B_2.truelist;$ $B.falselist\ =\ merge(B_1.falselist, B_2.falselist);\ \}$

- If B_1 is false, then jump instructions in $B_1.falselist$ is part of $B.falselist$
- If B_1 is true, then target of $B_1.truelist$ is marker M
  - Each instruction in $B_1.truelist$ will receive $M.instr$ as its target label

Translation Scheme with Backpatching

$B \rightarrow B_1 \mid\mid M B_2$	$\{ backpatch(B_1.falselist, M.instr);$ $B.truelist \ = \ merge(B_1.truelist, B_2.truelist);$ $B.falselist \ = \ B_2.falselist; \}$
$B \rightarrow B_1 \ \&\& \ M B_2$	$\{ \ backpatch(B_1.truelist, M.instr);$ $B.truelist \ = \ B_2.truelist;$ $B.falselist \ = \ merge(B_1.falselist, B_2.falselist); \}$
$B \rightarrow \ ! \, B_1$	$\{ \ B.truelist \ = \ B_1.falselist;$ $B.falselist \ = \ B_1 \, .truelist; \}$
$B \rightarrow (B_1)$	$\{ \ B.truelist \ = B_1.truelist;$ $B.falselist \ = \ B_1.falselist; \}$

Translation Scheme with Backpatching

$B \rightarrow E_1\ rel\ E_2$	{ $B.truelist\ = makelist(nextinstr)$; $B.falselist\ = makelist(nextinstr + 1)$; $emit($"if" $E_1.addr\ rel.op\ E_2.addr$ "goto $-$ "$)$; $emit($"goto $-$ "$)$; }
$B \rightarrow$ **true**	{ $B.truelist\ = makelist(nextinstr)$; $emit($"goto $-$ "$)$; }
$B \rightarrow$ **false**	{ $B.falselist\ = makelist(nextinstr)$; $emit($"goto $-$ "$)$; }
$M \rightarrow \epsilon$	{ $M.instr = nextinstr$; }

Example of Backpatching

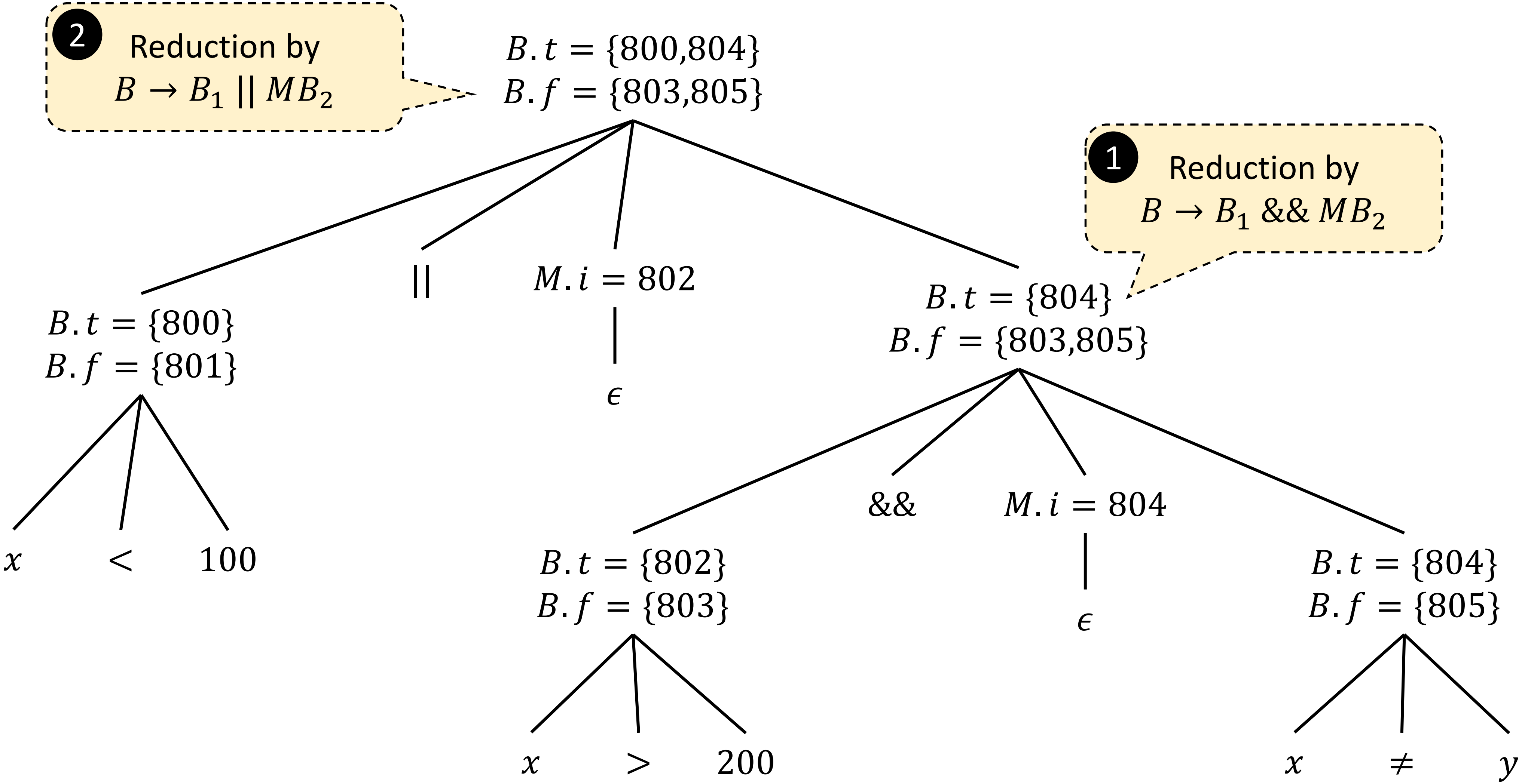
$x < 100 \mid\mid x > 200 \ \&\& \ x \neq y$

arbitrary start

```
800:   if x < 100 goto ...
801:   goto ...
802:   if x > 200 goto ...
803:   goto ...
804:   if x ≠ y goto ...
805:   goto ...
```

Annotated Parse Tree

Since all SDT actions appear at the right ends, they can be performed during reductions in a bottom-up parse.



Example of Backpatching

$x < 100 \mid\mid x > 200 \;\&\&\; x \neq y$

800: **if** $x < 100$ goto ...
801: goto **802**
802: **if** $x > 200$ goto **804**
803: goto ...
804: **if** $x \neq y$ goto ...
805: goto ...

Entire expression is true if `goto` at 800 or 804 is reached
Entire expression is false if `goto` at 803 or 805 is reached

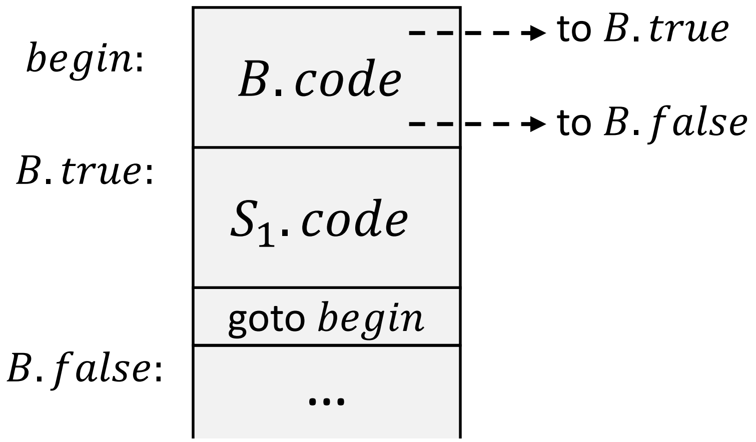
They will be filled in later as more targets become known

Backpatching Control Flow Statements

- S denotes a statement
- L denotes a statement list
- A is an assignment statement
- B is a Boolean expression

$$
\begin{aligned}
S &\rightarrow \textbf{if}\ (B)\ S \\
&\rightarrow \textbf{if}\ (B)\ S\ \textbf{else}\ S \\
&\rightarrow \textbf{while}\ (B)\ S \\
&\rightarrow \{\ L\ \} \mid A; \\
L &\rightarrow L\ S \mid S
\end{aligned}
$$

Backpatching While



$S \rightarrow$ **while** M_1 (B) M_2 S_1	$\{$ $backpatch(S_1.nextlist, M_1.instr);$ $backpatch(B.truelist, M_2.instr);$ $S.nextlist = B.falselist;$ $emit($"goto" $M_1.instr);$ $\}$

Backpatching Control Flow Statements

$S \rightarrow$ **if** $(B)\ M\ S_1$	$\{\ backpatch(B.truelist, M.instr);$ $S.nextlist = merge(B.falselist, S_1.nextlist);\ \}$
$S \rightarrow$ **if** $(B)\ M_1\ S_1\ N$ **else** $M_2\ S_2$	$\{\ backpatch(B.truelist, M_1.instr);$ $backpatch(B.falselist, M_2.instr);$ $temp = merge(S_1.nextlist, N.nextlist);$ $S.nextlist = merge(temp, S_2.nextlist);\ \}$
$S \rightarrow \{\ L\ \}$	$\{\ S.nextlist = L.nextlist;\ \}$
$S \rightarrow A;$	$\{\ S.nextlist = \text{null};\ \}$
$M \rightarrow \epsilon$	$\{\ M.instr = nextinstr;\ \}$
$N \rightarrow \epsilon$	$\{\ N.nextlist = makelist(nextinstr);$ $emit(\text{"goto} \ -\text{"});\ \}$
$L \rightarrow L_1\ M\ S$	$\{\ backpatch(L_1.nextlist, M.instr);$ $L.nextlist = S.nextlist;\ \}$
$L \rightarrow S$	$\{\ L.nextlist = S.nextlist;\ \}$

assumed to be a termination production, hence backpatching is not required

Intermediate 3AC for Procedures

$n = f(a[i]);$

$t_1 = i * 4$
$t_2 = a[t_1]$
$\text{param } t_2$
$t_3 = \text{call } f, 1$
$n = t_3$

$D \rightarrow \textbf{define } T \textbf{ id } (F) \{ S \}$
$F \rightarrow \epsilon \mid T \textbf{ id} , F$
$S \rightarrow \textbf{return } E ;$
$E \rightarrow \textbf{id } (A)$
$A \rightarrow \epsilon \mid E , A$

- Generate function types

  $\text{func } pop(): void \rightarrow integer$

- Check for correct usage of the function type
- Start a new symbol table after seeing **define** and **id**

References

- A. Aho et al. Compilers: Principles, Techniques, and Tools, 1st edition, Chapter 8.2.
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- K. Cooper and L. Torczon. Engineering a Compiler, 2nd edition, Chapter 5.