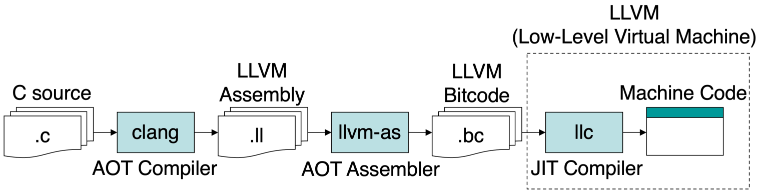
Code Generation

Multiple IRs in the Compiler

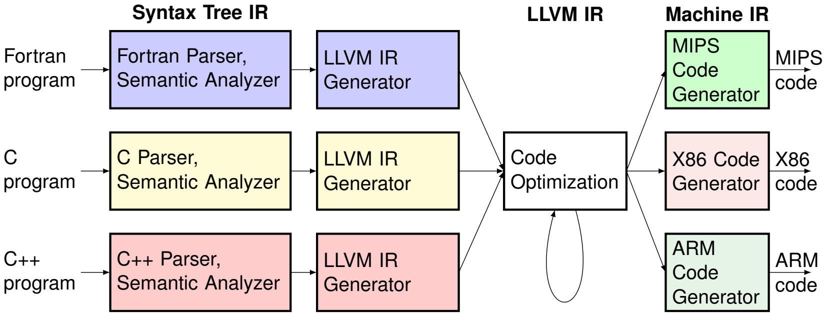
Modern Compiler Framework (Clang/LLVM)

- Remember this diagram from our first day?



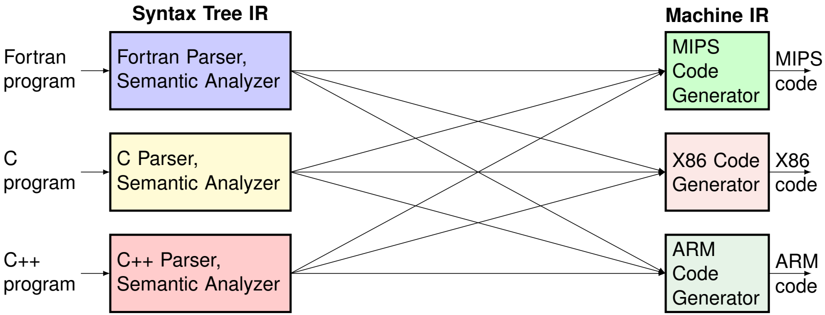
- LLVM Bitcode is in LLVM IR (Intermediate Representation)

Modern Compiler Framework (Clang/LLVM)



- Common LLVM IR for all languages and backends means:
  - ➢ Code optimizations need to be written only once
  - ➢ Implementation complexity of O(M + N) instead of O(M * N) (where M = number of frontends, N = number of backends)

Why O(M * N) when no common IR?



- Must translate M languages to N machine codes
  - Must also do optimizations during each of these translations

High-Level IRs

- Goal: Express the syntax and semantics of source code
- Examples: Abstract Syntax Tree, Parse Tree
- Differs on: Source code programming language
- Uses:
  - Generated by syntax analysis
  - Used by semantic analysis for binding and type checking
  - Language-specific optimizations

High-Level IRs: Language-specific Optimizations

- IR expresses language constructs specific to langauge
  → Suitable for language-specific optimizations

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- IR expresses language constructs specific to langauge
  $\rightarrow$ Suitable for language-specific optimizations
- E.g. Devirtualization for languages with polymorphism
  - Polymorphic method calls are indirect jumps using a vtable (Vtable: a table of function pointers specific to each class)
  - **Devirtualization**: changing polymorphic calls to direct calls
  - If runtime object type can be proven (using type inference)
    $\rightarrow$ Indirect call can be changed to direct call
    $\rightarrow$ Direct call can sometimes be inlined into caller method

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- E.g. Type specialization for languages with dynamic typing
  - Naively, all ops on variables needs dynamic type checking (A big switch/case statement with code for each type)
  - **Type specialization**: generating code for just one type
    - By proving runtime type of variable (using type inference)
    - By profiling type at runtime and generating code for that type

Low-Level IRs

- Goal: Express code in the ISA of an abstract machine
- Examples:
  - Three address code
  - Static Single Assignment (SSA) code
- Differs on: Language and back-end machine agnostic
- Uses:
  - A common IR that connects front-ends and back-ends
  - Language / machine independent optimizations

Low-Level IRs: Universal Optimizations

- IR is language and machine agnostic
  $\rightarrow$ Do optimizations common to all languages/machines

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  A=2; A=y; $\equiv$ A=y;

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  A=2; A=y; $\equiv$ A=y;
- **Redundancy elimination**: deletes repeated computation
  A=x+y; B=x+y+z; $\equiv$ A=x+y; B=A+z

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- **Redundancy elimination**: deletes repeated computation
  A=x+y; B=x+y+z; $\equiv$ A=x+y; B=A+z
- **Loop invariant code motion**: moves code out of loops

```
for (i = 0; i < 100; i++) { sum += i + x * y; }
≡
t = x * y;
for (i = 0; i < 100; i++) { sum += i + t; }
```

Machine IRs

- Goal: Generate code in the ISA of back-end machine
- Examples: x86 IR, ARM IR, MIPS IR
- Differs on: Back-end machine ISA
- Uses:
  - Register allocation / machine code generation
  - Machine-specific optimizations

Machine IRs: Machine-specific Optimizations

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- **Strength reduction**: replacing op with cheaper op
  A=2*a; $\equiv$ A=a«1;

Machine IRs: Machine-specific Optimizations

- IR expresses instructions specific to machine
  $\rightarrow$ Suitable for machine-specific optimizations

- **Strength reduction**: replacing op with cheaper op
  A=2*a; $\equiv$ A=a«1;
- **Vectorization**: using CPU vector units to parallelize
  for (i = 0; i < 64; i++) { C[i] = A[i] + B[i]; }
  $\equiv$
  vec_add_64 vec_register, A, B
  vec_store_64 C, vec_register

Low-Level IRs

Three Address Code

- In the form of **X = Y op Z** where X, Y, Z can be:
  - variables, constants, temporaries
  - temporaries: compiler-generated variables (holds intermediate values for long expressions)

- An example:

  x * y + z / w

  is translated to

  t1 = x * y ; t1, t2, t3 are temporary variables
  t2 = z / w
  t3 = t1 + t2

  - Internal nodes in AST are translated to temporary variables
  - Can be generated through a depth-first traversal of AST

Three Address Code: Ops for an abstract machine

- Characteristics
  - Long expressions are broken down to three address ops
  - Control flow statements are converted to jumps
  - Designed to be machine independent
    - Operators limited to those available on all machines
    - Function calls represented as generic call ops
    - Uses **variables** rather than **registers** to store values (Variables are assigned to registers in machine code)

- Why this form?
  - Boils language-specific ASTs down to actual computation
  - Optimizations done on abstract machine are pertinent (abstract machine ops are sufficiently similar to real ISAs)

Common Three-Address Statements (I)

- Binary operation statement:

  x = y op z

  where op is an arithmetic or logical operation (binary operation)
- Unary operation statement:

  x = op y

  where op is an unary operation such as -, not, shift)
- Copy statement:

  x = y
- Unconditional jump statement:

  goto L

  where L is label

Common Three-Address Statements (II)

- Conditional jump statement:

  if (x relop y) goto L

  where relop is a relational operator such as =, $\neq$, >, <

- Procedural call statement:

  param x_1, ..., param x_n, call F_y, n

  As an example, foo(x1, x2, x3) is translated to

  param x_1
  param x_2
  param x_3
  call foo, 3

- Procedural call return statement:

  return y

  where y is the return value (if applicable)

Common Three-Address Statements (III)

- Indexed assignment statement:

  x = y[i]

  or

  y[i] = x

  where x is an int and y is an array variable

- Address and pointer operation statement:

  x = & y ; a pointer x is set to the address of y

  y = * x ; y is set to value contained in the location

  ; pointed to by x

  ***y = x** ; location addressed by y gets value x

Static Single Assignment (SSA)

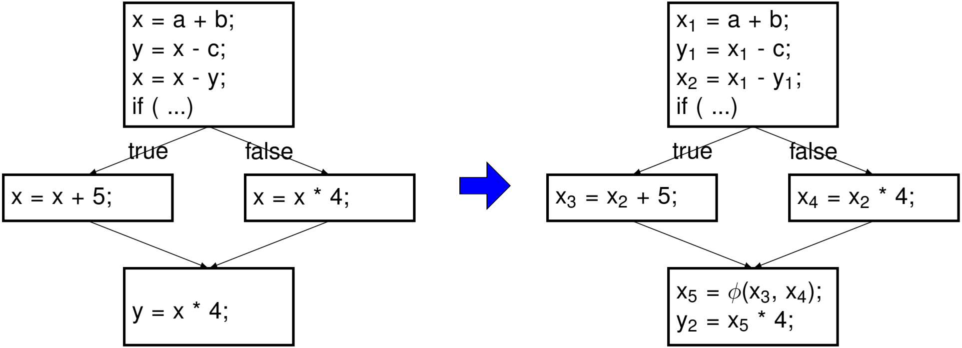
- Most modern IRs are both three address and SSA
  - Clang C/C++ Compiler LLVM IR
  - GCC C/C++ Compiler GIMPLE IR:
  - OpenJDK Java JIT-Compiler Ideal IR
  - Chrome V8 JavaScript JIT-Compiler Turboshaft IR

- Coined by Rosen, Wegman, Zadeck in "Global value numbers and redundant computations", 1988
  - Every variable is assigned to exactly once
  - Variable gains a version number whenever it is assigned to:

    int x, y;
    x_1 = 1; // Current version of x is 1
    a_1 = x_1 * 2; // Uses version 1 of x
    x_2 = x_1 + 1; // Current version of x is 2
    b_1 = x_2 * 2; // Uses version 2 of x

SSA example with control flow

- What if versions are different on control flow merge?
  Φ-function combines two versions into one new version



SSA helps compiler optimizations

- Dead Code Elimination (DCE):

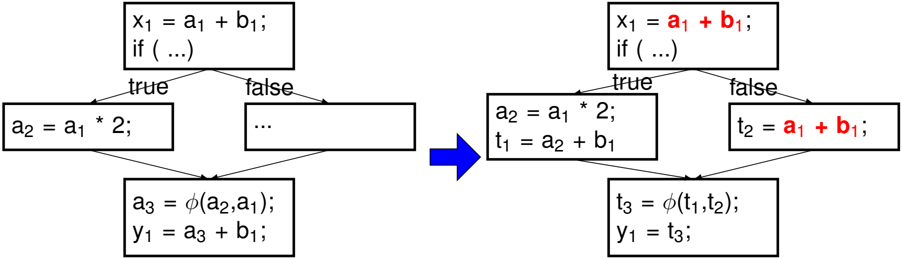
```
x = a + b;
x = c - d;
y = x * b;
```

$\Rightarrow$

x_1 **= a + b;**
x_2 = c - d;
y_1 = x_2 * b;

  - x_1 is defined but never used, so it is safe to remove.

- Partial Redundancy Elimination (PRE):



  - Redundant a + b on false branch can be replaced with x_1.

Why does SSA help optimizations?

- Data dependencies between instructions are made explicit
  - Variables with same name guaranteed to have same value
- Without SSA, same name does not mean same value
  - Must maintain data dependence graph to express this info
- We will discuss more in **compiler optimization** phase

Laying Out Memory

Layout of Variables in Stack Memory

- Local variables of a function are allocated on stack frame
  - Maintain **offset** from base of frame to allocate next variable
    - address(x) $\leftarrow$ offset
    - offset += sizeof(x.type)

```
void foo() {
    int a;
    int b;
    long long c;
    int d;
}
```

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```

Address	
0x0000	
0x0004	
0x0008	
0x000c	
0x0010	

Offset=0

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0x0010	

Offset=0
Addr(a)←0

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```

Address	
0x0000	a
0x0004	
0x0008	
0x000c	
0x0010	

Offset=4
Addr(a)$\leftarrow$0

Layout of Variables in Stack Memory

- Local variables of a function are allocated on stack frame
  - Maintain **offset** from base of frame to allocate next variable
    - address(x) $\leftarrow$ offset
    - offset += sizeof(x.type)

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void foo() {
    int a;
    int b;
    long long c;
    int d;
}
```

Address	
0x0000	a
0x0004	b
0x0008	
0x000c	
0x0010	

Offset=8
Addr(a)$\leftarrow$0

Addr(b)$\leftarrow$4

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}
```

Address	
0x0000	a
0x0004	b
0x0008	c
0x000c	c
0x0010	

Offset=16
Addr(a)$\leftarrow$0
Addr(b)$\leftarrow$4
Addr(c)$\leftarrow$8

Layout of Variables in Stack Memory

- Local variables of a function are allocated on stack frame
  - Maintain **offset** from base of frame to allocate next variable
    - address(x) $\leftarrow$ offset
    - offset += sizeof(x.type)

```
void foo() {
    int a;
    int b;
    long long c;
    int d;
}
```

Address	
0x0000	a
0x0004	b
0x0008	c
0x000c	c
0x0010	d

Offset=20
Addr(a)$\leftarrow$0
Addr(b)$\leftarrow$4
Addr(c)$\leftarrow$8
Addr(d)$\leftarrow$16

What if function has nested scopes?

- Let's take the below example code:

```
void foo() {
    int a;
    int b;
    {
        int i;
    }
    {
        {
            int j;
        }
        int k;
    }
}
```

- What is address(k)? 16?

Nested Scopes Example

```
void foo() {
      int a;
      int b;
        check point #1
      {
            int i;

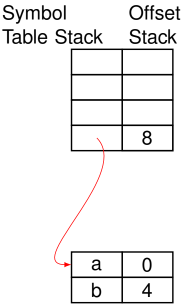
      }

      {
              {
                  int j;

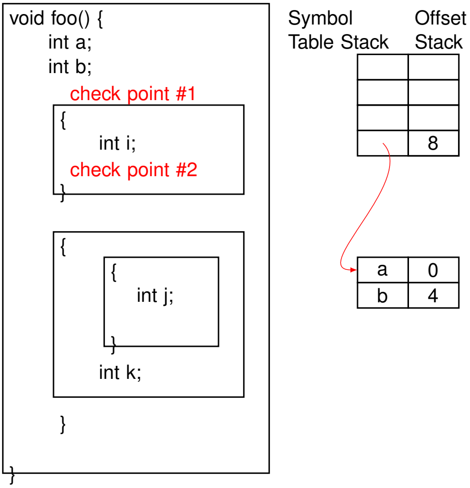
              }
            int k;

      }

}
```



Nested Scopes Example



Nested Scopes Example

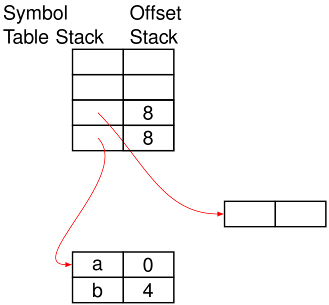
```
void foo() {
      int a;
      int b;
        check point #1
   {
        int i;
     check point #2
   }

   {
        {
          int j;

        }
        int k;
   }

   }

}
```



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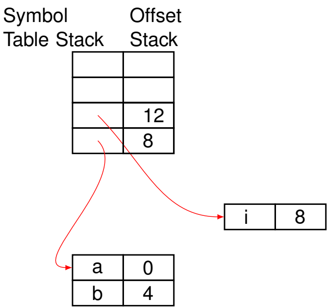
        check point #2
   }

   {
            {
                 int j;

            }
         int k;

   }

}
```



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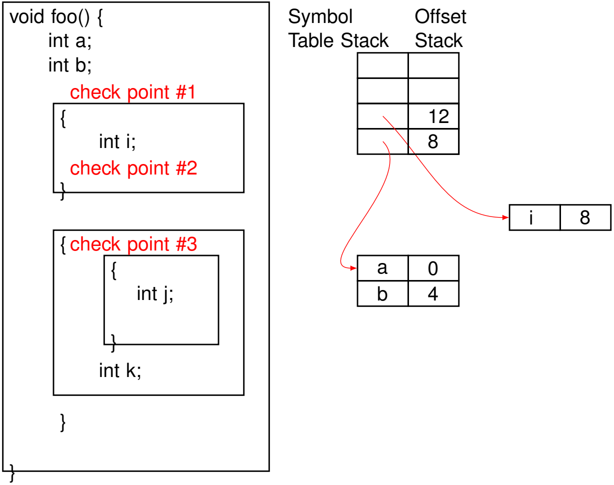

Nested Scopes Example

```
void foo() {
      int a;
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        check point #1
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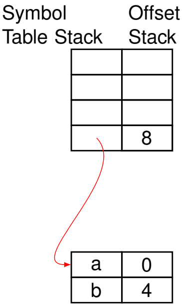
        check point #2
    }

    { check point #3
        {
            int j;

        }
          int k;

    }

}
```



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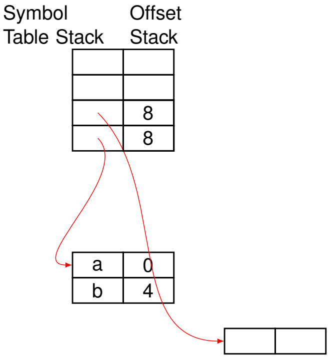

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        }
          int k;

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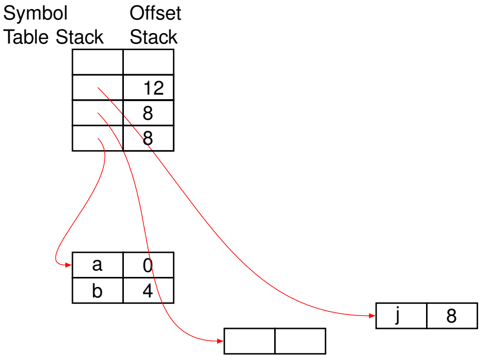
```



Nested Scopes Example

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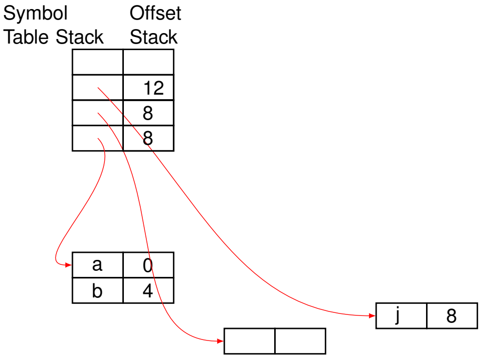
        check point #1
      {
            int i;
        check point #2
      }

      { check point #3
            {
                  int j;
        check point #4
            }
            int k;
        check point #5
      }

}
```



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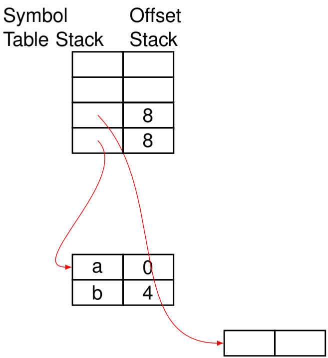

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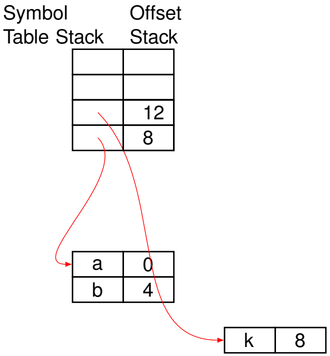


Consideration 1: Allocation Alignment

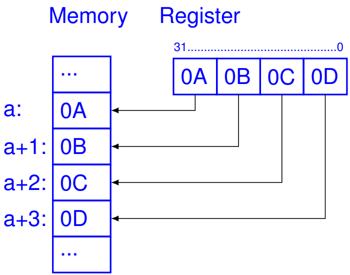
- Enforce **addr(var) mod sizeof(memory word) == 0**
  - Memory word: unit of memory access in given CPU
  - If not, need to load two words and shift & concatenate

```
void foo() {
    char a;         // addr(a) = 0;
    int b;          // addr(b) = 4; /* instead of 1 */
    int c;          // addr(c) = 8;
    long long d;    // addr(d) = 16; /* instead of 12 */
}
```

- This makes memory layout backend machine dependent
  - Memory layout made explicit only in Machine IR
  - Low-level IR needs to refer to locations in an abstract way

Consideration II: Endianness

- Endianness
  - **Big endian**: **MSB** (most significant byte) in lowest address
  - **Little endian**: **LSB** (least significant byte) in lowest address



Big-endian

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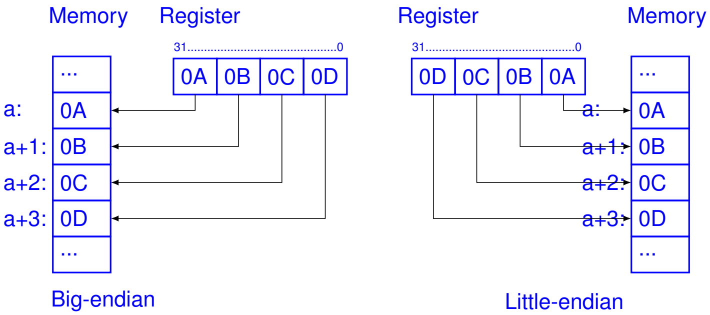

How about other memory besides stack memory?

- Static Memory
  - Where global variables and other static variables reside
  - Layout variables from base address in the same way

- Heap Memory
  - Where dynamically allocated memory using malloc reside
  - Handled by runtime memory management library
  - Compiler not much to do with how this memory is laid out

Generating IR

Generating IR from Language Constructs

- Goal: translate **language constructs** in syntax tree to IR
- Two ways to implement semantic rules for translation
  - By depth-first traversal of syntax tree built by parser
    - This is what you are doing for Project 4
  - By a **syntax directed translation scheme**
    - This is what we will discuss now (based on LR parser)
    - But most concepts apply to both implementations

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    - This is what we will discuss now (based on LR parser)
    - But most concepts apply to both implementations
- What language structures do we need to translate?
  - Declarations
    - Variables, functions (parameters and return types), ...
  - Statements
    - Assignment statements
    - Function call statements
    - Control flow statements (if-then-else, for/while loops)
  - Expressions
    - x + y, x - y, x < y, x > y, x == y, ...

Attributes to Evaluate in Translation

- Variable declaration:
  T V e.g. int a,b,c;
  - Type information **T.type T.width**
  - Variable information **V.type**, **V.offset**

- Statement **S**
  - **S.code**: synthesized attribute that holds IR code of S

- Expression **E**
  - **E.code**: synthesized attribute that holds IR code for E
  - **E.place**: temporary variable name to store result of E

Processing Declarations

- Translating declarations in a single scope
  - **enter(name, type, offset)**: insert variable into symbol table

S $\rightarrow$ M D	
M $\rightarrow$ ε	{ offset=0; } /* reset offset before layout */
D $\rightarrow$ D D	
D $\rightarrow$ T id;	{ enter(id.name, T.type, offset); offset += T.width; }
T $\rightarrow$ integer	{ T.type=integer; T.width=4; }
T $\rightarrow$ real	{ T.type=real; T.width=8;}
T $\rightarrow$ T1[num]	{ T.type=array(num.val, T1.type); T.width=num.val * T1.width; }
T $\rightarrow$ * T1	{ T.type=ptr(T1.type); T.width=4; }

Processing Declarations in Nested Scopes

- Translating declarations in nested scopes
  - **push(item, stack)**: Pushes item on to stack
  - **pop(stack)**: Pops item at the top of stack
  - **top(stack)**: Returns item at the top of stack

S $\rightarrow$ M D	{ pop(tblptr); pop(offset); }
M $\rightarrow$ ε	{ t=mktable(nil); push(t, tblptr); push(0,offset); }
D $\rightarrow$ D D	
D $\rightarrow$ { N D }	{ pop(tblptr); pop(offset); }
N $\rightarrow$ ε	{ t=mktable(nil); push(t, tblptr); push(top(offset), offset);
D $\rightarrow$ T id;	{ enter(id.name, T.type, top(offset)); top(offset) = top(offset)+ T.width; }

Processing Statements

- Statements rely on symbol table populated by declarations
  - **lookup (id)**: search id in symbol table, return nil if none
  - **emit(code)**: print three address IR for code
  - **newtemp()**: get a new temporary variable (or register)
    - E.g., in SSA form, it returns the next virtual register number
      int newtemp() { return virtual_register++; }

$S \rightarrow id = E$	{ P=lookup(id); if (P==nil) perror(...); else emit(P '=' E.place);}
$E \rightarrow E_1 + E_2$	{ E.place = newtemp(); emit(E.place '=' E_1.place '+' E_2.place); }
$E \rightarrow E_1 * E_2$	{ E.place = newtemp(); emit(E.place '=' E_1.place '*' E_2.place); }
$E \rightarrow - E_1$	{ E.place = newtemp(); emit(E.place '=' '-' E_1.place); }
$E \rightarrow (E_1)$	{ E.place = E_1.place; }
$E \rightarrow id$	{ P=lookup(id); E.place=P; }

Processing Array References

- Recall generalized row/column major addressing

- For example:
  1-dimension: int x[100]; ..... $x[i_1]$
  2-dimension: int x[100][200]; ..... $x[i_1][i_2]$
  3-dimension: int x[100][200][300]; ..... $x[i_1][i_2][i_3]$

- Row major: address of a k-dimension array item
  1-dimension: A_1 = base + a_1*width $\quad a_1 = i_1$
  2-dimension: A_2 = base + a_2*width $\quad a_2 = a_1 {}^*N_2 + i_2$
  3-dimension: A_3 = base + a_3*width $\quad a_3 = a_2 {}^*N_3 + i_3$
  ...
  k-dimension: A_k = base + a_k*width $\quad a_k = a_{k-1} {}^*N_k + i_k$

Processing Array References

- Processing an array reference (e.g. A[i], A[i][j], ...)
  - **L.place**: temporary variable name to store a_k
  - **L.base**, **L.width**, **L.bounds**:
    base address, element width, upper bounds of array
  - **L.dim**: current dimension (the k in a_k)

E → L { E.place = newtemp(); t= newtemp();
  emit(t '=' L.place '*' L.width);
  emit (E.place '=' '*' (L.base '+' t)); }

L → id [E] { L.base = lookup(id).base; L.width = lookup(id).width;
  L.bounds = lookup(id).bounds; L.dim=1;
  L.place = E.place; }

L → L_1 [E] { L.base = L_1.base; L.width = L_1.width;
  L.bounds = L_1.bounds; L.dim = L_1.dim + 1;
  L.place = newtemp();
  emit(L.place '=' L_1.place '*' L.bounds[L.dim]);
  emit(L.place '=' L.place '+' E.place); }

Processing Boolean Expressions

- Boolean expression: **a op b**
  - where op can be <, >, >=, &&, ||, ...

1. Without *short circuiting*
   - Short circuiting:
     - In expression A && B, not evaluating B when A is false
     - In expression A || B, not evaluating B when A is true
   - Without short circuiting, entire expression is evaluated:

S→ id = E	≡	lookup(id) = E.place
E→ (a < b) or (c < d and e < f)	≡	t1 = a < b
		t2 = c < d
		t3 = e < f
		t4 = t2 && t3
		E.place = t1 || t4

Processing Boolean Expressions

2. With short circuiting (e.g. C/C++/Java)
   - ➢ Processing simple boolean expressions:
     - **E.true**: address of code to execute on 'true'
     - **E.false**: address of code to execute on 'false'
     - **S.next**: address of code after S

     $S \rightarrow$ if E then S_1

     $E \rightarrow a < b \quad \equiv \quad$ E.true = code for S_1;

     E.false = S.next;

     emit(if E goto E.true);

     emit(goto E.false);
   - ➢ Processing compound boolean expressions:
     - Chain together multiple of above by updating E.true/E.false
     - $E \rightarrow E_1$ && E_2: E_1.true = code for E_2, E_1.false = S.next
     - $E \rightarrow E_1 \mid\mid E_2$: E_1.false = code for E_2, E_1.true = code for S_1

Processing Boolean Expressions

2. With short circuiting (cont'd)
   - A short circuited compound boolean expression
     $S \rightarrow$ if E then S_1
     $E \rightarrow$ (a < b) or (c < d and e < f) $\equiv$

```
     E.true = code for S1;
     E.false = S.next;
     emit(
     if (a<b) goto E.true
     goto L1
 L1: if (c<d) goto L2
     goto E.false
 L2: if (e<f) goto E.true
     goto E.false
     );
```

   - **Problem: E.true, E.false, S.next are non-L-attributes**
     - Depend on code that has not been generated yet
       E.true: Only available when S_1 is generated
       E.false: Only available when code after S is generated
     - Emitting any **forward jump** poses this problem

Syntax Directed Translation (SDT)

- Non-L-attributes complicates syntax directed translation
  - Even using parse tree, preclude simple left-to-right traversal
- Solutions: two methods
  - Two pass approach — process the code twice
    - Generate labels in the first pass
    - Replace labels with addresses in the second pass
  - One pass approach
    - Generate holes when address is needed but unknown
    - Backpatch holes when address is known later on
- We will discuss the more efficient one pass approach
  - It is also the method you will use in project 4.

One-Pass Based Syntax Directed Translation

- Non-L-attributes during code generation are unavoidable
  - Due to forward jumps to code on the right hand side
  - Example: E.true, E.false, S.next for boolean expressions
  - Is there a one-pass solution to the problem?

Idea:

1. Leave holes for non-L-attribute values we don't know
2. Fill the holes in when we know the values later on
   - *holelist*: synthesized attribute of 'holes' for one value
   - Holes are filled in by traversing list when value is known
   - All holes will be patched by the end of code generation (Since all forward jumps would be resolved by then)

One-Pass Based Syntax Directed Translation

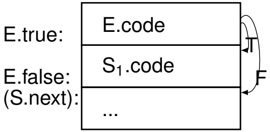
- Attributes for two pass based approach
  - Expression **E**
    —- Synthesized attributes: **E.code**
    E.holes_truelist, and **E.holes_falselist**
  - Statement **S**
    —- Synthesized attributes: **S.code** and **S.holes_nextlist**

- 3 functions for implementing backpatching
  - **makelist(i)**: create a holelist with statement index i
  - **merge(p1, p2)**: concatenate list p1 and list p2
  - **backpatch(p, i)**: insert index i in every hole in holelist p

Backpatching for if-then

- Given rule **S** $\rightarrow$ **if E then S$_1$**, below is done in one-pass:
  (1). Gen **E.code**, making **E.holes_truelist**, **E.holes_falselist**
  (2). Gen **S$_1$.code**, filling in **E.holes_truelist** and merging **S$_1$.holes_nextlist** with **E.holes_falselist**
  (3). Pass on merged list to **S.holes_nextlist**

S $\rightarrow$ if E then M S$_1$
{
backpatch(E.holes_truelist, M.index);
S.holes_nextlist = merge(S$_1$.holes_nextlist, E.holes_falselist);
}



M $\rightarrow \varepsilon$

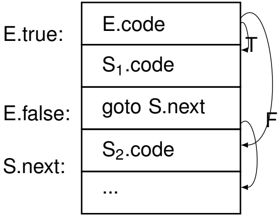
{ M.index = curIndex; }

Backpatching for if-then-else

- Given rule **S** $\rightarrow$ **if E then S$_1$ else S$_2$**:
  (1). Gen **E.code**, making **E.holes_truelist**, **E.holes_falselist**
  (2). Gen **S$_1$.code**, filling in **E.holes_truelist**
  (3). Emit goto to S.next before S_2, to skip over S_2
  (4). Gen **S$_2$.code**, filling in **E.holes_falselist**
  (5). Merge relevant holes into **S.holes_nextlist**

S $\rightarrow$ if E then M1 S_1 N else M2 S_2

```
{
backpatch(E.holes_truelist, M1.index);
backpatch(E.holes_falselist, M2.index);
templist = merge(S1.holes_nextlist, N.holes_nextlist);
S.holes_nextlist = merge(templist, S2.holes_nextlist);
}
```



N $\rightarrow \varepsilon$

```
{
N.holes_nextlist = makelist(curIndex);
emit('goto ___');
}
```

Backpatching for S.holes_nextlist

- When does the holes in S.holes_nextlist get patched?
  - When the instruction after S is generated of course!

- Given rule $\mathbf{S} \rightarrow \mathbf{S}_1\ \mathbf{S}_2$:
  (1). Gen $\mathbf{S}_1$**.code** making $\mathbf{S}_1$**.holes_nextlist**
  (2). Gen $\mathbf{S}_2$**.code** making $\mathbf{S}_2$**.holes_nextlist**
  (3). Fill in $\mathbf{S}_1$**.holes_nextlist** with index of $\mathbf{S}_2$**.code**
  (4). Pass on $\mathbf{S}_2$**.holes_nextlist** to **S.holes_nextlist**

$S \rightarrow S_1\ M\ S_2$

{
backpatch(S_1.holes_nextlist, M.index);
S.holes_nextlist = S_2.holes_nextlist;
}

$M \rightarrow \varepsilon$

{ M.index = curIndex; }

Backpatching for Boolean Expressions

$E \rightarrow E_1$ or M E_2	{ backpatch(E_1.holes_falselist, M.index); E.holes_truelist = merge(E_1.holes_truelist, E_2.holes_truelist); E.holes_falselist = E_2.holes_falselist; }
$E \rightarrow E_1$ and M E_2	{ backpatch(E_1.holes_truelist, M.index); E.holes_falselist = merge(E_1.holes_falselist, E_2.holes_falselist); E.holes_truelist = E_2.holes_truelist; }
$M \rightarrow \varepsilon$	{ M.index = curIndex; }

Backpatching for Boolean Expressions

$E \rightarrow$ not E_1	{ E.holes_truelist = E_1.holes_falselist; E.holes_falselist = E_1.holes_truelist; }
$E \rightarrow$ (E_1)	{ E.holes_truelist = E_1.holes_truelist; E.holes_falselist = E_1.holes_falselist; }
$E \rightarrow$ id1 relop id2	{ E.holes_truelist = makelist(curIndex); E.holes_falselist = makelist(curIndex+1); emit('if' id1.place 'relop' id2.place 'goto ___'); emit('goto ___'); }
$E \rightarrow$ true	{ E.holes_truelist = makelist(curIndex); emit('goto ___'); }
$E \rightarrow$ false	{ E.holes_falselist = makelist(curIndex); emit('goto ___'); }

Backpatching Example

- E $\rightarrow$ (a<b) or M1 (c<d and M2 e<f)

- When reducing (a<b) to E_1, we have
  100: if(a<b) goto ___ — E_1.hole_truelist=(100)
  101: goto ___ — E_1.hole_falselist=(101)
- When reducing ε to M1, we have — M1.index = 102
- When reducing (c<d) to E_2, we have
  102: if(c<d) goto ___ — E_2.hole_truelist=(102)
  103: goto ___ — E_2.hole_falselist=(103)
- When reducing ε to M2, we have — M2.index = 104
- When reducing (e<f) to E3, we have
  104: if(e<f) goto ___ — E3.hole_truelist=(104)
  105: goto ___ — E3.hole_falselist=(105)

Backpatching Example (cont.)

- When reducing (E_2 and M2 E3) to E4, we backpatch((102), 104);

```
102: if(c<d) goto 104        E4.hole_truelist=(104)
103: goto ___                E4.hole_falselist=(103,105)
104: if(e<f) goto ___
105: goto ___
```

- When reducing (E_1 or M1 E4) to E5, we backpatch((101), 102);

```
100: if(a<b) goto ___        E5.hole_truelist=(100, 104)
101: goto 102                E5.hole_falselist=(103,105)
102: if(c<d) goto 104
103: goto ___
104: if(e<f) goto ___
105: goto ___
```

Backpatching Example (cont.)

- When reducing (E_2 and M2 E3) to E4, we backpatch((102), 104);

```
102: if(c<d) goto 104          E4.hole_truelist=(104)
103: goto ___                  E4.hole_falselist=(103,105)
104: if(e<f) goto ___
105: goto ___
```

- When reducing (E_1 or M1 E4) to E5, we backpatch((101), 102);

```
100: if(a<b) goto ___          E5.hole_truelist=(100, 104)
101: goto 102                  E5.hole_falselist=(103,105)
102: if(c<d) goto 104
103: goto ___
104: if(e<f) goto ___
105: goto ___
```

- Are we done?

Backpatching Example (cont.)

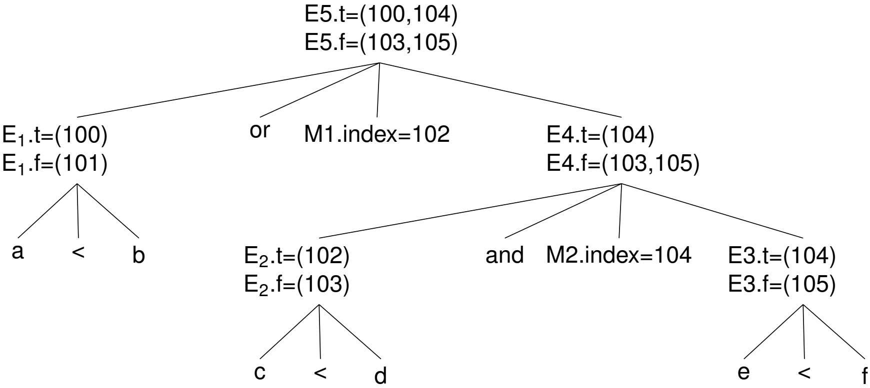
- When reducing (E_2 and M2 E3) to E4, we backpatch((102), 104);

102: if(c<d) goto **104**	E4.hole_truelist=(104)
103: goto ___	E4.hole_falselist=(103,105)
104: if(e<f) goto ___	
105: goto ___	

- When reducing (E_1 or M1 E4) to E5, we backpatch((101), 102);

100: if(a<b) goto ___	E5.hole_truelist=(100, 104)
101: goto **102**	E5.hole_falselist=(103,105)
102: if(c<d) goto 104	
103: goto ___	
104: if(e<f) goto ___	
105: goto ___	

- Are we done?
  - Yes for this expression


E5.t=(100,104)
E5.f=(103,105)
E_1.t=(100)
E_1.f=(101)
or
M1.index=102
E4.t=(104)
E4.f=(103,105)
a
<
b
E_2.t=(102)
E_2.f=(103)
and
M2.index=104
E3.t=(104)
E3.f=(105)
c
<
d
e
<
f