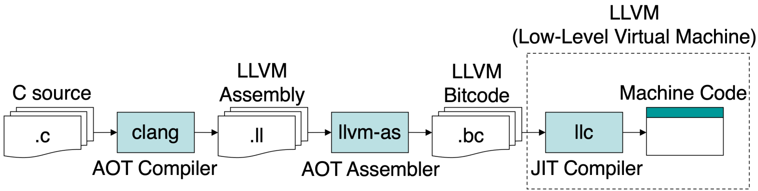
Code Generation

Multiple IRs in the Compiler

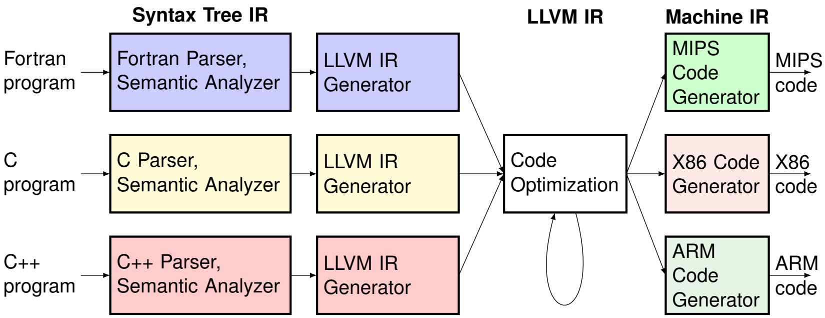
Modern Compiler Framework (Clang/LLVM)

- Remember this diagram from our first day?



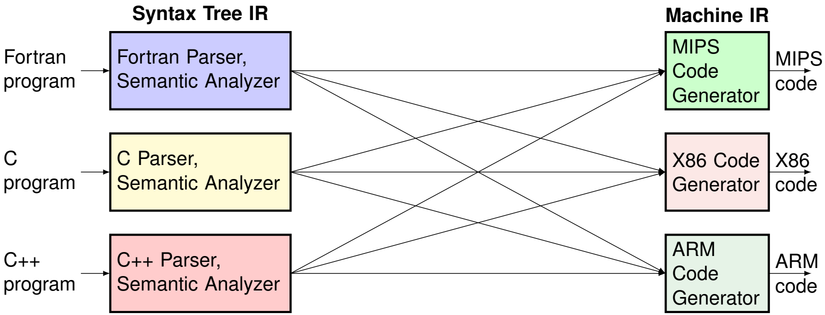
- LLVM Bitcode is in LLVM IR (Intermediate Representation)

Modern Compiler Framework (Clang/LLVM)



- Common LLVM IR for all languages and backends means:
  - Code optimizations need to be written only once
  - Implementation complexity if 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 (e.g. devirtualization)
  - Devirtualization: changing polymorphic calls to direct calls
    - Polymorphic method calls are indirect jumps using a vtable (A vtable is a table of function pointers for each class)
    - Sometimes the direct call is inlined into caller method

Low-Level IRs

- Goal: Express code in the ISA of an abstract machine
- Examples: Three address code, Static Single Assignment
- Differs on: Language and back-end machine agnostic
- Uses:
  - A common IR that connects front-ends and back-ends
  - Language / machine independent optimizations
    - Common subexpression elimination
    - Constant propagation
    - Loop invariant code motion
    - ...
  - Optimizations done in this common IR unless reason not to

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
    - Strength reduction (replacing op with cheaper op)
    - Vectorization (using CPU vector units if available)
    - ...

Low-Level IRs

Three Address Code

Generic form is **X = Y op Z**

where X, Y, Z can be variables, constants, or compiler-generated temporaries holding intermediate values

- Characteristics
  - Assembly code for an 'abstract machine'
  - Long expressions are converted to multiple instructions
  - Control flow statements are converted to jumps
  - Machine independent
    - Operations are generic (not tailored to specific machine)
    - Function calls represented as generic call nodes
    - Uses **symbolic names** rather than **register names** (Actual locations of symbols are yet to be determined)
- Why this form?
  - Allows all operations to be handled in a uniform way
  - Modifications to IR can be done much more easily (Optimizations don't worry about syntactic structure)

Example

- An example:

  x * y + z / w

  is translated to

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

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

Common Three-Address Statements (I)

- Assignment statement:

  x = y op z

  where op is an arithmetic or logical operation (binary operation)
- Assignment 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 a scalable variable and y is an array variable
- Address and pointer operation statement:

  x = & y ; a pointer x is set to location of y

  y = * x ; y is set to the content of the address

  ; stored in pointer x

  ***y = x** ; object pointed to by y gets value x

Implementation of Three-Address Code

- There are three possible ways to store the code
  - quadruples
  - triples
  - indirect triples
- Using quadruples

  op arg1, arg2, result
  - There are four(4) fields at maximum
  - Arg1 and arg2 are optional
  - Arg1, arg2, and result are usually pointers to the symbol table

Examples:

x = a + b	=> + a, b, x
x = - y	=> - y, , x
goto L	=> goto , , L

Using Triples

- To avoid putting temporaries into the symbol table, we can refer to temporaries by the positions of the instructions that compute them

Example: **a = b * (-c) + b * (-c)**

	Quadruples				Triples		
	op	arg1	arg2	result	op	arg1	arg2
(0)	-	c		t1	-	c	
(1)	*	b	t1	t2	*	b	(0)
(2)	-	c		t3	-	c	
(3)	*	b	t3	t4	*	b	(2)
(4)	+	t2	t4	t5	+	(1)	(3)
(5)	=	t5		a	=	a	(4)

More About Triples

- Triples for array statements

  x[i] = y

  is translated to

  (0) [] x i

  (1) = (0) y

  - That is, one statement is translated to two triples

Using Indirect Triples

- Problem with triples
  - Cannot move code around because instruction numbers will change

	Quadruples				Triples		
	op	arg1	arg2	result	op	arg1	arg2
(0)	-	c		t1	-	c	
(1)	*	b	t1	t2	*	b	(0)
(2)	-	c		t3	-	c	
(3)	*	b	t3	t4	*	b	(2)
(4)	+	t2	t4	t5	+	(1)	(3)
(5)	=	t5		a	=	a	(4)

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	Quadruples				Triples		
	op	arg1	arg2	result	op	arg1	arg2
(0)	-	c		t1	-	c	
(1)	*	b	t1	t2	*	b	(0)
(2)	+	t2	t2	t5	+	(1)	(1)
(3)	=	t5		a	=	a	(4)

Using Indirect Triples

- IR is a listing of pointers to triples instead of triples themselves
- Triples are stored in a separate triple 'database'
- Can modify listing as long as the database does not change
- Slightly more overhead but allows optimizations

	Indirect Triples (ptr to triple database)
(0)	(0)
(1)	(1)
(2)	(2)
(3)	(3)
(4)	(4)
(5)	(5)

	Triples op	arg1	arg2
(0)	-	c	
(1)	*	b	(0)
(2)	-	c	
(3)	*	b	(2)
(4)	+	(1)	(3)
(5)	=	a	(4)

After Optimization

	Indirect Triples (ptr to triple database)
(0)	(0)
(1)	(1)
(2)	(4)
(3)	(5)

	Triple Database		
	op	arg1	arg2
(0)	-	c	
(1)	*	b	(0)
(2)	-	c	
(3)	*	b	(2)
(4)	+	(1)	(1)
(5)	=	a	(4)

- After optimization, some entries in database can be reused
  - i.e. Entries in triple database do not have to be contiguous

After Optimization

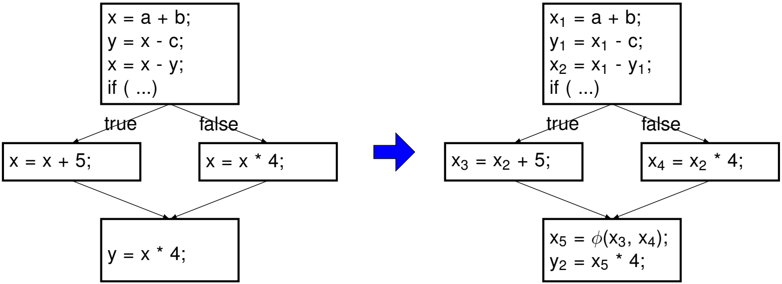
	Indirect Triples (ptr to triple database)
(0)	(0)
(1)	(1)
(2)	(4)
(3)	(5)

	Triple Database		
	op	arg1	arg2
(0)	-	c	
(1)	*	b	(0)
(2)	(empty)		
(3)	(storing new triple)		
(4)	+	(1)	(1)
(5)	=	a	(4)

- After optimization, some entries in database can be reused
  - i.e. Entries in triple database do not have to be contiguous

Static Single Assignment (SSA)

- Developed by R. Cytron, J. Ferrante, *et al.* in 1980s
  - Every variable is assigned exactly once i.e. one **DEF**
  - Convert original variable name to $\text{name}_{version}$
    e.g. $x \rightarrow x_1$, x_2 in different places
  - Use ϕ-function to combine two DEFs of same original variable on a control flow merge



Benefits of SSA

- SSA can assist compiler optimizations
  - e.g. remove dead code

Before		After
x = a + b;	⇒	x_1 = a + b;
x = c - d;		x_2 = c - d;
y = x * b;		y_1 = x_2 * b;

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

- Will discuss more in **compiler optimization** phase
- Intuition: Makes data dependency relationships between instructions more apparent in the IR

Generating IR using Syntax Directed Translation

Generating IR

Our next task is to translate **language constructs** to IR using **syntax directed translation scheme**

Generating IR

Our next task is to translate **language constructs** to IR using **syntax directed translation scheme**

- What is our parsing scheme?
  - Bottom-up LR/LALR parsing
    - Natural to translate synthesized attributes
    - Hack to translate L-attributed inherited attributes

Generating IR

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Generating IR

Our next task is to translate **language constructs** to IR using **syntax directed translation scheme**

- What is our parsing scheme?
  - Bottom-up LR/LALR parsing
    - Natural to translate synthesized attributes
    - Hack to translate L-attributed inherited attributes
- What language structures do we need to translate?
  - Declarations
    - variables, procedures (need to enforce static scoping), ...
  - Assignment statement
  - Flow of control statement
    - if-then-else, while-do, for-loop, ...
  - Procedure call
  - ...

Attributes to Evaluate in Translation

- Statement **S**
  - **S.code** — a synthesized attribute that holds IR code of S
- Expression **E**
  - **E.code** — a synthesized attribute that holds IR code for computing E
  - **E.place** — a synthesized attribute that holds the location where the result of computing E is stored
- Variable declaration:

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

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

  ..... What is **V.offset**?

Storage Layout of Variables in a Procedure

- When there are multiple variables defined in a procedure,
  - we layout the variable sequentially
  - use variable **offset**, to get address of **x**
    - address(x) $\leftarrow$ offset
    - offset += sizeof(x.type)

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

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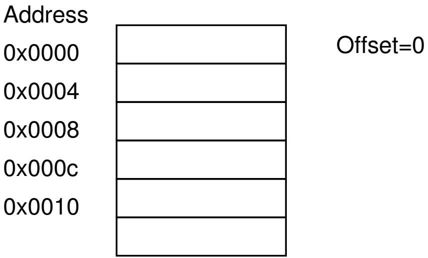

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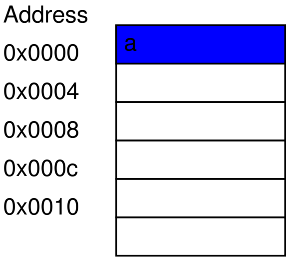

Offset=0
Addr(a)$\leftarrow$0

Storage Layout of Variables in a Procedure

- When there are multiple variables defined in a procedure,
  - ➢ we layout the variable sequentially
  - ➢ use variable **offset**, to get address of **x**
    - address(x) ← offset
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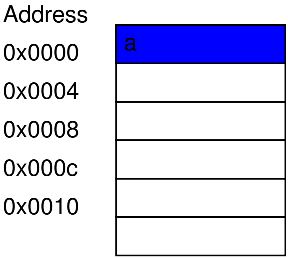


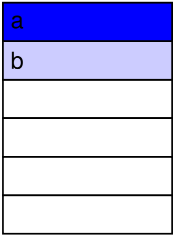
Offset=4
Addr(a)←0

Storage Layout of Variables in a Procedure

- When there are multiple variables defined in a procedure,
  - we layout the variable sequentially
  - use variable **offset**, to get address of **x**
    - address(x) $\leftarrow$ offset
    - offset += sizeof(x.type)

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

Address
0x0000
0x0004
0x0008
0x000c
0x0010

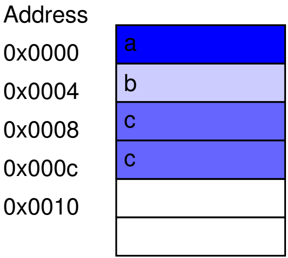


Offset=8
Addr(a)$\leftarrow$0
Addr(b)$\leftarrow$4

Storage Layout of Variables in a Procedure

- When there are multiple variables defined in a procedure,
  - ➢ we layout the variable sequentially
  - ➢ use variable **offset**, to get address of **x**
    - address(x) $\leftarrow$ offset
    - offset += sizeof(x.type)

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



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

Storage Layout of Variables in a Procedure

- When there are multiple variables defined in a procedure,
  - we layout the variable sequentially
  - use variable **offset**, to get address of **x**
    - address(x) ← 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)←0
Addr(b)←4
Addr(c)←8
Addr(d)←16

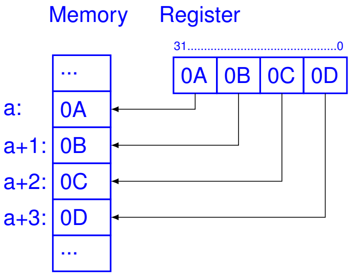
More About Storage Layout (I)

- Allocation alignment
  - Enforce **addr(x) mod sizeof(x.type) == 0**
  - Most machine architectures are designed such that computation is most efficient at sizeof(x.type) boundaries
    - E.g. Most machines are designed to load integer values at integer word boundaries
    - If not on word boundary, 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 */
}
```

More About Storage Layout (II)

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



Big-endian

More About Storage Layout (II)

- Endianness
  - Big endian stores **MSB** (most significant byte) in lowest address
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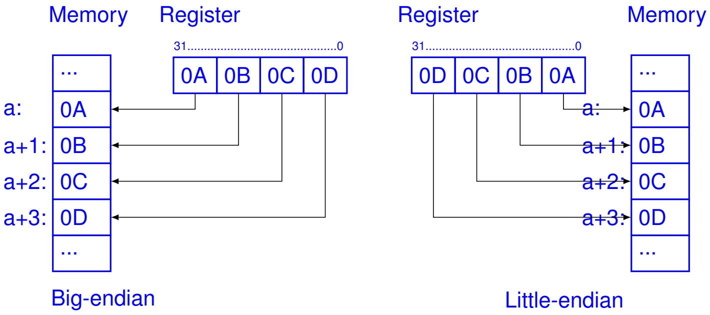


More About Storage Layout (III)

- Questions still unanswered
  - How are non-local variables laid out?
  - How dynamically allocated variables laid out?

Processing Declarations

- Translating the declaration in a single procedure
  - enter(name, type, offset) — insert the variable into the symbol table

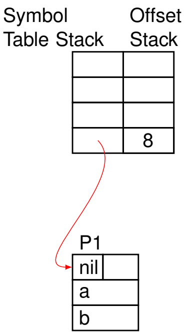
P $\rightarrow$ M D	
M $\rightarrow$ ε	{ offset=0; } /* reset offset before layout */
D $\rightarrow$ D ; D	
D $\rightarrow$ T id	{ enter(id.name, T.type, offset); offset += T.width; }
T $\rightarrow$ integer	{ T.type=integer; T.width=4; }
T $\rightarrow$ real	{ T.type=real; T.width=8;}
T $\rightarrow$ 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 Nested Declarations

- Need scope information for each level of nesting.
- When encountering a nested procedure declaration...
  1. Create a new symbol table when encountering a sub-procedure declaration
     - mktable(ptr); — ptr points back to its parent table
  2. Store procedure name in parent symbol table, with a pointer pointing to the new table
     - enterproc(parent_table_ptr, proc_id, child_table_ptr)
  3. Suspend the processing of parent symbol table
     - Push new table in the **active symbol table stack**
     - Push the current offset in the **offset stack**
  4. When done, resume the processing of parent symbol table
     - Pop entries in **active symbol table stack**, **offset stack** for nested procedure
     - Restore current offset from the **offset stack**

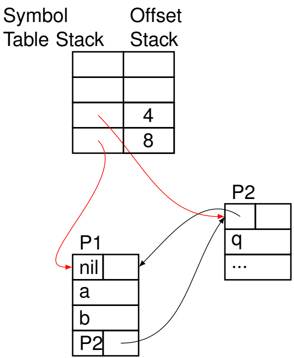
Nested Declaration Example

```
void P1() {
    int a;
    int b;
     check point #1
    void P2() {
        int q;

    }

    void P3() {
        void P4() {
            use a

        }
        int J;
    }
    use q

}
```



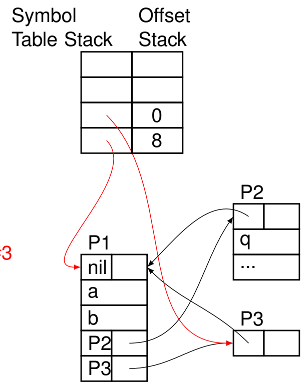
Nested Declaration Example

```
void P1() {
    int a;
    int b;
     check point #1
    void P2() {
        int q;
          check point #2
    }

    void P3() {
        void P4() {
            use a

        }
        int J;
    }
    use q

}
```



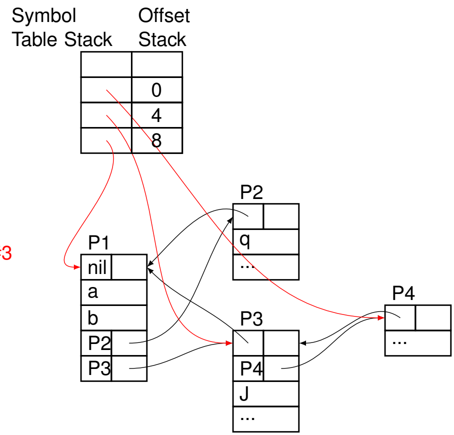
Nested Declaration Example

```
void P1() {
      int a;
      int b;
       check point #1
   void P2() {
         int q;
            check point #2
   }

   void P3() { check point #3
      void P4() {
         use a
      }
         int J;
   }
      use q

}
```



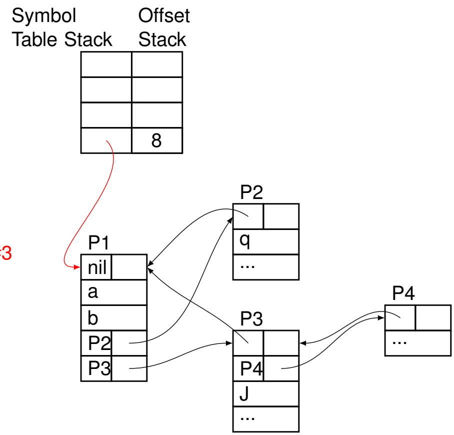
Nested Declaration Example

```
void P1() {
      int a;
      int b;
       check point #1
       void P2() {
             int q;
                check point #2
       }

       void P3() { check point #3
          void P4() {
              use a
                check point #4
          }
             int J;
       }
      use q

}
```



Nested Declaration Example

```
void P1() {
    int a;
    int b;
     check point #1
    void P2() {
        int q;
          check point #2
    }

    void P3() {  check point #3
        void P4() {
            use a
              check point #4
        }
        int J;
    }
    use q
     check point #5
}
```



Processing Nested Declarations

- Syntax directed translation rules

P $\rightarrow$ M D	{ pop(tblptr); pop(offset); }
M $\rightarrow$ ε	{ t=mktable(nil); push(t, tblptr); push(0,offset); }
D $\rightarrow$ D1; D2	
D $\rightarrow$ void pid() { N D1; S }	{ t=top(tblptr); pop(tblptr); pop(offset); enter proc(top(tblptr), pid, t); } /* new symbol table */
D $\rightarrow$ T id;	{ enter(top(tblptr), id, T.type, top(offset)); top(offset) = top(offset)+ T.width; }
N $\rightarrow$ ε	{ t=mktable(top(tblptr)); push(t, tblptr); push(0, offset);

Processing Statements

- Statements are processed sequentially after processing declarations
  - useful functions:
    lookup (id) — search id in symbol table, return nil if none
    emit() — print three address IR
    newtemp() — get a new temporary variable

S $\rightarrow$ id = E	{ P=lookup(id); if (P==nil) perror(...); else emit(P '=' E.place);}
E $\rightarrow$ E1 + E2	{ E.place = newtemp(); emit(E.place '=' E1.place '+' E2.place); }
E $\rightarrow$ E1 * E2	{ E.place = newtemp(); emit(E.place '=' E1.place '*' E2.place); }
E $\rightarrow$ - E1	{ E.place = newtemp(); emit(E.place '=' '-' E1.place); }
E $\rightarrow$ (E1)	{ E.place = E1.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: addressing a k-dimension array item (low_i = base = 0)
  1-dimension: $A_1 = a_1$*width $\qquad a_1 = i_1$
  2-dimension: $A_2 = a_2$*width $\qquad a_2 = a_1{*}N_2{+}i_2$
  3-dimension: $A_3 = a_3$*width $\qquad a_3 = a_2{*}N_3{+}i_3$
  ...
  k-dimension: $A_k = a_k$*width $\qquad a_k = a_{k-1}{*}N_k + i_k$

Processing Array References

- Processing an array assignment (e.g. A[i] = B[j];)

```
S → L = E        { t = newtemp(); emit( t '=' L.place '*' L.width);
                   emit(t '=' L.base '+' t); emit ('*'t '=' E.place); }
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.dim=1;
                   L.place = E.place; }

L → L1 [ E ]     { L.base = L1.base; L.width = L1.width; L.dim = L1.dim + 1;
                   L.place = newtemp();
                   emit( L.place '=' L1.place '*' L.max[L.dim]);
                   emit( L.place '=' L.place '+' E.place); }
```

Processing Boolean Expressions

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

1. Compute just like any other arithmetic expression
   - Good for languages with no *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 as usual

     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. Implement as a series of jumps
   - For languages with short circuiting (e.g. C/C++), evaluations sometimes have to be 'jumped'
   - Processing a boolean expression:
     S→ if E then S1
     E→ a < b ≡ E.true = S1.label;
     E.false = S.next
     if E goto E.true
     goto E.false
     S1.label: label created at the address of code S1
     S.next: address of code after S
     E.true: code to execute on 'true'
     E.false: code to execute on 'false'
   - Processing compound boolean expressions:
     - Chain together multiple of above by updating E.true/E.false
     - E→ E1 && E2: E1.true = code for E2, E1.false = S.next
     - E→ E1 || E2: E1.false = code for E2, E1.true = S1.label

Processing Boolean Expressions

2. Implement as a series of jumps (cont'd)
   - A short circuited compound boolean expression
     $E \rightarrow (a < b)$ or $(c < d$ and $e < f) \equiv$
     ```
         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
     ```
   - Can apply to other control flow statements
     S $\rightarrow$ if E then S1 | if E then S1 else S2 | while E do S1
   - **Problem: E.true, E.false, S.next are non-L-attributes**
     - Depend on code that has not been generated yet
       S.next: Only available when code after S is generated
       E.true: Only available when S1 is generated

Syntax Directed Translation

- A non-L-attributed grammar may preclude a one pass syntax directed translation scheme
  - Both top-down and bottom-up SDTS rely on L-attributed grammars
- How to handle non-L attributes?
  - **E.true, E.false, S.next**
- 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
    - Fill in holes when addresses is known later on
    - Finish code generation in one pass

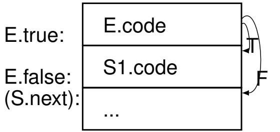
Two-Pass Based Syntax Directed Translation Scheme

- Attributes for two pass based approach
  - Expression **E**
    - —- Synthesized attributes: **E.code**
    - —- non-L inherited attributes: **E.true**, **E.false**
  - Statement **S**
    - —- Synthesized attributes: **S.code**
    - —- non-L inherited attributes: **S.next**
- Evaluation order:
  Given rule **S** $\rightarrow$ **if E then S1**, the two passes are:
  (1). Generate **E.code** and **S1.code** making a label for E.true
  (2). Replace label **E.true** with actual address of S1
  (Labels **E.false** and **S1.next** are inheried from **S.next**)
  Given rule **S** $\rightarrow$ **S1 S2**, the two passes are:
  (1). Generate **S1.code** and **S2.code** making a label for S1.next
  (2). Replace label **S1.next** with the actual address of S2
  (Label **S2.next** is inheried from **S.next**)

Two Pass based Rules

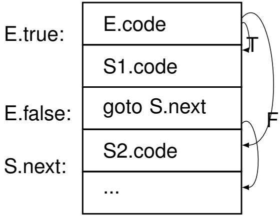
S $\rightarrow$ if E then S1

{ E.true = newlabel;
E.false = S.next;
S1.next = S.next;
S.code = E.code || gen(E.true':') || S1.code; }



S $\rightarrow$ if E then S1 else S2

{ S1.next = S2.next = S.next;
E.true = newlabel;
E.false = newlabel;
S.code = E.code || gen(E.true':') ||
S1.code || gen('goto ' S.next) ||
gen(E.false ':') || S2.code; }



More Two Pass based SDT Rules

E $\rightarrow$ id1 relop id2	{ E.code=gen('if' id1.place 'relop' id2.place 'goto' E.true) || gen('goto' E.false); }
E $\rightarrow$ E1 or E2	{ E1.true = E2.true = E.true; E1.false = newlabel; E2.false = E.false; E.code = E1.code || gen(E1.false ':') || E2.code; }
E $\rightarrow$ E1 and E2	{ E1.false = E2.false = E.false; E1.true = newlabel; E2.true = E.true; E.code = E1.code || gen(E1.true ':') || E2.code; }
E $\rightarrow$ not E1	{ E1.true = E.false; E1.false = E.true; E.code = E1.code; }
E $\rightarrow$ true	{ E.code = gen('goto' E.true); }
E $\rightarrow$ false	{ E.code = gen('goto' E.false); }

Problem

- Try this at home. Refer to textbook Chapter 6.6.
- Write SDT rule (two pass) for the following statement

```
S → while (a<b) do
          if (c<d)
          then S
          endif
      endwhile
```

Backpatching

- If grammar contains L-attributes only, then it can be processed in one pass
- However, **we know** there are occasions for non-L attributes
  - Example: E.true, E.false, S.next during code generation
  - Is there a general solution to this problem?

Solution:

- Leave holes for non-L attributes, record their locations in holelists, and fill in the holes when we know the target values
  - *holelist*: synthesized attribute of 'holes' to be filled in for a particular target value
  - Holes are filled in one shot when target value is known
  - All holes can be replaced at the end of code generation

One-Pass Based Syntax Directed Translation Scheme

- 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**
- Evaluation order:
  Given rule **S** $\rightarrow$ **if E then S1**, below is done in one-pass:
  (1). Gen **E.code**, making **E.holes_truelist**, **E.holes_falselist**
  (2). Gen **S1.code**, filling in **E.holes_truelist** and merging **S1.holes_nextlist** with **E.holes_falselist**
  (3). Pass on merged list to **S.holes_nextlist**
  Given rule **S** $\rightarrow$ **S1 S2**, below is done in one-pass:
  (1). Gen **S1.code** making **S1.holes_nextlist**
  (2). Gen **S2.code** filling in **S1.holes_nextlist** and making **S2.holes_nextlist**
  (3). Pass on **S2.holes_nextlist** to **S.holes_nextlist**

Backpatching Rules for Boolean Expressions

- 3 functions for implementing backpatching for IR generation
  - makelist(i) — creates a new list with statement index i
  - merge(p1, p2) — concatenates list p1 and list p2
  - backpatch(p, i) — insert i as target label for each statement in list p

E $\rightarrow$ E1 or M E2 { backpatch(E1.holes_falselist, M.quad);
E.holes_truelist = merge(E1.holes_truelist, E2.holes_truelist);
E.holes_falselist = E2.holes_falselist; }

E $\rightarrow$ E1 and M E2 { backpatch(E1.holes_truelist, M.quad);
E.holes_falselist = merge(E1.holes_falselist, E2.holes_falselist);
E.holes_truelist = E2.holes_truelist; }

M $\rightarrow \varepsilon$ { M.quad = nextquad; }

More One Pass SDT Rules

E → not E1	{ E.holes_truelist = E1.holes_falselist; E.holes_falselist = E1.holes_truelist; }
E → (E1)	{ E.holes_truelist = E1.holes_truelist; E.holes_falselist = E1.holes_falselist; }
E → id1 relop id2	{ E.holes_truelist = makelist(nextquad); E.holes_falselist = makelist(nextquad+1); emit('if' id1.place 'relop' id2.place 'goto ___'); emit('goto ___'); }
E → true	{ E.holes_truelist = makelist(nextquad); emit('goto ___'); }
E → false	{ E.holes_falselist = makelist(nextquad); emit('goto ___'); }

Backpatching Example

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

- When reducing (a<b) to E1, we have
  100: if(a<b) goto ___   E1.hole_truelist=(100)
  101: goto ___   E1.hole_falselist=(101)
- When reducing ε to M1, we have   M1.quad = 102
- When reducing (c<d) to E2, we have
  102: if(c<d) goto ___   E2.hole_truelist=(102)
  103: goto ___   E2.hole_falselist=(103)
- When reducing ε to M2, we have   M2.quad = 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 (E2 and M2 E3) to E4, we backpatch((102), 104);

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

- When reducing (E1 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 (E2 and M2 E3) to E4, we backpatch((102), 104);

```
100: if(a<b) goto ___
101: goto ___
102: if(c<d) goto 104
103: goto ___
104: if(e<f) goto ___
105: goto ___
```

E4.hole_truelist=(104)
E4.hole_falselist=(103,105)

- When reducing (E1 or M1 E4) to E5, we backpatch((101), 102);

```
100: if(a<b) goto ___
101: goto 102
102: if(c<d) goto 104
103: goto ___
104: if(e<f) goto ___
105: goto ___
```

E5.hole_truelist=(100, 104)
E5.hole_falselist=(103,105)

- Are we done?

Backpatching Example (cont.)

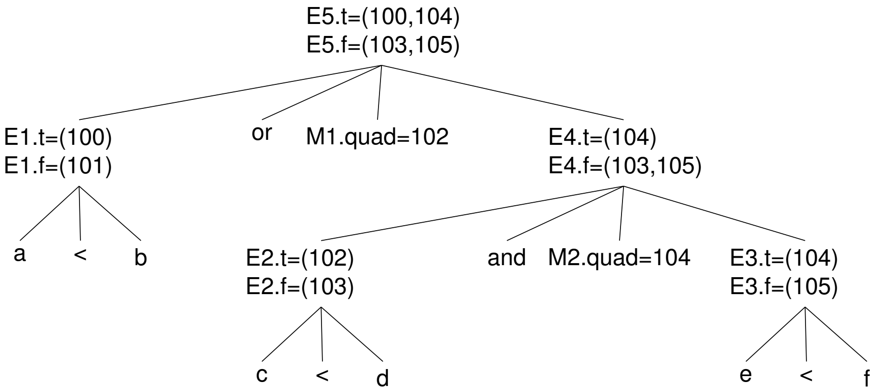
- When reducing (E2 and M2 E3) to E4, we backpatch((102), 104);

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

- When reducing (E1 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)
E1.t=(100)
E1.f=(101)
or
M1.quad=102
E4.t=(104)
E4.f=(103,105)
a
<
b
E2.t=(102)
E2.f=(103)
and
M2.quad=104
E3.t=(104)
E3.f=(105)
c
<
d
e
<
f

Problem

- Try this at home. Refer to textbook Chapter 6.6, 6.7.
- Write SDT rule (one pass using backpatching) for the following statement

  S $\rightarrow$ while E1 do
          if E2
          then S2
          endif
      endwhile

Solution Hint

- S $\rightarrow$ while E1 do if E2 then S2 endif endwhile

	Known Attributes	Attributes to Evaluate/Process
Two Pass	E1.code E2.code S2.code S.next	E1.true, E1.false E2.true, E2.false S2.next S.code
One Pass	E1.code, E1.hole_truelist E1.hole_falselist E2.code, E2.hole_truelist E2.hole_falselist S.code, S.hole_nextlist	S.code S.hole_nextlist (E1.hole_truelist,E1.hole_falselist) (E2.hole_truelist,E2.hole_falselist)