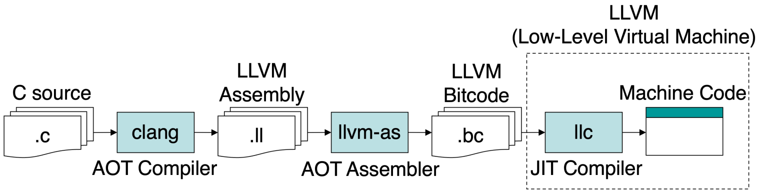
Code Generation

Multiple IRs in the Compiler

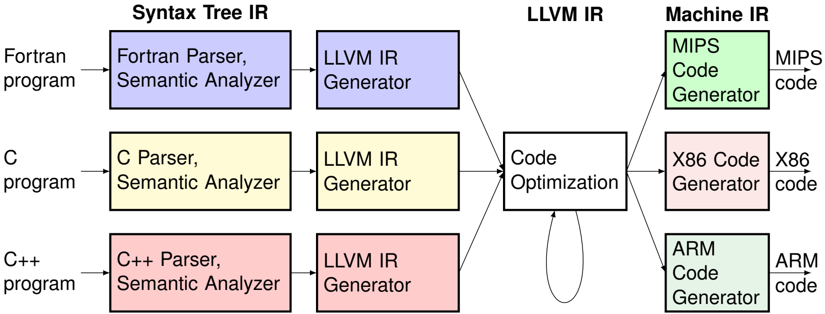
Modern Compiler Framework (Clang/LLVM)

- Remember this diagram from our first day?



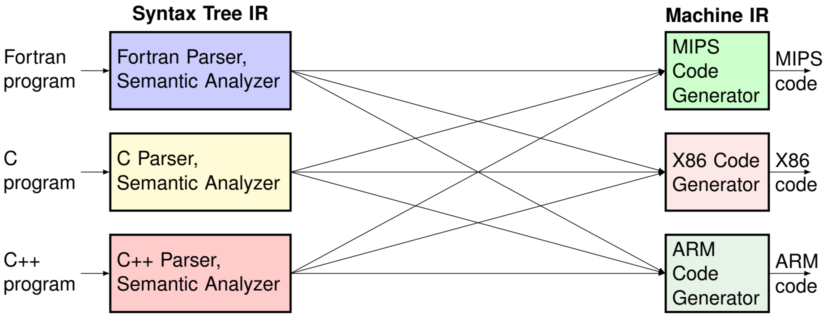
- LLVM Bitcode is in LLVM IR (Intermediate Representation)

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 IR to be generated in a machine-agnostic way
  - Optimizations on 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 $\mathbf{x}_1$, ..., param $\mathbf{x}_n$, call $\mathbf{F}_y$, 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

Implementation of Three-Address Code

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

  op src1, src2, dest

  - There are four fields at maximum
  - Src1 and src2 are optional
  - Src1, src2, dest are variables (including temporaries)

Examples:

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

Using Triples

- Tripes have only three fields. How?
  - ➢ Destination field of instruction is always a temporary (With the exception of assignments to variables)
  - ☞ Replace use of temporary wth pointer to that instruction
  - ☞ Instruction no longer needs a destination field!

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

	Quadruples				Triples		
	op	src1	src2	dest	op	src1	src2
(0)	-	c		t1	-	c	
(1)	*	b	t1	t1	*	b	(0)
(2)	-	c		t2	-	c	
(3)	*	b	t2	t2	*	b	(2)
(4)	+	t1	t2	t1	+	(1)	(3)
(5)	=	t1		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
  - ➢ No code moving allowed because triple locations change (that would invalidate pointers to those locations, right?)

	Quadruples				Triples		
	op	src1	src2	dest	op	src1	src2
(0)	-	c		t1	-	c	
(1)	*	b	t1	t1	*	b	(0)
(2)	-	c		t2	-	c	
(3)	*	b	t2	t2	*	b	(2)
(4)	+	t1	t2	t1	+	(1)	(3)
(5)	=	t1		a	=	a	(4)

Using Indirect Triples

- Problem with triples
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	Quadruples				Triples		
	op	src1	src2	dest	op	src1	src2
(0)	-	c		t1	-	c	
(1)	*	b	t1	t1	*	b	(0)
(2)	+	t1	t1	t1	+	(1)	(1)
(3)	=	t1		a	=	a	(4)

Using Indirect Triples

- IR is now a listing of **pointers** to triples
- Triples are stored in a separate instruction storage
  (Typically triple objects are stored in program heap)
- Now code movement will not change locations of triples

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

	Triple Storage		
	op	src1	src2
(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 Storage		
	op	src1	src2
(0)	-	c	
(1)	*	b	(0)
(2)	-	c	
(3)	*	b	(2)
(4)	+	(1)	(1)
(5)	=	a	(4)

- After optimization, triple objects sometimes can be freed
  - Free space will get reused by heap management system

After Optimization

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

	Triple Storage		
	op	src1	src2
(0)	-	c	
(1)	*	b	(0)
(2)	(free space)		
(3)	(free space)		
(4)	+	(1)	(1)
(5)	=	a	(4)

- After optimization, triple objects sometimes can be freed
  - Free space will get reused by heap management system

After Optimization

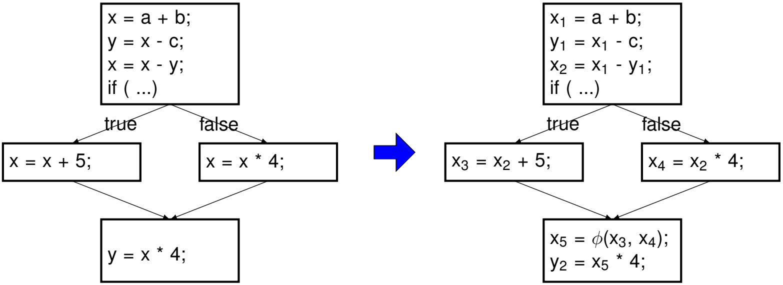
	Indirect Triples (ptr to triple database)
(0)	(0)
(1)	(1)
(2)	(4)
(3)	(5)

	Triple Storage		
	op	src1	src2
(0)	-	c	
(1)	*	b	(0)
(2)	(free space)		
(3)	(free space)		
(4)	+	(1)	(1)
(5)	=	a	(4)

- After optimization, triple objects sometimes can be freed
  - Free space will get reused by heap management system
- LLVM IR is represented in memory in this way as well

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 $name_{version}$
    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



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, it is safe to remove

- Partial Redundancy Elimination (PRE):

$x_1 = a_1 + b_1;$
if (...)

true: $a_2 = a_1 * 2;$

false: ...

$a_3 = \phi(a_2, a_1);$
$y_1 = a_3 + b_1;$

$\Rightarrow$

$x_1 = a_1 + b_1;$
if (...)

true: $a_2 = a_1 * 2;$
$t_1 = a_2 + b_1$

false: $t_2 = x_1;$

$t_3 = \phi(t_1, t_2);$
$y_1 = t_3;$

Redundant a + b computation on false branch is removed

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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void foo() {
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}
```

Address		
0x0000		Offset=0
0x0004		
0x0008		
0x000c		
0x0010		

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    - address(x) $\leftarrow$ offset
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```
void foo() {
    int a;
    int b;
    long long c;
    int d;
}
```

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

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

Layout of Variables in Stack Memory

- Local variables of a function are allocated on stack frame
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    - offset += sizeof(x.type)

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

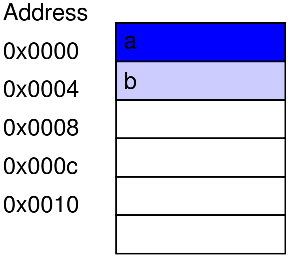
Address	
0x0000	a
0x0004	
0x0008	
0x000c	
0x0010	

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) ← offset
    - offset += sizeof(x.type)

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



Offset=8
Addr(a)←0
Addr(b)←4

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) ← offset
    - offset += sizeof(x.type)

```
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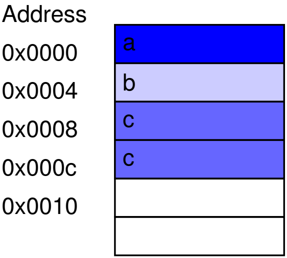
    int d;
}
```



Offset=16
Addr(a)←0
Addr(b)←4
Addr(c)←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) ← 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

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;

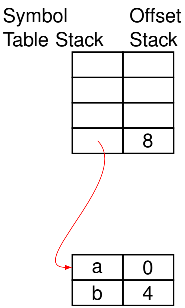
    }

    {
        {
            int j;

        }
        int k;

    }

}
```



Nested Scopes Example

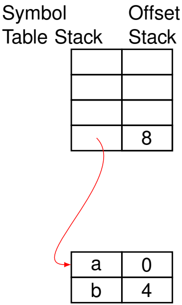
```
void foo() {
    int a;
    int b;
      check point #1
      {
          int i;
      check point #2
      }

      {
            {
                int j;

            }
          int k;

      }

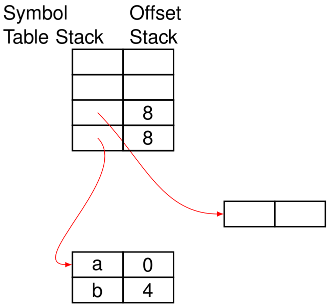
}
```



Nested Scopes Example

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

      {
            {
                  int j;
            }
            int k;
      }
}
```



Nested Scopes Example

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        {
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        }
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}
```
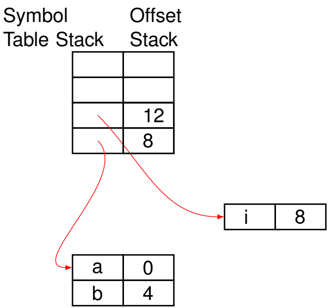
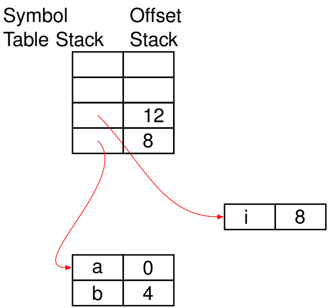



Nested Scopes Example

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

   { check point #3
         {
               int j;

         }
         int k;

   }

}
```



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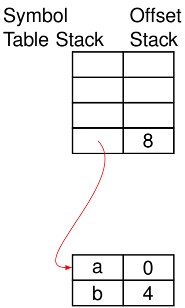

Nested Scopes Example

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              }
              int k;

        }

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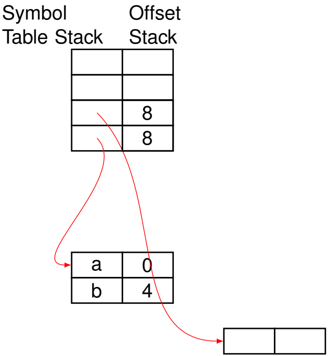
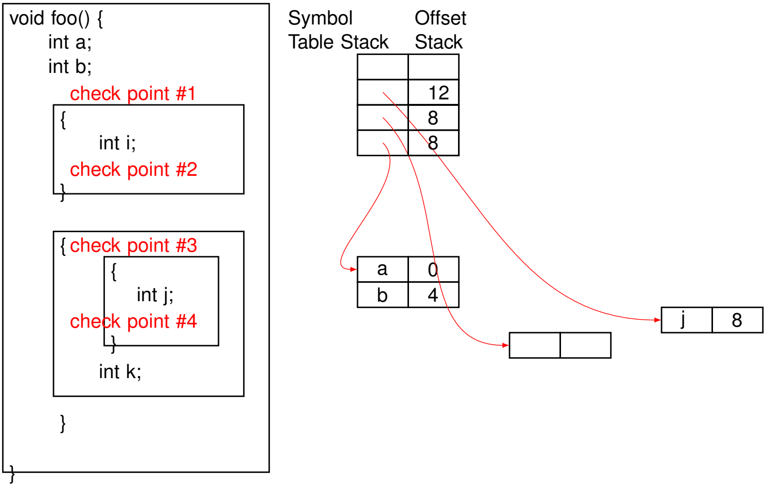
```



Nested Scopes Example



Nested Scopes Example

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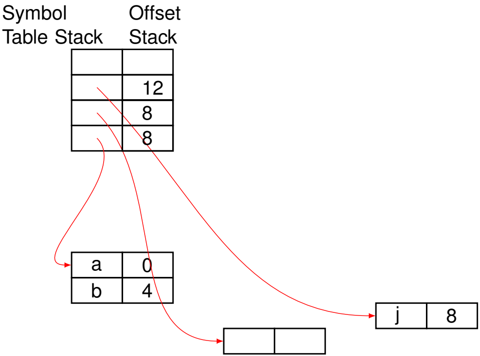
      check point #1
    {
        int i;
      check point #2
    }

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

}
```



Nested Scopes Example

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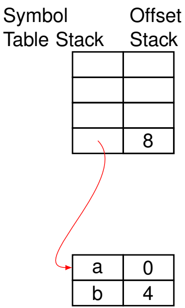

Nested Scopes Example

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   }

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```
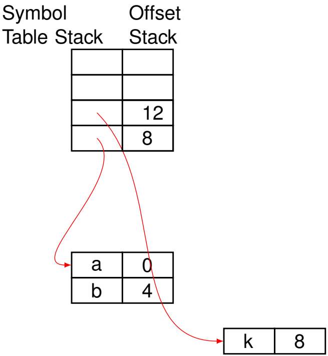



Consideration 1: Allocation Alignment

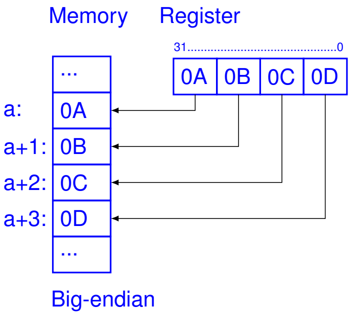
- Enforce **addr(var) mod sizeof(memory word) == 0**
  - Memory word: unit of memory access in given CPU
  - If not, need to load two words and shift & concatenate

```
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 refers 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



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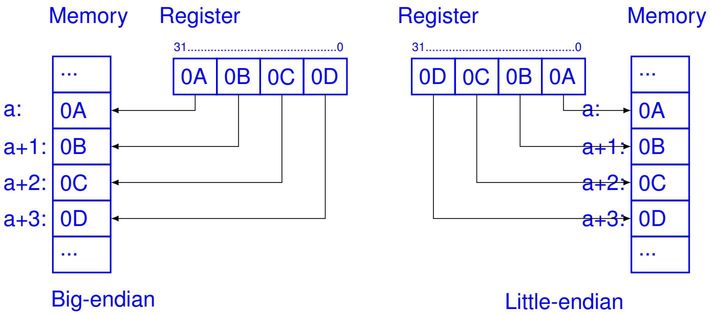

How about other memory besides stack memory?

- 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**: synthesized attribute for temporary variable name to store result of E (for SSA, virtual register name)

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); }

$M \rightarrow \varepsilon$ { t=mktable(nil); push(t, tblptr); push(0,offset); }

$D \rightarrow D\ D$

$D \rightarrow \{\ N\ D\ \}$ { pop(tblptr); pop(offset); }

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

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. 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$\rightarrow$ id = E	$\equiv$	lookup(id) = E.place
E$\rightarrow$ (a < b) or (c < d and e < f)	$\equiv$	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:
     S$\rightarrow$ if E then S1
     E$\rightarrow$ a < b $\equiv$ 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$\rightarrow$ E1 && E2: E1.true = code for E2, E1.false = S.next
     - E$\rightarrow$ 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 precludes a one pass syntax directed translation scheme
  - Both LL and LR parsers 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

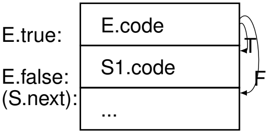
Two-Pass Based Syntax Directed Translation Scheme

- 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

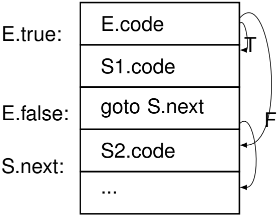
S $\rightarrow$ if E then S1

{ 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 SDD 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 SDD rule (two pass) for the following statement

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

Backpatching

- Non-L-attributes during code generation are unavoidable
  - 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 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
  - **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

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

M $\rightarrow$ ε { M.index = curIndex; }

More One Pass SDD 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(curIndex); E.holes_falselist = makelist(curIndex+1); emit('if' id1.place 'relop' id2.place 'goto ___'); emit('goto ___'); }
E → true	{ E.holes_truelist = makelist(curIndex); emit('goto ___'); }
E → 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 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.index = 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.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 (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 ___          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?

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 ___
```

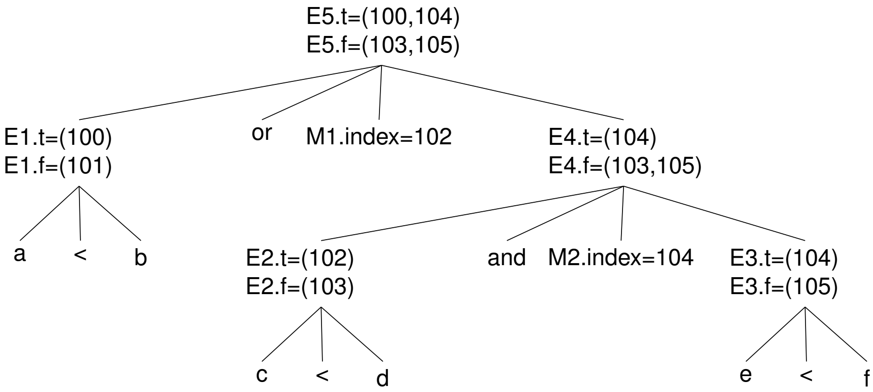
E4.hole_truelist=(104)
E4.hole_falselist=(103,105)

- 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?
  - Yes for this expression


E5.t=(100,104)
E5.f=(103,105)
E1.t=(100)
E1.f=(101)
or
M1.index=102
E4.t=(104)
E4.f=(103,105)
a
<
b
E2.t=(102)
E2.f=(103)
and
M2.index=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 SDD rule (one pass using backpatching) for the following statement

```
S → while E1 do
            if E2
            then S2
            endif
        endwhile
```

Solution Hint

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

	Known Attributes	New Attributes to Evaluate
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 S2,code	S.code S.hole_nextlist