Module 07: CS-1319-1: Programming Language Design and Implementation (PLDI)

Machine Independent Translation

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Module Objectives

- Understand Intermediate Representations
- Symbol Tables
- Understand Syntax Directed Translation
- Understand how Semantic Actions be guided by Syntactic Translation (using Attributed Grammars)

Exclude slides:

- 07.23 (Symbol Table: Static & Dynamic Scope Rules)
- 07.100-101 (Control Construct: Handling of `goto`)
- 07.102 (Control Construct: Handling of `switch`)
- 07.103 (Control Construct: Handling of `break` and `continue`)
- 07.152-172 (Type Expressions)
- 07.178-201 (Lexical Scope Management)
- 07.202-203 (Additional Features)

Module Outline

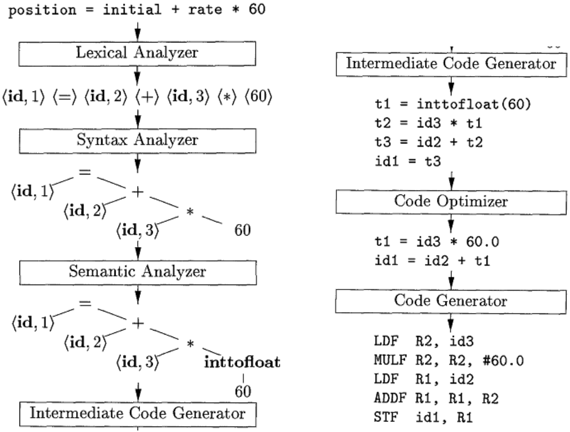
Intermediate Representations

Dragon Book: Pages 359-360 (Variants of Syntax Tree)
Dragon Book: Pages 363-370 (Three Address Code)
Examples by PPD

Intermediate Representations (IR)

- Each compiler uses 2-3 IRs
- Multi-Level Intermediate Representations
  - High-Level Representations (HIR)
    - Preserves loop structure and array bounds
    - Abstract Syntax Tree (AST) / DAG
      - Condensed form of parse tree
      - Useful for representing language constructs
      - Depicts the natural hierarchical structure of the source program
        - Each internal node represents an operator
        - Children of the nodes represent operands
        - Leaf nodes represent operands
      - DAG is more compact than AST because common sub expressions are eliminated
  - Mid-Level Representations (MIR):
    - Reflects range of features in a set of source languages
    - Language independent
    - Good for code generation for a number of architectures
    - Appropriate for most optimization opportunities
    - Three-Address Code (TAC)
  - Low-Level Representations (LIR):
    - Corresponds one to one to target machine instructions
    - Assembly Language of Processors (like x86)

Three IRs in Translation



Source: Dragon Book

Figure: Syntax Tree, Three Address Code and Assembly

Alternate / Supplementary Intermediate Representations

- SSA: Single Static Assignment
  - Each variable be assigned exactly once, and
  - Every variable be defined before it is used
- RTL: Register Transfer Language
  - Describes data flow at the register-transfer level of an architecture
- Stack Machines: P-code
- CFG: Control Flow Graph
  - Graph notation
  - All paths in a program during its execution
- DFG: Data Flow Graph
  - Graph notation
  - Data dependancies between a number of operations
- CDFG: Control and Data Flow Graph = CFG + DFG
- Dominator Trees / DJ-graph: Dominator tree augmented with join edges
- PDG: Program Dependence Graph
- VDG: Value Dependence Graph
- GURRR: Global unified resource requirement representation. Combines PDG with resource requirements
- Java intermediate bytecodes
- ...

Three Address Code

- Concepts
  - Address
  - Instruction

  In general these could be classes, specializing for every specific type.
- Uses only up to 3 addresses in every instruction
- Every 3 address instruction is represented by a quad – opcode, argument 1, argument 2, and result

Three Address Code

- Address Types
  - *Name*:
    Source program names appear as addresses in 3-Address Codes.
  - *Constant*:
    Many different types and their (implicit) conversions are allowed as deemed addresses.
  - *Compiler-Generated Temporary*:
    Create a distinct name each time a temporary is needed - good for optimization.
  - *Labels*:
    Used to (optionally) mark positions of 3 address instructions

Three Address Code

- Instruction Types
  For Addresses `x`, `y`, `z`, and Label `L`
  - *Binary Assignment Instruction*: For a binary `op` (including arithmetic, logical, or bit operators):

    `x = y op z`
  - *Unary Assignment Instruction*: For a unary operator `op` (including unary minus, logical negation, shift operators, conversion operators):

    `x = op y`
  - *Copy Assignment Instruction*:

    `x = y`

Three Address Code

- Instruction Types
  For Addresses `x`, `y`, and Label `L`
  - *Unconditional Jump*:
    ```
    goto L
    ```
  - *Conditional Jump*:
    - *Value-based*:
      ```
      if x goto L
      ifFalse x goto L
      ```
    - *Comparison-based*: For a relational operator op (including $<$, $>$, $==$, $!=$, $\leq$, $\geq$):
      ```
      if x relop y goto L
      ```

Three Address Code

- Instruction Types
  For Addresses `p`, `x1`, `x2`, and `xN`
  - Procedure Call: A procedure call `p(x1, x2, ..., xN)` having $N \geq 0$ parameters is coded as:

    ```
    param x1
    param x2
    ...
    param xN
    y = call p, N
    ```

    Note that `N` is not redundant as procedure calls can be nested.
    Parameters may be stacked in the left-to-right or right-to-left order
  - Return Value: Returning a return value and /or assigning it is optional. If there is a return value it is returned from the procedure `p` as:

    ```
    return n
    ```

Three Address Code

- Instruction Types
  For Addresses `x`, `y`, and `i`
  - *Indexed Copy Instructions*:
    ```
    x = y[i]
    x[i] = y
    ```
  - *Address and Pointer Assignment Instructions*:
    ```
    x = &y
    x = *y
    *x = y
    ```

Three Address Code

- Example

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

  translates to

  ```
  L: t1 = i + 1
     i = t1
     t2 = i * 8
     t3 = a[t2]
     if t3 < v goto L
  ```

  The symbolic label is then given positional numbers as:

  ```
  100: t1 = i + 1
  101: i = t1
  102: t2 = i * 8
  103: t3 = a[t2]
  104: if t3 < v goto 100
  ```

Three Address Code

- For

```
L: t1 = i + 1
   i = t1
   t2 = i * 8
   t3 = a[t2]
   if t3 < v goto L
```

quads are represented as:

	op	**arg 1**	**arg 2**	**result**
0	+	i	1	t1
1	=	t1	null	i
2	*	i	8	t2
3	=[]	a	t2	t3
4	<	t3	v	L

Symbol Table

Dragon Book: Pages 85-91 (Symbol Table)
Examples by PPD

Symbol Table: Notion & Purpose

- Symbol table is a data structure created and maintained by compilers in order to store information about the occurrence of various entities such as variable names, function names, objects, classes, interfaces, etc.
- Symbol table is used by both the analysis and the synthesis parts of a compiler.
- A symbol table may serve the several purposes depending upon the language in hand:
  - To store the names of all entities in a structured form at one place
  - To verify if a variable has been declared
  - To implement type checking, by verifying assignments and expressions in the source code are semantically correct
  - To determine the scope of a name (scope resolution)
- A symbol table is a table which maintains an entry for each name in the following format:

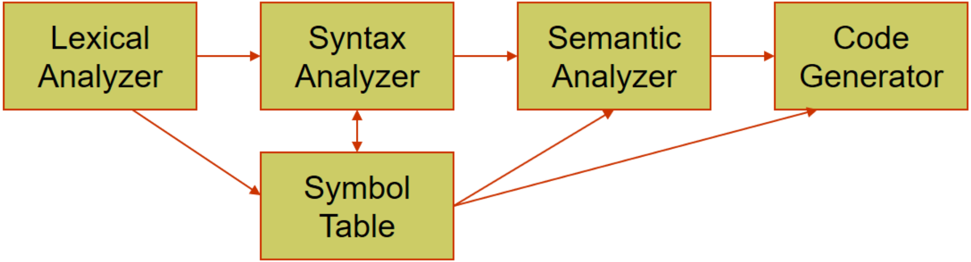
  `<symbol name, type, attribute>`

Symbol Table: Notion & Purpose

- Built in lexical and syntax analysis phases.
- Information collected by the analysis phases of compiler and is used by synthesis phases to generate code.
- Used by compiler to achieve compile time efficiency.
- Used by various phases of compiler as follows:
  - **Lexical Analysis**: Creates new table entries in the table, example like entries about token.
  - **Syntax Analysis**: Adds information regarding attribute type, scope, dimension, line of reference, use, etc.
  - **Semantic Analysis**: Uses information in the table to check for semantics, that is, to verify that expressions and assignments are semantically correct (type checking) and update it accordingly.
  - **Intermediate Code generation**: Refers symbol table for knowing how much and what type of run-time is allocated and table helps in adding temporary variable information.
  - **Code Optimization**: Uses information present in symbol table for machine dependent optimization.
  - **Target Code Generation**: Generates code by using address information of identifier present in the table.

Symbol Table

- When identifiers are found by the lexical analyzer, they are entered into a **Symbol Table**, which will hold all relevant information about identifiers.
- This information is updated later by Syntax Analyzer, and used & updated even later by the Semantic Analyzer and the Code Generator.



Note the directionality of arrows with Symbol Table

Symbol Table: Entries

- An ST stores varied information about identifiers:
  - Name (as a string)
    - ▷ Name may be qualified for scope or overload resolution
  - Data type (explicit or pointer to Type Table)
  - Block level
  - Scope (global, local, parameter, or temporary)
  - Offset from the base pointer (for local variables and parameters only) – to be used in Stack Frames
  - Initial value (for global and local variables), default value (for parameters)
  - Others (depending on the context)
- A Name (Symbol) may be any one of:
  - Variable (user-define / unnamed temporary)
  - Constant (String and non-String)
  - Function / Method (Global / Class)
  - Alias
  - Type – Class / Structure / Union
  - Namespace

Symbols Table: More Uses

- **String Table**: Various string constants
- **Constant Table**: Various non-string consts, const objects
- **Label Table**: Target labels
- **Keywords Table**: Initialized with keywords (KW)
  - KWs tokenized as id's and later marked as KWs on parsing
    - Simplifies lexical analysis
    - Good for languages where keywords are not reserved. *Note*: Keywords in C/C++ are reserved, while those in FORTRAN are not (how to know if an 'IF' is a keyword or an identifier?)
    - Good for languages like EDIF with user-defined keywords
- **Type Table**:
  - *Built-in Types*: `int`, `float`, `double`, `char`, `void` etc.
  - *Derived Types*: Types built with type builders like array, struct, pointer, enum etc. May need equivalence of type expressions like `int[]` & `int*`, separate tables etc.
  - *User-defined Types*: `class`, `struct` and `union` as types
  - *Type Alias*: `typedef`
  - *Named Scopes*: `namespace`

Scopes Management by Symbol Tables

- Symbol Tables manage symbols according to various scopes and associated rules
- A scope may be static (lexical - region of program with visibility) or dynamic (run-time). We use statid here.
- Every scope has an ST organized as a tree with ST.global at root
- An ST is used for symbol resolution in multiple phases and for deciding memory static and automatic memory layout

Scope	Entities Managed	Role of Symbol Table
Global / Static	• Mgmt. of symbols in global and file static scope, static members in class scope (data members & methods), and local static in functions: Variables, functions, classes, name spaces, type alias, extern symbols etc.	• Vars go to static table • All symbols listed for linking • Symbols resolved in multiple phases
Name space	• Mgmt. of symbols in name space scope defined by `namespace` with or without a name: Variables, functions, classes, nested name spaces & type alias, etc.	• Vars go to static table • Symbols resolved in multiple phases
Function	• Mgmt. of symbols in function scope (block scope attached to a function with a name): Params, local variables, temps, classes and type alias	• Vars & temps go to AR of function • Symbols resolved in multiple phases
Block	• Mgmt. of symbols in block scope – attached to a function (Function Scope), part of a statement (unnamed), or nested in another block (unnamed): Local vars, temps, classes, and type alias	• Vars & temps go to AR of the function containing the block. Flattening is used for this • Symbols resolved in multiple phases
Class	• Mgmt. of symbols in class scope defined by `class`, `struct`, or `union` with or without a name: Data members, methods, nested classes, and type alias, etc.	• This is a Symbols Table for types • Symbols resolved in multiple phases

Function / Class may be templates. Java has a package scope

Symbol Table: Static & Dynamic Scope Rules

- Scoping of Symbols may be static (compile time) or dynamic (run time)

Static Scoping

```
const int b = 5;

int foo() { // Uses lexical context for b
    int a = b + 5; // b in global
    return a;
}
int bar() {
    int b = 2;
    return foo(); // b taken as 5
}
int main() {
    foo(); // b taken as 5. Returns 10
    bar(); // b taken as 5. Returns 10

    return 0;
}
```

- Used in C / C++ / Java – run-time polymorphism in C++ is an exception
- Good for compilers
- Needs symbol table at compile-time only
- We use static scoping in the course

Dynamic Scoping

```
const int b = 5;

int foo() { // Uses run-time context for b
    int a = b + 5; // b in global or in bar
    return a;
}
int bar() {
    int b = 2;
    return foo(); // b taken as 2
}
int main() {
    foo(); // b taken as 5. Returns 10
    bar(); // b taken as 2. Returns 7

    return 0;
}
```

- Used in Python / Lisp
- Good for interpreters
- Needs symbol table at compile-time as well as run-time

Symbol Table: Scope and Visibility

- Scope (visibility) of identifier = portion of program where identifier can be referred to
- Lexical scope = textual region in the program
  - Statement block
  - Method body
  - Class body
  - Module / package / file
  - Whole program (multiple modules)

Symbol Table: Scope and Visibility

- Global scope
  - Names of all classes defined in the program
  - Names of all global functions defined in the program
- Class scope
  - Instance scope: all fields and methods of the class
  - Static scope: all static methods
  - Scope of subclass nested in scope of its superclass
- Method scope
  - Formal parameters and local variables in code block of body method
- Code block scope
  - Variables defined in block

Symbol Table: Interface and Implementation

- Interface
  - Create Symbol Table
  - Search (lookup)
  - Insert
  - Search & Insert
  - Update Attribute
- Implementation
  - Linear List
  - Hash Table
  - Binary Search Tree

Symbol Management in Multiple Scopes using Symbol Tables

```
int a = 10;                 // Ln1: Glb Scp ST.glb
int f(int x, int y) {       // Ln2: Prm in Fn Scp ST.f()
    static int s = 2;       // Ln3: Static in Fn Scp ST.glb
                            // Init. as static
                            // Retain value across calls
    int p = x - 4;          // Ln4: Auto in Fn Scp ST.f()
    int q = s;              // Ln5: Auto in Fn Scp ST.f()
    s = q * p + a;          // s@Ln3, q@Ln5, p@Ln4, a@Ln1
    {                       // Blk Scp ST.f().B
        int p = y + 3;      // Ln6: Auto in Blk Scp ST.f().B
                            // Hides p in Ln4. Use y@Ln2
        s = p + q;          // s@Ln3, p@Ln6, q@Ln5
    }                       // Blk Scp ST.f().B
    return x + p;           // x@Ln2, p@Ln4
}                           // Fn Scp ST.f()
int b = 6;                  // Ln7: Glb Scp ST.glb
int main() {                // Fn Scp ST.main()
    int c;                  // Ln8: Auto in Fn Scp ST.main()
    c = f(a, b);            // c@Ln8, a@Ln1, b@Ln7
    {                       // Blk Scp ST.main().B
        int a = 4;          // Ln9: Auto in Blk Scp ST.main().B
                            // Hides a in Ln1
        c = f(c, a);        // c@Ln8, a@Ln9
    }                       // Blk Scp ST.main().B
    return 0;
}                           // Fn Scp ST.main()
```

ST.glb				Parent: *Null*
a_g	int	glb	4	0
f	$int^2 \rightarrow int$	func	0	ST.f()
s@f	int	lstat	4	+4
b_g	int	glb	4	+8
main	void $\rightarrow$ int	func	0	ST.main()
ST.f()				**Parent: *ST.glb***
y, x	int	prm	4	+8, +4
p, q	int	lcl	4	0, –4
ST.f().B				**Parent: *ST.f()***
p	int	lcl	4	0
ST.main()				**Parent: *ST.glb***
c	int	lcl	4	0
ST.main().B				**Parent: *ST.main()***
a	int	lcl	4	0

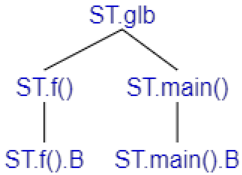
On Flattening

ST.f()				Parent: *ST.glb*
y, x	int	prm	4	+8, +4
p, q	int	lcl	4	0, –4
p@f.B	int	blcl	4	–8
ST.main()				**Parent: *ST.glb***
c	int	lcl	4	0
a@main.B	int	blcl	4	–4

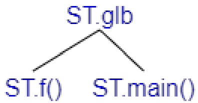
Symbol Management in Multiple Scopes using Symbol Tables

```
int a = 10;               // Ln1: ST.glb
int f(int x, int y) {     // Ln2: ST.f()
    static int s = 2;     // Ln3:  ST.glb
                          // Use as static
    int p = x - 4;        // Ln4: ST.f()
    int q = s;            // Ln5:  ST.f()
    s = q * p + a;        // s@Ln3, q@Ln5
                          // p@Ln4, a@Ln1
    {                     // ST.f().B
        int p = y + 3;    // Ln6: ST.f().B
                          // Hides p@Ln4. y@Ln2
        s = p + q;        // s@Ln3, p@Ln6, q@Ln5
    }                     // ST.f().B
    return x + p;         // x@Ln2, p@Ln4
}                         // ST.f()
int b = 6;                // Ln7: ST.glb
int main() {              // ST.main()
    int c;                // Ln8: ST.main()
    c = f(a, b);          // c@Ln8, a@Ln1, b@Ln7
    {                     // ST.main().B
        int a = 4;        // Ln9: ST.main().B
                          // Hides a@Ln1
        c = f(c, a);      // c@Ln8, a@Ln9
    }                     // ST.main().B
    return 0;
}                         // ST.main()
```

```
f: t1 = x - 4
   p = t1
   q = s@f
   t2 = q * p
   t3 = t2 + a
   s@f = t3
   t4 = y + 3
   p@f.B = t4
   t5 = p@f.B + q
   s@f = t5
   t6 = x + p
   return t6

   a_g = 10 // glb
   b_g = 6  // glb
   s@f = 2  // loc stat
main: param b_g
   param a_g
   c = call f, 2
   a@main.B = 4
   param a@main.B
   param c
   c = call f, 2
   return 0
```



Tree of Symbol Tables



Compacted Tree of Symbol Tables

STs of nested blocks flattened within ST of function

Example:
Translation to TAC with Symbol Table

Examples by PPD

Global & Function Scopes

Ex. 1

```
int m_dist(int x1, int y1, int x2, int y2) {
    int d, x_diff, y_diff;
    x_diff = (x1 > x2) ? x1 - x2 : x2 - x1;
    y_diff = (y1 > y2) ? y1 - y2 : y2 - y1;
    d = x_diff + y_diff;
    return d;
}
int x1 = 0, y1 = 0; // Global static
int main(int argc, char *argv[]) {
    int x2 = -2, y2 = 3, dist = 0;
    dist = m_dist(x1, y1, x2, y2); return 0;
}
```

```
m_dist: if x1 > x2 goto L1
   t1 = x2 - x1
   goto L2
L1:t1 = x1 - x2
L2:x_diff = t1
   if y1 > y2 goto L3
   t2 = y1 - y2
   goto L4
L3:t2 = y2 - y1
L4:y_diff = t2
   d = x_diff + y_diff
   return d
```

```
// global initialization
   x1_g = 0
   y1_g = 0
main: x2 = -2
   y2 = 3
   dist = 0
   param y2
   param x2
   param y1_g
   param x1_g
   dist = call m_dist, 4
   return 0
```

ST.glb				Parent: *Null*
m_dist	$int^4 \rightarrow int$	func	0	ST.m_dist
x1_g	int	global	4	0
y1_g	int	global	4	+4
main	$int \times arr(*, char*) \rightarrow int$	func	0	ST.main
ST.m_dist()				Parent: *ST.glb*
y2	int	param	4	+20
x2	int	param	4	+16
y1	int	param	4	+12
x1	int	param	4	+8
d	int	local	4	−4
x_diff	int	local	4	−8
y_diff	int	local	4	−12

ST.m_dist() Continued				Parent: *ST.glb*
t1	int	temp	4	−16
t2	int	temp	4	−20
ST.main()				Parent: *ST.glb*
argv	arr(*,char*)	param	4	+8
argc	int	param	4	+4
x2	int	local	4	−4
y2	int	local	4	−8
dist	int	local	4	−12

- `T f(T1, T2)` *has type:* $T1 \times T2 \rightarrow T$
- *Base pointer is 0*
- *RA and RV are not shown*
- *STs form a tree with ST.glb as the root*

Global, Function & Block Scopes Ex. 2

```
int m_dist(int x1, int y1, int x2, int y2) {
    int d; { int x_diff; // Nested block: $2
    { int y_diff; // Nested nested block: $1
        x_diff = (x1 > x2) ? x1 - x2 : x2 - x1;
        y_diff = (y1 > y2) ? y1 - y2 : y2 - y1;
        d = x_diff + y_diff;
    } }
    return d;
}
int x1 = 0, y1 = 0; // Global static
int main() {
    int x2 = -2, y2 = 3, dist = 0;
    dist = m_dist(x1, y1, x2, y2); return 0; }
```

```
m_dist: if x1 > x2 goto L1
   t1 = x2 - x1
   goto L2
L1:t1 = x1 - x2
L2:x_diff_$2 = t1
   if y1 > y2 goto L3
   t2 = y1 - y2
   goto L4
L3:t2 = y2 - y1
L4:y_diff_$1 = t2
   d = x_diff_$2 + y_diff_$1
   return d
```

```
// global initialization
   x1_g = 0
   y1_g = 0
main: x2 = -2
   y2 = 3
   dist = 0
   param y2
   param x2
   param y1_g
   param x1_g
   dist = call m_dist, 4
   return 0
```

ST.glb				Parent: *Null*
m_dist	$int^4 \rightarrow int$	func	0	ST.m_dist
x1_g	int	global	4	0
y1_g	int	global	4	+4
main	$void \rightarrow int$	func	0	ST.main
ST.m_dist()				Parent: *ST.glb*
y2, x2	int	param	4	+20, +16
y1, x1	int	param	4	+12, +8
d	int	local	4	−4
x_diff_$2	int	local	4	−8
y_diff_$1	int	local	4	−12
t1, t2	int	temp	4	−16, −20

ST.m_dist().$2		Parent: *ST.m_dist*		
x_diff	int	local	4	0
ST.m_dist().$1		Parent: *ST.m_dist.$2*		
y_diff	int	local	4	0
ST.main()		Parent: *ST.glb*		
x2	int	local	4	−4
y2	int	local	4	−8
dist	int	local	4	−12

- Static Allocation
- Automatic Allocation
- Embedded Automatic Allocation

Global & Function Scopes + struct, typedef — Ex. 3

```
typedef struct { int _x, _y; } Point;
int m_dist(Point p, Point q) {
    int d, x_diff, y_diff;
    x_diff=(p._x>q._x)?p._x-q._x: q._x-p._x;
    y_diff=(p._y>q._y)?p._y-q._y: q._y-p._y;
    d = x_diff + y_diff;
    return d; }
Point p = { 0, 0 }; // Global static
int main(int argc, char *argv[]) {
    Point q = { -2, 3 };
    int dist = 0;
    dist = m_dist(p, q);
    return 0; }
```

```
m_dist:
   if p._x > q._x goto L1
   t1 = q._x - p._x
   goto L2
L1:t1 = p._x - q._x
L2:x_diff = t1
   if p._y > q._y goto L3
   t2 = q._y - p._y
   goto L4
L3:t2 = p._y - q._y
L4:y_diff = t2
   d = x_diff + y_diff
   return d
```

```
// global initialization
   p_g._x = 0
   p_g._y = 0
main:
   q._x = -2 // Offset(q)
   q._y = 3  // Offset(q)-4
   dist = 0
   param q
   param p_g
   dist = call m_dist, 2
   return 0
```

ST.glb				Parent: *Null*
Point	struct Point	alias	0	ST.Point
m_dist	Point × Point → int	func	0	ST.m_dist
p_g	Point	global	8	0
main	int × arr(*,char*) → int	func	0	ST.main

ST.m_dist()				Parent: *ST.glb*
q, p	Point	param	8	+16, +8
d	int	local	4	–4
x_diff	int	local	4	–8
y_diff	int	local	4	–12
t1, t2	int	temp	4	–16, –20

ST_type.struct Point				Parent: *ST.glb*
_x	int	member	4	0
_y	int	member	4	–4

ST.main()				Parent: *ST.glb*
argv	arr(*,char*)	param	4	+8
argc	int	param	4	+4
q	Point	local	8	–12
dist	int	local	4	–20

Global, Function & Class Scopes Ex. 4

```
class Point { public: int _x, _y;
    Point(int x, int y) : _x(x), _y(y) { }
    ~Point() { };
};
int m_dist(Point p, Point q) {
    int d, x_diff, y_diff;
    x_diff=(p._x>q._x)?p._x-q._x:q._x-p._x;
    y_diff=(p._y>q._y)?p._y-q._y:q._y-p._y;
    d = x_diff + y_diff;
    return d; }
Point p = { 0, 0 }; // Global static
int main() {
    Point q = {-2, 3}; int dist = m_dist(p, q);
    return 0;
}
```

```
m_dist: if p._x > q._x goto L1
   t1 = q._x - p._x
   goto L2
L1:t1 = p._x - q._x
L2:x_diff = t1
   if p._y > q._y goto L3
   t2 = q._y - p._y
   goto L4
L3:t2 = p._y - q._y
L4:y_diff = t2
   d = x_diff + y_diff
   return d
crt: param 0 // Sys Caller
     param 0
     &p_g = call Point, 2
     param argv // crt cont.
     param argc
     result = call main, 2
     param &p_g
     call ~Point, 1
     return
main:param 3
     param -2
     &q = call Point, 2
     param q
     param p_g
     dist = call m_dist, 2
     param &q
     call ~Point, 1
     return 0
```

ST.glb				Parent: *Null*
m_dist	Point^2 → int	func	0	ST.m_dist
p_g	Point	glb	8	0
main	void → int	func	0	ST.main
ST.m_dist()				Parent: *ST.glb*
q, p	Point	prm	8	+16, +8
d	int	lcl	4	−4
x_diff	int	lcl	4	−8
y_diff	int	lcl	4	−12
t1, t2	int	tmp	4	−16, −20

ST_type.class Point				Parent: *ST.glb*
_x, _y	int	mem	4	0, −4
Point	int^2 → Point	mtd	0	ST.Point()
~Point	Point* → void	mtd	0	ST.~Point()
ST.main()				Parent: *ST.glb*
q	class Point	lcl	8	−24
dist	int	lcl	4	−32

- *Name, Type, Category, Size, Offset*
- ST.Point() *and* ST.~Point() *not shown*

User Defined Types (UDT) Ex. 5

```
class Point { public: int _x, _y;
    Point(int x, int y) : _x(x), _y(y) { }
    ~Point() { }; };
class Rect { Point _lt, _rb; public:
    Rect(Point& lt,Point& rb): _lt(lt),_rb(rb) {}
    ~Rect() { }
    Point get_LT() { return _lt; }
    Point get_RB() { return _rb; }
};
```

```
int m_dist(Point p, Point q) { int d, x_diff, y_diff;
    x_diff=(p._x>q._x)?p._x-q._x:q._x-p._x;
    y_diff=(p._y>q._y)?p._y-q._y:q._y-p._y;
    d = x_diff + y_diff; return d; }
Point p = { 0, 0 }; // Global static
int main() {
    Point q = { -2, 3 }; Rect r(p, q);
    int dist = m_dist(r.get_LT(), r.get_RB());
    return 0; }
```

ST.glb				Parent: *Null*
m_dist	Point^2 → int	func	0	ST.m_dist
p_g	Point	glb	8	0
main	void → int	func	0	ST.main
ST.m_dist()				**Parent: *ST.glb***
q, p	Point	prm	8	+16, +8
d	int	lcl	4	–4
x_diff	int	lcl	4	–8
y_diff	int	lcl	4	–12
t1, t2	int	tmp	4	–16, –20
ST.main()				**Parent: *ST.glb***
argv	T_2d_Arr	prm	4	+8
argc	int	prm	4	+4
q	Point	lcl	8	–24
r	Rect	lcl	16	–24
dist	int	lcl	4	–32

ST_type.glb				Parent: *Null*
Point	class Point	type	8	ST.Point
Rect	class Rect	type	16	ST.Rect
T_2d_Arr	arr(*,char*)		4	0
ST_type.class Point				**Parent: *ST_type.glb***
_x, _y	int	mem	4	0, –4
Point	int^2 → Point	mtd	0	ST.Point()
~Point	Point* → void	mtd	0	ST.~Point()
ST_type.class Rect				**Parent: *ST_type.glb***
_lt, _rb	Point	mem	8	0, –8
Rect	Point&^{2} → Rect	mtd	0	ST.Rect()
~Rect	Rect* → void	mtd	0	ST.~Rect()
get_LT	Rect* → Point	mtd	0	ST.get_LT()
get_RB	Rect* → Point	mtd	0	ST.get_RB()

Integer Addition

Ex. 6

```
int add(int x, int y) {
    int z;
    z = x + y;
    return z;
}
int main(int argc, char* argv[]) {
    int a, b, c;
    a = 2;
    b = 3;
    c = add(a, b);
    return 0;
}
```

```
add:    t1 = x + y
        z = t1
        return z
main:   t1 = 2
        a = t1
        t2 = 3
        b = t2
        param b
        param a
        c = call add, 2
        return
```

ST.glb				*Parent = null*
add	int × int → int	func	0	ST.add
main	int × array(*, char*) → int	func	0	ST.main
ST.add()				*Parent = ST.glb*
y	int	param	4	+8
x	int	param	4	+4
z	int	local	4	0
t1	int	temp	4	–4

ST.main()				*Parent = ST.glb*
argv	array(*, char*)	param	4	+8
argc	int	param	4	+4
a	int	local	4	0
b	int	local	4	–4
c	int	local	4	–8
t1	int	temp	4	–12
t2	int	temp	4	–16

- *Name, Type, Category, Size, & Offset*
- *RA & RV skipped*

Integer Addition: Peep-hole Optimized

Ex. 6A

```
int add(int x, int y) {
    int z;
    z = x + y;
    return z;
}
int main(int argc, char* argv[]) {
    int a, b, c;
    a = 2;
    b = 3;
    c = add(a, b);
    return 0;
}
```

```
add:    z = x + y
        return z
main:   a = 2
        b = 3
        param b
        param a
        c = call add, 2
        return
```

ST.glb				*Parent = null*
add	int × int → int	func	0	ST.add
main	int × array(*, char*) → int	func	0	ST.main
ST.add()				*Parent = ST.glb*
y	int	param	4	+8
x	int	param	4	+4
z	int	local	4	0

ST.main()				*Parent = ST.glb*
argv	array(*, char*)	param	4	+8
argc	int	param	4	+4
a	int	local	4	0
b	int	local	4	–4
c	int	local	4	–8

- *Name, Type, Category, Size, & Offset*
- *RA & RV skipped*

Floating Point Addition


```
double d_add(double x, double y) {
    double z;
    z = x + y;
    return z;
}
int main() {
    double a, b, c;
    a = 2.5;
    b = 3.4;
    c = d_add(a, b);
    return 0;
}
```

```
d_add:  t1 = x + y
        z = t1
        return z
main:   a = 2.5
        b = 3.4
        param b
        param a
        c = call d_add, 2
        return
```

ST.glb				*Parent = null*
d_add	double × double → double	func	0	ST.d_add
main	void → int	func	0	ST.main
ST.d_add()				*Parent = ST.glb*
y	double	param	8	+16
x	double	param	8	+8
z	double	local	8	0
t1	double	temp	8	–4

ST.main()				*Parent = ST.glb*
a	double	local	8	0
b	double	local	8	–8
c	double	local	8	–16

- *Name, Type, Category, Size, & Offset*
- *RA & RV skipped*

Swap

Ex. 8

```
void swap(int *x, int *y) {
    int t;
    t = *x;
    *x = *y;
    *y = t;
    return;
}
int main() {
    int a = 1, b = 2;
    swap(&a, &b);
    return 0;
}
```

```
swap:   t = *x;
        *x = *y;
        *y = t;
        return
main:   a = 1
        b = 2
        t1 = &b
        param t1
        t2 = &a
        param t2
        call swap, 2
        return
```

ST.glb				*Parent = null*
swap	int* × int* → void	func	0	ST.swap
main	void → int	func	0	ST.main

ST.swap()				*Parent = ST.glb*
y	int*	param	4	+8
x	int*	param	4	+4
t	int	local	4	0

ST.main()			*Parent = ST.glb*	
a	int	local	4	0
b	int	local	4	−4
t1	int*	temp	4	−8
t2	int*	temp	4	−12

- *Name, Type, Cat., Size, & Offset*
- *RA & RV skipped*

Complex Addition Ex. 9


```
typedef struct { double re, im; } Complex;
Complex C_add(Complex x, Complex y) {
    Complex z;
    z.re = x.re + y.re;
    z.im = x.im + y.im;
    return z;
}
int main() {
    Complex a = { 2.3, 6.4 };
    Complex b = { 3.5, 1.4 };
    Complex c = { 0.0, 0.0 };
    c = C_add(a, b);
    return 0;
}
```

```
C_add:  t1 = x.re + y.re
        z.re = t1
        t2 = x.im + y.im
        z.im = t2
        RV = z
        return
```

```
main:  a.re = 2.3
       a.im = 6.4
       b.re = 3.5
       b.im = 1.4
       c.re = 0.0
       c.im = 0.0
       param b
       param a
       c = call C_add, 2
       return
```

ST.glb				*Parent = null*
Complex	struct Complex	alias	0	ST.Complex
C_add	$\text{Complex}^2 \rightarrow \text{Complex}$	func	0	ST.C_add
main	$\text{void} \rightarrow \text{int}$	func	0	ST.main
ST.C_add()				*ST.C_add.parent = ST.glb*
y, x	Complex	param	16	+32, +48
RV	Complex	rval	16	+16
z	Complex	local	16	0
t1, t2	Complex	local	16	−16, −32

ST.Complex		*Parent = ST.glb*		
re	double	local	8	0
im	double	local	8	+8
ST.main()		*Parent = ST.glb*		
RV	int	rval	4	+4
a	Complex	local	16	0
b	Complex	local	16	−16
c	Complex	local	16	−32

- *Name, Type, Cat., Size, & Offset*
- *RA skipped*

Sum of an Array


```
#include <stdio.h>
int Sum(int a[], int n) {
    int i, s = 0;
    for(i = 0; i < n; ++i) {
        int t; t = a[i]; s += t;
    } return s;
}
int main() { int a[3], i, s, n = 3;
    for(i = 0; i < n; ++i) a[i] = i;
    s = Sum(a, n);
    printf("%d\n", s);
}
```

```
Sum: s = 0
     i = 0
L0:  if i < n goto L2
     goto L3
L1:  t1 = i + 1
     i = t1
     goto L0
L2:  t2 = i * 4
     t_1 = a[t2]
     t3 = s + t_1
     s = t3
     goto L1
L3:  return s
```

```
main: n = 3
      i = 0
L0:   if i < n goto L2
      goto L3
L1:   t1 = i + 1
      i = t1
      goto L0
L2:   t2 = i * 4
      a[t2] = i
      goto L1
L3:   param n
      param a
      s = call Sum, 2
      param s
      param "%d\n"
      call printf, 2
      return
```

- *Parameter* `s` *of* `printf` *is handled through varargs.*
- *Block local variable* `t` *is named as* `t_1` *to qualify for the unnamed block within which it occurs.*

ST.glb				*Parent = null*
Sum	array(*, int) × int → int	func	0	ST.Sum
main	void → int	func	0	ST.main
ST.main()				*Parent = ST.glb*
a	array(3, int)	local	12	0
i, s, n	int	local	4	−12, −16, −20
t1, t2	int	temp	4	−24, −28

ST.Sum()				*Parent = ST.glb*
n	int	param	4	+8
a	int[]	param	4	+4
i	int	local	4	0
s	int	local	4	−4
t_1 (t)	int	blk_local	4	−8
t1...t3	int	temp	4	−12...−20

- *Name, Type, Cat., Size, & Offset*

Using function (pointer) parameter

Ex. 11

```
int trans(int a, int(*f)(int), int b)
{ return a + f(b); }

int inc(int x) { return x + 1; }
int dec(int x) { return x - 1; }

int main() { int x, y, z;
    x = 2; y = 3;
    z = trans(x, inc, y) +
        trans(x, dec, y);
    return 0;
}
```

```
trans:  param b
        t1 = call f, 1
        t2 = a + t1
        return t2

inc:    t1 = x + 1
        return t1

dec:    t1 = x - 1
        return t1
```

```
main:   x = 2
        y = 3
        param y
        param inc
        param x
        t1 = call trans, 3
        param y
        param dec
        param x
        t2 = call trans, 3
        t3 = t1 + t2
        z = t3
        return
```

ST.glb				*Parent* = *null*
trans	int × ptr(int → int) × int → int	func	0	ST.trans
inc	int → int	func	0	ST.inc
dec	int → int	func	0	ST.dec
main	void → int	func	0	ST.main
ST.trans()				*Parent* = *ST.glb*
b	int	prm	4	+12
f	ptr(int → int)	prm	4	+8
a	int	prm	4	+4
t1, t2	int	tmp	4	0, −4

ST.inc()				*Parent* = *ST.glb*
x	int	prm	4	+4
t1	int	tmp	4	0
ST.dec()				*Parent* = *ST.glb*
x	int	prm	4	+4
t1	int	tmp	4	0
ST.main()				*Parent* = *ST.glb*
x, y, z	int	lcl	4	0, −4, −8
t1...t3	int	tmp	4	−12...−20

- *Name, Type, Cat., Size, & Offset. RA & RV skipped.*

Nested Blocks

Ex. 12

```
int a; // global scope
int f(int x) { // function scope f
    int t, u;
    t = x; // t in f, x in f
    { // un-named block scope f_1
        int p, q, t;
        p = a; // p in f_1, a in global
        t = 4; // t in f_1, hides t in f
        { // un-named block scope f_1_1
            int p;
            p = 5; // p in f_1_1, hides p in f_1
        }
        q = p; // q in f_1, p in f_1
    }
    return u = t; // u in f, t in f
}
```

```
f: // function scope f
   // t in f, x in f
   t = x
   // p in f_1, a in global
   p@f_1 = a@glb
    // t in f_1, hides t in f
   t@f_1 = 4
   // p in f_1_1, hides p in f_1
   p@f_1_1 = 5
   // q in f_1, p in f_1
   q@f_1 = p@f_1
   // u in f, t in f
   u = t
```

ST.glb				*Parent = null*	
a	int	global	4	0	null
f	int → int	func	0	0	ST.f
ST.f()				*Parent = ST.glb*	
x	int	param	4	+4	null
t, u	int	local	4	0, −4	null
f_1	null	block	–		ST.f_1

ST.f_1				*Parent = ST.f*	
p, q, t	int	local	4	0, −4, −8	null
f_1_1	null	block	–		ST.f_1_1
ST.f_1_1				*Parent = ST.f_1*	
p	int	local	4	0	null

- *Name, Type, Cat., Size, Offset, & Symtab*

Grammar and Parsing for this example is discussed with the Parse Tree in 3-Address Code Generation

Nested Blocks Flattened

Ex. 12A

```
f: // function scope f
   // t in f, x in f
   t = x
   // p in f_1, a in global
   p@f_1 = a@glb
   // t in f_1, hides t in f
   t@f_1 = 4
   // p in f_1_1, hides p in f_1
   p@f_1_1 = 5
   // q in f_1, p in f_1
   q@f_1 = p@f_1
   // u in f, t in f
   u = t
```

```
f: // function scope f
   // t in f, x in f
   t = x
   // p in f_1, a in global
   p#1 = a@glb   // p@f_1
   // t in f_1, hides t in f
   t#3 = 4       // t@f_1
   // p in f_1_1, hides p in f_1
   p#4 = 5       // p@f_1_1
   // q in f_1, p in f_1
   q#2 = p#1     // q@f_1, p@f_1
   // u in f, t in f
   u = t
```

ST.glb				*Parent = null*	
x	int	param	4	+4	null
t, u	int	local	4	0, −4	null
f_1	null	block	–		ST.f_1
ST.f_1				*Parent = ST.f*	
p, q, t	int	local	4	0, −4, −8	null
f_1_1	null	block	–		ST.f_1_1
ST.f_1_1				*Parent = ST.f_1*	
p	int	local	4	0	null

ST.f()				*Parent = ST.glb*	
x	int	param	4	+4	null
t	int	local	4	0	null
u	int	local	4	−4	null
p#1 (p@f_1)	int	blk-local	4	−8	null
q#2 (q@f_1)	int	blk-local	4	−12	null
t#3 (t@f_1)	int	blk-local	4	−16	null
p#4 (p@f_1_1)	int	blk-local	4	−20	null

- *Name, Type, Cat., Size, Offset, & Symtab*

Global & Function Scope with Array

Ex. 13

```
int x, ar[2][3], y;
int add(int x, int y);
double a, b;
int add(int x, int y) {
    int t; t = x + y;
    return t;
}
int main() { int c;
    x = 1; y = ar[x][x];
    c = add(x, y);
    return 0;
}
```

```
add:    t#1 = x + y
        t = t#1
        return t
```

```
main:   t#1 = 1
        x = t#1
        t#2 = x * 12
        t#3 = x * 4
        t#4 = t#2 + t#3
        y = ar[t#4]
        param x
        param y
        c = call add, 2
        return
```

ST.glb					*Parent = null*
x	int	global	4	0	null
ar	array(2, array(3, int))	global	24	4	null
y	int	global	4	28	null
add	int × int → int	func	0	32	ST.add
a	double	global	8	32	null
b	double	global	8	40	null
main	void → int	func	0	48	ST.main

- *Name, Type, Cat., Size, Offset, & Symtab*

ST.add()		*Parent = ST.glb*		
x, y	int	param	4	0, 4
t	int	local	4	8
t#1	int	temp	4	12

ST.main()		*Parent = ST.glb*		
c	int	local	4	0
t#1	int	temp	4	4
t#2	int	temp	4	8
t#3	int	temp	4	12
t#4	int	temp	4	16

Grammar and Parsing for this example is discussed with the Parse Tree in 3-Address Code Generation

Global, Extern & Local Static Data

Ex. 14

```
// File Main.c
extern int n;
int Sum(int x) {
    static int lclStcSum = 0;
    lclStcSum += x;
    return lclStcSum;
}
int sum = -1;
int main() { int a = n;
    Sum(a); a *= a;
    sum = Sum(a);
    return 0;
}
// File Global.c
int n = 5;
```

```
      lclStcSum = 0
Sum:  lclStcSum = lclStcSum + x
      return lclStcSum

      sum = -1
main: a = glb_n
      param a
      call Sum, 1
      a = a * a
      param a
      sum = call Sum, 1
      return
```

ST.glb (Main.c)			*Parent = null*	
n	int	extern	4	0
Sum	int → int	func	0	ST.Sum
sum	int	global	4	0
main	void → int	func	0	ST.main
ST.glb (Global.c)			*Parent = null*	
n	int	global	4	0

ST.Sum()		*Parent = ST.glb* (Main.c)		
x	int	param	4	0
lclStcSum	int	static	4	4
ST.main()		*Parent = ST.glb* (Main.c)		
a	int	local	4	0

- *Name, Type, Cat., Size, & Offset*

Binary Search

Ex. 15

```
int bs(int a[], int l, int r, int v) {
    while (l <= r) {
        int m = (l + r) / 2;
        if (a[m] == v)
            return m;
        else
            if (a[m] > v)
                r = m - 1;
            else
                l = m + 1;
    }
    return -1;
}
```

```
100: if l <= r goto 102
101: goto 121
102: t1 = l + r
103: t2 = t1 / 2
104: m = t2
105: t3 = m * 4
106: t4 = a[t3]
107: if t4 == v goto 109
108: goto 111
109: return m
110: goto 100
111: t5 = m * 4
112: t6 = a[t5]
113: if t6 > v goto 115
114: goto 118
115: t7 = m - 1
116: r = t7
117: goto 100
118: t8 = m + 1
119: l = t8
120: goto 100
121: t9 = -1
122: return t9
```

ST.glb				*Parent = null*
bs	array(*, int) $\times$ int^3 $\to$ int	func	0	ST.bs

- *Name, Type, Cat., Size, & Offset*

Temporary variables are numbered in the function scope – the effect of the respective block scope in the numbering is not considered. Hence, we show only a flattened symbol table

ST.bs()				*Parent = ST.glb*
a	array(*, int)	param	4	+16
l	int	param	4	+12
r	int	param	4	+8
v	int	param	4	+4
m	int	local	4	0
t1...t9	int	temp	4	–4...–36

Transpose

Ex. 16

```
int main() {
    int a[3][3];
    int i, j;
    for (i = 0; i < 3; ++i) {
        for (j = 0; j < i; ++j) {
            int t;
            t = a[i][j];
            a[i][j] = a[j][i];
            a[j][i] = t;
        }
    }
    return 0;
}
```

```
100: t01 = 0
101: i = t01
102: t02 = 3
103: if i < t02 goto 108
104: goto 134
105: t03 = i + 1
106: i = t03
107: goto 103
108: t04 = 0
109: j = t04
110: if j < i goto 115
111: goto 105
112: t05 = j + 1
113: j = t05
114: goto 110
115: t06 = 12 * i
116: t07 = 4 * j
117: t08 = t06 + t07
118: t09 = a[t08]
119: t = t09
120: t10 = 12 * i
121: t11 = 4 * j
122: t12 = t10 + t11
123: t13 = 12 * j
124: t14 = 4 * i
125: t15 = t13 + t14
126: t16 = a[t15]
127: a[t12] = t16
128: t17 = 12 * j
129: t18 = 4 * i
130: t19 = t17 + t18
131: a[t19] = t
132: goto 112
133: goto 105
134: return
```

ST.glb				*Parent = null*
main	void → int	func	0	ST.main

- *Name, Type, Cat., Size, & Offset*

ST.main()				*Parent = ST.glb*
a	array(3, array(3, int))	param	4	0
i	int	local	4	−4
j	int	local	4	−8
t01...t19	int	temp	4	−12...−84

Machine Independent Translation

Dragon Book: Pages 378-384 (Translation of Expressions)
Dragon Book: Pages 386-398 (Type Checking)
Dragon Book: Pages 399-408 (Control Flow)
Dragon Book: Pages 410-417 (Backpatching)
Examples by PPD

Arithmetic Expressions

A Calculator Grammar

$$
\begin{array}{rlll}
1: & L & \rightarrow & L\ S\ \backslash\text{n} \\
2: & L & \rightarrow & S\ \backslash\text{n} \\
3: & S & \rightarrow & \textbf{id} = E \\
4: & E & \rightarrow & E + E \\
5: & E & \rightarrow & E - E \\
6: & E & \rightarrow & E * E \\
7: & E & \rightarrow & E\ /\ E \\
8: & E & \rightarrow & (E) \\
9: & E & \rightarrow & -E \\
10: & E & \rightarrow & \textbf{num} \\
11: & E & \rightarrow & \textbf{id}
\end{array}
$$

Attributes for Expression

$E.loc$: – Location to store the value of the expression.
– This will exist in the Symbol Table.

id.*loc*: – Location to store the value of the identifier **id**.
– This will exist in the Symbol Table.

num.*val*: – Value of the numeric (integer) constant.

Auxiliary Methods for Translation

$gentemp()$:
- Generates a new temporary and inserts it in the Symbol Table
- Returns a pointer to the new entry in the Symbol Table

$emit(result, arg1, op, arg2)$:

- Spits a 3 Address Code of the form:
  `result = arg1 op arg2`
- op usually is a binary operator
- If `arg2` is missing, op is unary
- If op also is missing, this is a copy instruction

Expression Grammar with Actions

$$
\begin{array}{rlcll}
1: & L & \rightarrow & L\ S\ \backslash\mathrm{n} & \{\ \} \\
2: & L & \rightarrow & S\ \backslash\mathrm{n} & \{\ \} \\
3: & S & \rightarrow & \mathbf{id} = E & \{\ emit(\mathbf{id}.loc = E.loc);\ \} \\
4: & E & \rightarrow & E_1 + E_2 & \{\ E.loc = gentemp(); \\
 & & & & \quad emit(E.loc = E_1.loc + E_2.loc);\ \} \\
5: & E & \rightarrow & E_1 - E_2 & \{\ E.loc = gentemp(); \\
 & & & & \quad emit(E.loc = E_1.loc - E_2.loc);\ \} \\
6: & E & \rightarrow & E_1 * E_2 & \{\ E.loc = gentemp(); \\
 & & & & \quad emit(E.loc = E_1.loc * E_2.loc);\ \} \\
7: & E & \rightarrow & E_1\ /\ E_2 & \{\ E.loc = gentemp(); \\
 & & & & \quad emit(E.loc = E_1.loc / E_2.loc);\ \} \\
8: & E & \rightarrow & (E_1) & \{\ E.loc = E_1.loc;\ \} \\
9: & E & \rightarrow & -\ E_1 & \{\ E.loc = gentemp(); \\
 & & & & \quad emit(E.loc = -E_1.loc);\ \} \\
10: & E & \rightarrow & \mathbf{num} & \{\ E.loc = gentemp(); \\
 & & & & \quad emit(E.loc = \mathbf{num}.val);\ \} \\
11: & E & \rightarrow & \mathbf{id} & \{\ E.loc = \mathbf{id}.loc;\ \}
\end{array}
$$

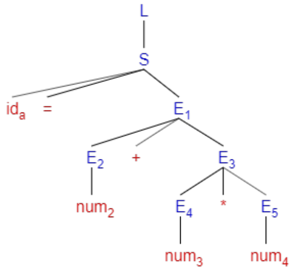
Comments: rule 3 — **// No new temporary, copy code**; rule 8 — **// No new temporary, no code**; rule 11 — **// No new temporary, no code**

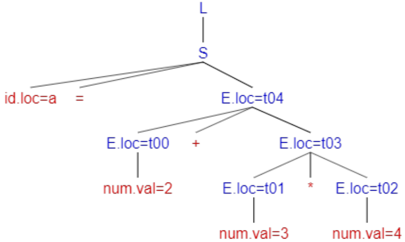
Intermediate 3 address codes are emitted as soon as they are formed.

Translation Example

```
$ ./a.out
a = 2 + 3 * 4
    t00 = 2
    t01 = 3
    t02 = 4
    t03 = t01 * t02
    t04 = t00 + t03
    a = t04
$
$
```

Reductions	TAC
$E \rightarrow \textbf{num}$	`t00 = 2`
$E \rightarrow \textbf{num}$	`t01 = 3`
$E \rightarrow \textbf{num}$	`t02 = 4`
$E \rightarrow E_1 * E_2$	`t03 = t01 * t02`
$E \rightarrow E_1 + E_2$	`t04 = t00 + t03`
$S \rightarrow \textbf{id} = E$	`a = t04`





Bison Specs (calc.y) for Calculator Grammar

```
%{
#include <string.h>
#include <iostream>
#include "parser.h"
extern int yylex();
void yyerror(const char *s);
#define NSYMS 20 /* max # of symbols */
symboltable symtab[NSYMS];
%}
%union {
    int intval;
    struct symtab *symp;
}
%token <symp> NAME
%token <intval> NUMBER

%left '+' '-'
%left '*' '/'
%nonassoc UMINUS

%type <symp> expression
%%

stmt_list: statement '\n'
         | stmt_list statement '\n'
         ;
```

```
statement: NAME '=' expression
    { emit($1->name, $3->name); }
         ;
expression: expression '+' expression
    { $$ = gentemp();
      emit($$->name, $1->name, '+', $3->name); }
          | expression '-' expression
    { $$ = gentemp();
      emit($$->name, $1->name, '-', $3->name); }
          | expression '*' expression
    { $$ = gentemp();
      emit($$->name, $1->name, '*', $3->name); }
          | expression '/' expression
    { $$ = gentemp();
      emit($$->name, $1->name, '/', $3->name); }
          | '(' expression ')'
    { $$ = $2; }
          | '-' expression %prec UMINUS
    { $$ = gentemp();
      emit($$->name, $2->name, '-');  }
          | NAME { $$ = $1; }
          | NUMBER
    { $$ = gentemp();
      emit($$->name, $1); }
          ;
%%
```

Bison Section Specs (calc.y) for Calculator Grammar


```
/* Look-up Symbol Table */
symboltable *symlook(char *s) {
    char *p;
    struct symtab *sp;
    for(sp = symtab;
        sp < &symtab[NSYMS]; sp++) {
        /* is it already here? */
        if (sp->name &&
           !strcmp(sp->name, s))
            return sp;
        if (!sp->name) {
        /* is it free */
            sp->name = strdup(s);
            return sp;
        }
        /* otherwise continue to next */
    }
    yyerror("Too many symbols");
    exit(1); /* cannot continue */
} /* symlook */

/* Generate temporary variable */
symboltable *gentemp() {
    static int c = 0; /* Temp counter */
    char str[10]; /* Temp name */
    /* Generate temp name */
    sprintf(str, "t%02d", c++);
    /* Add temporary to symtab */
    return symlook(str);
}
```

```
/* Output 3-address codes */
void emit(char *s1,      // Result
          char *s2,      // Arg 1
          char c = 0,    // Operator
          char *s3 = 0) // Arg 2
{
    if (s3)
        /* Assignment with Binary operator */
        printf("\t%s = %s %c %s\n",s1, s2, c, s3);
    else
        if (c)
            /* Assignment with Unary operator */
            printf("\t%s = %c %s\n",s1, c, s2);
        else
            /* Simple Assignment */
            printf("\t%s = %s\n",s1, s2);
}

void yyerror(const char *s) {
    std::cout << s << std::endl;
}

int main() {
    yyparse();
}
```

Header (y.tab.h) for Calculator

```
/* A Bison parser, made by GNU Bison 2.5.  */
/* Tokens. */
#ifndef YYTOKENTYPE
# define YYTOKENTYPE
   /* Put the tokens into the symbol table, so that GDB and other debuggers know about them. */
   enum yytokentype {
     NAME = 258,
     NUMBER = 259,
     UMINUS = 260
   };
#endif
/* Tokens. */
#define NAME 258
#define NUMBER 259
#define UMINUS 260

#if ! defined YYSTYPE && ! defined YYSTYPE_IS_DECLARED
typedef union YYSTYPE {
#line 11 "calc.y" /* Line 2068 of yacc.c  */

    int intval;
    struct symtab *symp;

#line 67 "y.tab.h" /* Line 2068 of yacc.c  */
} YYSTYPE;
# define YYSTYPE_IS_TRIVIAL 1
# define yystype YYSTYPE /* obsolescent; will be withdrawn */
# define YYSTYPE_IS_DECLARED 1
#endif

extern YYSTYPE yylval;
```

Header (parser.h) for Calculator

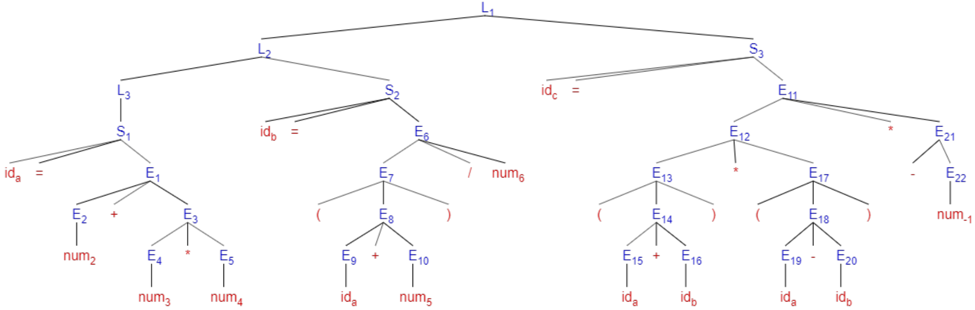
```
#ifndef __PARSER_H
#define __PARSER_H

/* Symbol Table Entry */
typedef struct symtab {
    char *name;
    int value;
} symboltable;

/* Look-up Symbol Table */
symboltable *symlook(char *);

/* Generate temporary variable */
symboltable *gentemp();

/* Output 3-address codes */
/* if s3 != 0 ==> Assignment with Binary operator */
/* if s3 == 0 && c != 0 ==> Assignment with Unary operator */
/* if s3 == 0 && c == 0 ==> Simple Assignment */
void emit(char *s1, char *s2, char c = 0, char *s3 = 0);

#endif // __PARSER_H
```

Flex Specs (calc.l) for Calculator Grammar

```
%{
#include <math.h>
#include "y.tab.h"
#include "parser.h"
%}

ID        [A-Za-z][A-Za-z0-9]*

%%
[0-9]+    {
            yylval.intval = atoi(yytext);
            return NUMBER;
          }

[ \t]     ;         /* ignore white space */


{ID}      { /* return symbol pointer */
            yylval.symp = symlook(yytext);
            return NAME;
          }

"$"       { return 0; /* end of input */ }

\n|.      return yytext[0];
%%
```

Sample Run

```
$ ./a.out
a = 2 + 3 * 4
    t00 = 2
    t01 = 3
    t02 = 4
    t03 = t01 * t02
    t04 = t00 + t03
    a = t04
b = (a + 5) / 6
    t05 = 5
    t06 = a + t05
    t07 = 6
    t08 = t06 / t07
    b = t08
c = (a + b) * (a - b) * -1
    t09 = a + b
    t10 = a - b
    t11 = t09 * t10
    t12 = 1
    t13 = - t12
    t14 = t11 * t13
    c = t14
$
```



Handling of a = 2 + 3 * 4 \n $

Grammar

L	$\rightarrow$	$L\ S$ \n	E	$\rightarrow$	$E * E$
L	$\rightarrow$	S \n	E	$\rightarrow$	$E\ /\ E$
S	$\rightarrow$	**id** $= E$	E	$\rightarrow$	(E)
E	$\rightarrow$	$E + E$	E	$\rightarrow$	$-E$
E	$\rightarrow$	$E - E$	E	$\rightarrow$	**num**
			E	$\rightarrow$	**id**

Reductions

$$\textbf{id}_a = \underline{\textbf{num}_2} + \textbf{num}_3 * \textbf{num}_4\ \backslash\text{n} \ldots$$
$$\Rightarrow \textbf{id}_a = E + \underline{\textbf{num}_3} * \textbf{num}_4\ \backslash\text{n} \ldots$$
$$\Rightarrow \textbf{id}_a = E + E * \underline{\textbf{num}_4}\ \backslash\text{n} \ldots$$

Stack

num	2	
=		
id	$\rightarrow$	"a"

num	3	
+		
E	$\rightarrow$	"t00"
=		
id	$\rightarrow$	"a"

E	$\rightarrow$	"t01"
+		
E	$\rightarrow$	"t00"
=		
id	$\rightarrow$	"a"

Symtab

a	?

a	?
t00	?

a	?
t00	?
t01	?

Handling of a $=$ 2 $+$ 3 * 4 \n $

Grammar

$$
\begin{array}{lcl|lcl}
L & \rightarrow & L\ S\ \backslash n & E & \rightarrow & E * E \\
L & \rightarrow & S\ \backslash n & E & \rightarrow & E\ /\ E \\
S & \rightarrow & \mathbf{id} = E & E & \rightarrow & (E) \\
E & \rightarrow & E + E & E & \rightarrow & -E \\
E & \rightarrow & E - E & E & \rightarrow & \mathbf{num} \\
 & & & E & \rightarrow & \mathbf{id}
\end{array}
$$

Reductions

$$
\begin{array}{ll}
\Rightarrow & \mathbf{id}_a = E + E * \underline{\mathbf{num}_4}\ \backslash n \ldots \\
\Rightarrow & \mathbf{id}_a = E + \underline{E * E}\ \backslash n \ldots \\
\Rightarrow & \mathbf{id}_a = \underline{E + E}\ \backslash n \ldots
\end{array}
$$

Stack

num	4	
*		
E	$\rightarrow$	"t01"
$+$		
E	$\rightarrow$	"t00"
$=$		
id	$\rightarrow$	"a"

Symtab

a	?
t00	?
t01	?

E	$\rightarrow$	"t02"
*		
E	$\rightarrow$	"t01"
$+$		
E	$\rightarrow$	"t00"
$=$		
id	$\rightarrow$	"a"

a	?
t00	?
t01	?
t02	?

E	$\rightarrow$	"t03"
$+$		
E	$\rightarrow$	"t00"
$=$		
id	$\rightarrow$	"a"

a	?
t00	?
t01	?
t02	?
t03	?

Handling of **a = 2 + 3 * 4 \n $**

Grammar

$$
\begin{array}{lcl|lcl}
L & \rightarrow & L\ S\ \backslash\mathrm{n} & E & \rightarrow & E * E \\
L & \rightarrow & S\ \backslash\mathrm{n} & E & \rightarrow & E\ /\ E \\
S & \rightarrow & \mathbf{id} = E & E & \rightarrow & (E) \\
E & \rightarrow & E + E & E & \rightarrow & -\ E \\
E & \rightarrow & E - E & E & \rightarrow & \mathbf{num} \\
 & & & E & \rightarrow & \mathbf{id}
\end{array}
$$

Reductions

$$
\begin{array}{ll}
\Rightarrow & \mathbf{id}_a = \underline{E + E}\ \backslash\mathrm{n}\ \ldots \\
\Rightarrow & \underline{\mathbf{id}_a = E}\ \backslash\mathrm{n}\ \ldots \\
\Rightarrow & \underline{S\ \backslash\mathrm{n}}\ \ldots \\
\Rightarrow & \underline{L}\ \ldots
\end{array}
$$

Stack

E	$\rightarrow$	"t01"
$+$		
E	$\rightarrow$	"t00"
$=$		
id	$\rightarrow$	"a"

E	$\rightarrow$	"t00"
$=$		
id	$\rightarrow$	"a"

\n	
S	

Symtab

a	?
t00	?
t01	?

a	?
t00	?
t01	?
t02	?

a	?
t00	?
t01	?
t02	?
t03	?

Handling of a = 2 + 3 * 4 \n $

Grammar

$$
\begin{array}{lcl|lcl}
L & \rightarrow & L\ S\ \backslash n & E & \rightarrow & E * E \\
L & \rightarrow & S\ \backslash n & E & \rightarrow & E\ /\ E \\
S & \rightarrow & \textbf{id} = E & E & \rightarrow & (E) \\
E & \rightarrow & E + E & E & \rightarrow & -E \\
E & \rightarrow & E - E & E & \rightarrow & \textbf{num} \\
 & & & E & \rightarrow & \textbf{id}
\end{array}
$$

Reductions

$\Rightarrow \textbf{id}_a = E + E * \underline{\textbf{num}_4}\ \backslash n \ldots$

$\Rightarrow \textbf{id}_a = E + \underline{E * E}\ \backslash n \ldots$

$\Rightarrow \textbf{id}_a = \underline{E + E}\ \backslash n \ldots$

Stack

num	4	
*		
E	→	"t01"
+		
E	→	"t00"
=		
id	→	"a"

E	→	"t02"
*		
E	→	"t01"
+		
E	→	"t00"
=		
id	→	"a"

E	→	"t03"
+		
E	→	"t00"
=		
id	→	"a"

Symtab

a	?
t00	?
t01	?

a	?
t00	?
t01	?
t02	?

a	?
t00	?
t01	?
t02	?
t03	?

Handling of a = 8 + 9 \n a + 4 \n $

Grammar

L	$\rightarrow$	$L\ S$ \n	E	$\rightarrow$	$E * E$
L	$\rightarrow$	S \n	E	$\rightarrow$	$E\ /\ E$
S	$\rightarrow$	**id** $= E$	E	$\rightarrow$	(E)
S	$\rightarrow$	E	E	$\rightarrow$	$-\ E$
E	$\rightarrow$	$E + E$	E	$\rightarrow$	**num**
E	$\rightarrow$	$E - E$	E	$\rightarrow$	**id**

Reductions

$\mathbf{id}_a = \underline{\mathbf{num}_8} + \mathbf{num}_9 \ \backslash\mathrm{n}\ \mathbf{id}_a + \mathbf{num}_4 \ \backslash\mathrm{n}\ \$$

$\Rightarrow \mathbf{id}_a = E + \underline{\mathbf{num}_9} \ \backslash\mathrm{n}\ \mathbf{id}_a + \mathbf{num}_4 \ \backslash\mathrm{n}\ \$$

$\Rightarrow \mathbf{id}_a = \underline{E + E} \ \backslash\mathrm{n}\ \mathbf{id}_a + \mathbf{num}_4 \ \backslash\mathrm{n}\ \$$

$\Rightarrow \underline{\mathbf{id}_a = E} \ \backslash\mathrm{n}\ \mathbf{id}_a + \mathbf{num}_4 \ \backslash\mathrm{n}\ \$$

$\Rightarrow \underline{S \ \backslash\mathrm{n}}\ \mathbf{id}_a + \mathbf{num}_4 \ \backslash\mathrm{n}\ \$$

$\Rightarrow L\ \underline{\mathbf{id}_a} + \mathbf{num}_4 \ \backslash\mathrm{n}\ \$$

Stack

num	8
$=$	
id	$\rightarrow$

"a"
?

num	9
$+$	
E	8
$=$	
id	$\rightarrow$

"a"
?

E	9
$+$	
E	8
$=$	
id	$\rightarrow$

"a"
?

Symtab

a	?

a	?

a	?

Stack

E	17
$=$	
id	$\rightarrow$

"a"
?

\n	
S	

L	

Symtab

a	?

a	17

a	17

Handling of a = 8 + 9 \n a + 4 \n $

Grammar

L	$\rightarrow$	$L\ S$ \n	E	$\rightarrow$	$E * E$
L	$\rightarrow$	S \n	E	$\rightarrow$	$E\ /\ E$
S	$\rightarrow$	**id** $= E$	E	$\rightarrow$	(E)
S	$\rightarrow$	E	E	$\rightarrow$	$-\ E$
E	$\rightarrow$	$E + E$	E	$\rightarrow$	**num**
E	$\rightarrow$	$E - E$	E	$\rightarrow$	**id**

Reductions

$\Rightarrow$ L $\underline{\textbf{id}_a}$ $+$ $\textbf{num}_4$ \n **\$**
$\Rightarrow$ L E $+$ $\underline{\textbf{num}_4}$ \n **\$**
$\Rightarrow$ L E $+$ $\underline{E}$ \n **\$**
$\Rightarrow$ L $\underline{E + E}$ \n **\$**
$\Rightarrow$ L $\underline{E}$ \n **\$**
$\Rightarrow$ $\underline{L\ S \text{ \\n}}$ **\$**
$\Rightarrow$ L **\$**

Stack

id	$\rightarrow$
L	

"a"
17

num	4
$+$	
E	17
L	

E	4
$+$	
E	17
L	

Symtab

a	17

a	17

a	17

Stack

E	21
L	

\n	
S	
L	

L	

Symtab

a	17

a	17

a	17

Output

$= 21$

Translation with Lazy Spitting

Intermediate 3 address codes are formed as quads and stored in an array. The quads are spit at the end to output. This can help optimization later.

Note on Bison Specs (calc.y)

- `class quad` is used to represent a quad
- It has the following fields:

Name	Type	Remarks
`op`	`opcodeType`	Specifies the type of 3-address instruction. This can be binary operator, unary operator or copy
`arg1`	`char *`	First argument. If the actual argument is a numeric constant, we use decimal form as a string
`arg2`	`char *`	Second argument
`result`	`char *`	Result

Bison Specs (calc.y) for Calculator Grammar

```
%{
#include <string.h>
#include <iostream>
#include "parser.h"
extern int yylex();
void yyerror(const char *s);
#define NSYMS 20    // max # of symbols
symboltable symtab[NSYMS];
quad *qArray[NSYMS]; // Store of Quads
int quadPtr = 0; // Index of next quad
%}

%union {
    int intval;
    struct symtab *symp;
}

%token <symp> NAME
%token <intval> NUMBER

%left '+' '-'
%left '*' '/'
%nonassoc UMINUS

%type <symp> expression
%%
```

```
statement_list:    statement '\n'
              |    statement_list statement '\n'
              ;
statement: NAME '=' expression
  { qArray[quadPtr++] =
    new quad(COPY, $1->name, $3->name); }
         ;
expression: expression '+' expression
  { $$ = gentemp(); qArray[quadPtr++] =
  new quad(PLUS, $$->name, $1->name, $3->name); }
          | expression '-' expression
  { $$ = gentemp(); qArray[quadPtr++] =
  new quad(MINUS, $$->name, $1->name, $3->name); }
          | expression '*' expression
  { $$ = gentemp(); qArray[quadPtr++] =
  new quad(MULT, $$->name, $1->name, $3->name); }
          | expression '/' expression
  { $$ = gentemp(); qArray[quadPtr++] =
  new quad(DIV, $$->name, $1->name, $3->name); }
          | '(' expression ')'      { $$ = $2; }
          | '-' expression %prec UMINUS
  { $$ = gentemp(); qArray[quadPtr++] =
  new quad(UNARYMINUS, $$->name, $2->name); }
          | NAME                    { $$ = $1; }
          | NUMBER
  { $$ = gentemp(); qArray[quadPtr++] =
```

Bison Specs (calc.y) for Calculator Grammar

```
/* Look-up Symbol Table */
symboltable *symlook(char *s) {
    char *p;
    struct symtab *sp;
    for(sp = symtab;
        sp < &symtab[NSYMS]; sp++) {
        /* is it already here? */
        if (sp->name &&
           !strcmp(sp->name, s))
            return sp;
        if (!sp->name) {
        /* is it free */
            sp->name = strdup(s);
            return sp;
        }
        /* otherwise continue to next */
    }
    yyerror("Too many symbols");
    exit(1); /* cannot continue */
} /* symlook */

/* Generate temporary variable */
symboltable *gentemp() {
    static int c = 0; /* Temp counter */
    char str[10]; /* Temp name */
    /* Generate temp name */
    sprintf(str, "t%02d", c++);
    /* Add temporary to symtab */
    return symlook(str);
}
```

```
void yyerror(const char *s) {
    std::cout << s << std::endl;
}

int main() {
    yyparse();
}
```

Header (y.tab.h) for Calculator

```
/* A Bison parser, made by GNU Bison 2.5.  */
/* Tokens. */
#ifndef YYTOKENTYPE
# define YYTOKENTYPE
   /* Put the tokens into the symbol table, so that GDB and other debuggers know about them. */
   enum yytokentype {
     NAME = 258,
     NUMBER = 259,
     UMINUS = 260
   };
#endif
/* Tokens. */
#define NAME 258
#define NUMBER 259
#define UMINUS 260

#if ! defined YYSTYPE && ! defined YYSTYPE_IS_DECLARED
typedef union YYSTYPE {
#line 13 "calc.y" /* Line 2068 of yacc.c  */

    int intval;
    struct symtab *symp;

#line 67 "y.tab.h" /* Line 2068 of yacc.c  */
} YYSTYPE;
# define YYSTYPE_IS_TRIVIAL 1
# define yystype YYSTYPE /* obsolescent; will be withdrawn */
# define YYSTYPE_IS_DECLARED 1
#endif

extern YYSTYPE yylval;
```

Header (parser.h) for Calculator


```
#ifndef __PARSER_H
#define __PARSER_H

#include<stdio.h>

/* Symbol Table Entry */
typedef struct symtab {
    char *name;
    int value;
}symboltable;

/* Look-up Symbol Table */
symboltable *symlook(char *);

/* Generate temporary variable */
symboltable *gentemp();

typedef enum {
    PLUS = 1,
    MINUS,
    MULT,
    DIV,
    UNARYMINUS,
    COPY,
} opcodeType;
```

```
class quad {
    opcodeType op;
    char *result, *arg1, *arg2;
public:
    quad(opcodeType op1, char *s1, char *s2, char *s3=0):
        op(op1), result(s1), arg1(s2), arg2(s3) { }
    quad(opcodeType op1, char *s, int num):
        op(op1), result(s1), arg1(0), arg2(0)
    {
        arg1 = new char[15];
        sprintf(arg1, "%d", num);
    }
    void print() {
        if ((op <= DIV) && (op >= PLUS)) { // Binary Op
            printf("%s = %s ",result, arg1);
            switch (op) {
                case PLUS: printf("+"); break;
                case MINUS: printf("-"); break;
                case MULT: printf("*"); break;
                case DIV: printf("/"); break;
            }
            printf(" %s\n",arg2);
        }
        else
            if (op == UNARYMINUS) // Unary Op
                printf("%s = - %s\n",result, arg1);
            else // Copy
                printf("%s = %s\n",result, arg1);
    }
};
#endif // __PARSER_H
```

Flex Specs (calc.l) for Calculator Grammar

```
%{
#include <math.h>
#include "y.tab.h"
#include "parser.h"
%}

ID          [A-Za-z][A-Za-z0-9]*

%%
[0-9]+      {
              yylval.intval = atoi(yytext);
              return NUMBER;
            }

[ \t]       ;         /* ignore white space */


{ID}        { /* return symbol pointer */
              yylval.symp = symlook(yytext);
              return NAME;
            }

"$"         { return 0; /* end of input */ }

\n|.        return yytext[0];
%%
```

Sample Run

Output

```
$ ./a.out
a = 2 + 3 * 4
b = (a + 5) / 6
c = (a + b) * (a - b) * -1
    t00 = 2
    t01 = 3
    t02 = 4
    t03 = t01 * t02
    t04 = t00 + t03
    a = t04
    t05 = 5
    t06 = a + t05
    t07 = 6
    t08 = t06 / t07
    b = t08
    t09 = a + b
    t10 = a - b
    t11 = t09 * t10
    t12 = 1
    t13 = - t12
    t14 = t11 * t13
    c = t14
$
```

Practice Exercise 1: Arithmetic Expression

Using the grammar and actions for arithmetic expressions, translate the following snippets starting from quad location 100. Show the parse tree, the working of the translation with the parser and attribute stacks, and the generated sequence of quads for each case.

[1]

```
a=-3*4+-2/7+-(2/7)
```

[2]

```
d = a - b - c
d = a - (b - c)
d = (a - b) - c
```

[3]

```
a = (2-3)*(2+3)
b = (a+7)/3
c = -a + b
```

Practice Exercise 2: Arithmetic Expression

Consider the expression `a = 2 + 3 * 4`. According to the current scheme, this translates to:

```
[100]: t00 = 2
[101]: t01 = 3
[102]: t02 = 4
[103]: t03 = t01 * t02
[104]: t04 = t00 + t03
[105]: a = t04
```

This clearly generates several redundant temporary variables. It would be better to translate this to:

```
[100]: t03 = 3 * 4
[101]: t04 = 2 + t03
[102]: a = t04
```

- Modify the actions appropriately generate the above code (that is, copy propagation).
- Show the working of the modified scheme (parse tree, stack trace, and quads) for `a = 2 + 3 * 4`

Further, it is possible to evaluate an expression (while generating the quad) if the values of its operand/s is/are known.

- Modify the actions appropriately achieve this constant folding.
- Show the working of the modified scheme (parse tree, stack trace, and quads) for `a = 2 + 3 * 4`

Practice Exercise 3: Arithmetic Expression

Consider the expression `i = i + 1`. According to the current scheme, this translates to:

```
[100]: t00 = 1
[101]: t01 = i + t00
[102]: i = t01
```

Or, at best:

```
[100]: t01 = i + 1
[101]: i = t01
```

Clearly the expression increments (possibly) an index variable and it will be good to capture this information for later use. So we introduce a unary operator `inc` in TAC so that we can generate:

```
[100]: i = inc i
```

- Modify the actions appropriately generate the above code.
- Show the working of the modified scheme (parse tree, stack trace, and quads) for `i = i + 1`
- Would your scheme work for `i = 1 + i`

Boolean Expressions

Boolean Expression Grammar

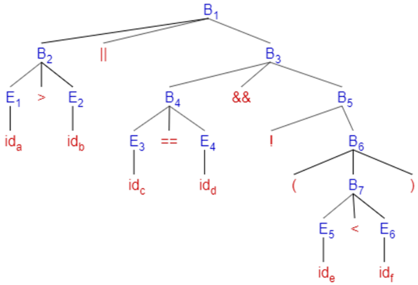
$$
\begin{array}{llll}
1: & B & \rightarrow & B_1 \texttt{ || } B_2 \\
2: & B & \rightarrow & B_1 \texttt{ \&\& } B_2 \\
3: & B & \rightarrow & \texttt{!} B_1 \\
4: & B & \rightarrow & \texttt{(} B_1 \texttt{)} \\
5: & B & \rightarrow & E_1 \texttt{ relop } E_2 \\
6: & B & \rightarrow & \texttt{true} \\
7: & B & \rightarrow & \texttt{false}
\end{array}
$$

- Operator `relop` has highest precedence followed by operator NOT (`!`), operator AND (`&&`), and operator OR (`||`) in decreasing order. All operators generated from E has precedence higher than `relop`.
- Operator `relop` is non-associative, operator NOT (`!`) is right associative, and operators AND (`&&`) and operator OR (`||`) are left associative.
- Non-terminals B and E are sub-scripted to distinguish multiple instances on the right hand side of a rule
- `relop` is any one of: `<`, `<=`, `>`, `>=`, `==`, `!=`

Boolean Expression Example: Translation by Value

a > b || c == d && !(e < f)

```
100: t1 = a > b
101: t2 = c == d
102: t3 = e < f
103: t4 = !t3
104: t5 = t3 && t4
105: t6 = t1 || t5
```

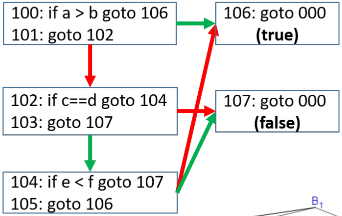


Translation by Value:

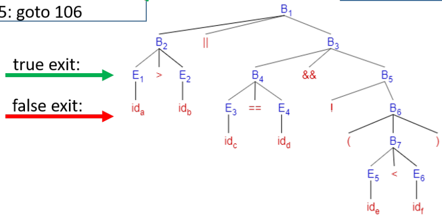
- May not be very useful, as Boolean values are typically used for control flow
- May not use short-cut of computation

Boolean Expression Example: Translation by Control Flow

a > b || c == d && !(e < f)




```
100: if a > b goto 106
101: goto 102
102: if c==d goto 104
103: goto 107
104: if e < f goto 107
105: goto 106
106: goto 000 (true)
107: goto 000 (false)
```

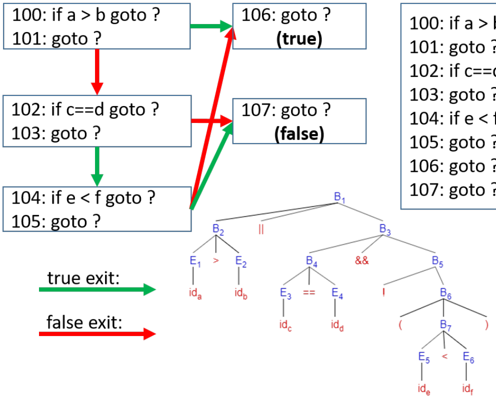


Translation by Control:

- Useful for control flow
- Uses short-cut of computation

Boolean Expression Example: Translation by Control Flow

a > b || c == d && !(e < f)



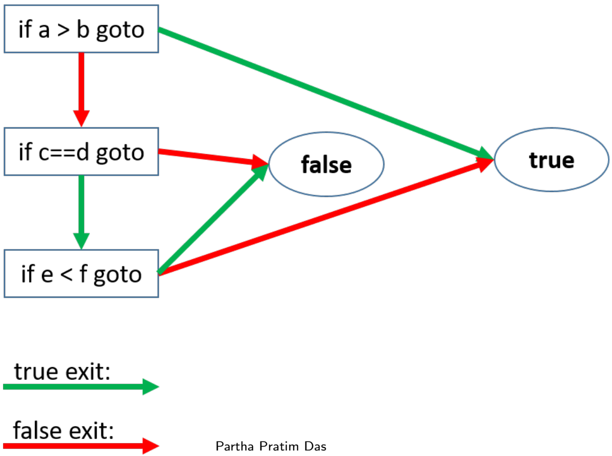

```
100: if a > b goto ?
101: goto ?
102: if c==d goto ?
103: goto ?
104: if e < f goto ?
105: goto ?
106: goto ? (true)
107: goto ? (false)
```

Translation by Control:

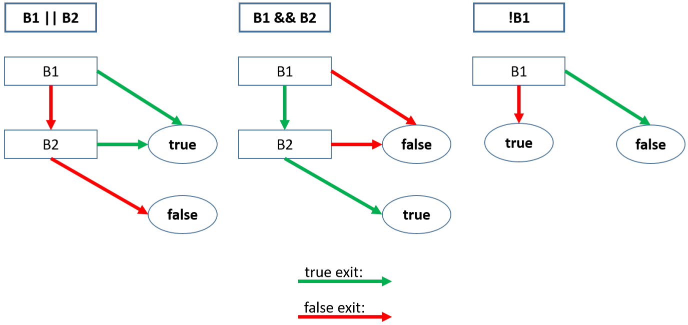
- How to get the target address of goto's?
- Can we optimize goto to goto's / fall-through's

Boolean Expression Example: Translation by Control Flow: Abstracted

a > b || c == d && !(e < f)



Boolean Expression: Scheme of Translation by Control Flow



Attributes / Global for Boolean Expression

- $B.truelist$: – List of (indices of) quads having dangling **true exits** for the Boolean expression.
- $B.falselist$: – List of (indices of) quads having dangling **false exits** for the Boolean expression.
- $B.loc$: – Location to store the value of the Boolean expression (optional).
- $nextinstr$: – Global counter to the array of quads – the index of the next quad to be generated.
- $M.instr$: – Index of the quad generated at M.

Auxiliary Methods for Back-patching

$makelist(i)$:
- Creates a new list containing only i, an index into the array of quad's.
- Returns a pointer to the newly created list

$merge(p_1, p_2)$:
- Concatenates the lists pointed to by p_1 and p_2.
- Returns a pointer to the concatenated list

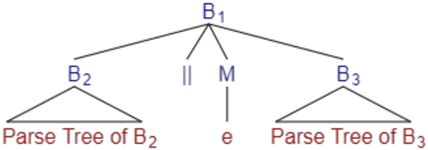
$backpatch(p, i)$:
- Inserts i as the target label for each of the quads on the list pointed to by p.

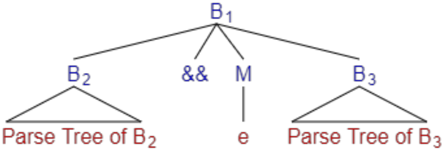
Back-patching Boolean Expression Grammar

$$
\begin{array}{llll}
1: & B & \rightarrow & B_1 \texttt{ || } M \; B_2 \\
2: & B & \rightarrow & B_1 \texttt{ \&\& } M \; B_2 \\
3: & B & \rightarrow & \texttt{!} B_1 \\
4: & B & \rightarrow & \texttt{(} B_1 \texttt{)} \\
5: & B & \rightarrow & E_1 \texttt{ relop } E_2 \\
6: & B & \rightarrow & \texttt{true} \\
7: & B & \rightarrow & \texttt{false} \\
8: & M & \rightarrow & \epsilon \; // \text{ Marker rule}
\end{array}
$$

Back-patching Boolean Expression Grammar with Actions

$$
\begin{array}{llll}
1: & B & \rightarrow & B_1 \mid\mid M\ B_2 \\
 & & & \quad \{ \ backpatch(B_1.falselist, M.instr); \\
 & & & \quad\ \ B.truelist = merge(B_1.truelist, B_2.truelist); \\
 & & & \quad\ \ B.falselist = B_2.falselist; \ \} \\
2: & B & \rightarrow & B_1\ \&\&\ M\ B_2 \\
 & & & \quad \{ \ backpatch(B_1.truelist, M.instr); \\
 & & & \quad\ \ B.truelist = B_2.truelist; \\
 & & & \quad\ \ B.falselist = merge(B_1.falselist, B_2.falselist); \ \} \\
3: & B & \rightarrow & !B_1 \quad \{ \ B.truelist = B_1.falselist; \\
 & & & \quad\quad\ \ B.falselist = B_1.truelist; \ \} \\
4: & B & \rightarrow & (B_1) \quad \{ \ B.truelist = B_1.truelist; \\
 & & & \quad\quad\ \ B.falselist = B_1.falselist; \ \}
\end{array}
$$



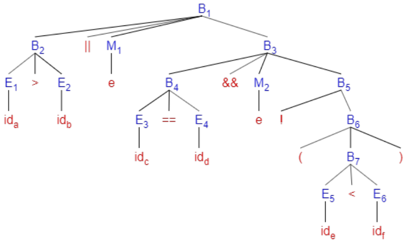


Back-patching Boolean Expression Grammar with Actions

5:	B	$\rightarrow$	E_1 `relop` E_2	
				$\{\ B.truelist = makelist(nextinstr);$
				$B.falselist = makelist(nextinstr+1);$
				$emit(\text{"}if\text{"}, E_1.loc,\ relop.op,\ E_2.loc,\ \text{"}goto\text{"},\ \text{"}.....\text{"});\ \}$
				$emit(\text{"}goto\text{"},\ \text{"}.....\text{"});\ \}$
6:	B	$\rightarrow$	`true`	$\{\ B.truelist = makelist(nextinstr);$
				$emit(\text{"}goto\text{"},\ \text{"}.....\text{"});\ \}$
7:	B	$\rightarrow$	`false`	$\{\ B.falselist = makelist(nextinstr);$
				$emit(\text{"}goto\text{"},\ \text{"}.....\text{"});\ \}$
8:	M	$\rightarrow$	ϵ	$\{\ M.instr = nextinstr;\ \}$

Example: Boolean Expression

```
a > b || c == d && !(e < f)
nextinstr = 100
```



Order of Reductions

Seq. #: (Prod. #)	Production		
1:(5)	B_2	$\rightarrow$	E_1 relop E_2
2:(8)	M_1	$\rightarrow$	ϵ
3:(5)	B_4	$\rightarrow$	E_3 relop E_4
4:(8)	M_2	$\rightarrow$	ϵ
5:(5)	B_7	$\rightarrow$	E_5 relop E_6
6:(4)	B_6	$\rightarrow$	(B_7)
7:(3)	B_5	$\rightarrow$	$!B_6$
8:(2)	B_3	$\rightarrow$	B_4 && M_2 B_5
9:(1)	B_1	$\rightarrow$	B_2 || M_1 B_3

```
[1] 100: if a > b goto ?
[1] 101: goto ? 102           // [9] BP(B2.FL, M1.I)
[3] 102: if c == d goto ? 104 // [8] BP(B4.TL, M2.I)
[3] 103: goto ?
[5] 104: if e < f goto ?
[5] 105: goto ?

---------------------------

[1] B2.TL = {100} // nextinstr = 100
[1] B2.FL = {101}
[2] M1.I  = 102
[3] B4.TL = {102} // nextinstr = 102
[3] B4.FL = {103}
[4] M2.I  = 104
[5] B7.TL = {104} // nextinstr = 104
[5] B7.FL = {105}
[6] B6.TL = B7.TL = {104}
[6] B6.FL = B7.FL = {105}
[7] B5.TL = B6.FL = {105}
[7] B5.FL = B6.TL = {104}
[8] B3.TL = B5.TL = {105}
[8] B3.FL = B4.FL U B5.FL = {103, 104}
[9] B1.TL = B2.TL U B3.TL = {100, 105}
[9] B1.FL = B3.FL = {103, 104}

---------------------------
[#] Reduction Sequence #
```

Practice Exercise 1: Boolean Expression

Translate the following expressions starting from `quad` location `100`

[1] `a == b + c && !false || c - a < d`

[2] `a < b || a == b || a > b`

[3] `true && (false || true)`

[4] `3 < 4 && (5 > 2 + 1 || a == a)`

Practice Exercise 2: Boolean Expression

Consider the Exclusive OR operation ^ in the production rule:

$$B \rightarrow B_1 \mathbin{\hat{}} B_2$$

Exclusive OR is left associative and has the same precedence as OR.

[1] Modify the rule suitably for translation.

[2] Write the semantic action for your modified rule.

[3] Translate `a > b ^ c == d && a != c` starting from `quad` location `100`

Support for Exclusive OR: Solution

9: $B \rightarrow B_1 \,\hat{}\, M\ B_2$

$\{$ $backpatch(B_1.truelist, nextinstr);$
$emit(B_1.loc, "=", true);$
$emit("goto", M.instr);$
$backpatch(B_1.falselist, nextinstr);$
$emit(B_1.loc, "=", false);$
$emit("goto", M.instr);$

$B.truelist = makelist(nextinstr);$
$backpatch(B_2.falselist, nextinstr);$
$emit("if", B_1.loc, "goto", ".....");$
$B.falselist = makelist(nextinstr);$
$emit("goto", ".....");$

$temp = makelist(nextinstr);$
$B.falselist = merge(B.falselist, temp);$
$backpatch(B_2.truelist, nextinstr);$
$emit("if", B_1.loc, "goto", ".....");$
$temp = makelist(nextinstr);$
$B.truelist = merge(B.truelist, temp);$
$emit("goto", "....."); \}$

Control Constructs

Control Construct Grammar

$$
\begin{array}{llll}
1: & S & \rightarrow & \{\ L\ \} \\
2: & S & \rightarrow & \textbf{id} = \ E\ \textbf{;} \\
3: & S & \rightarrow & \textbf{if}\ (B)\ S \\
4: & S & \rightarrow & \textbf{if}\ (B)\ S\ \textbf{else}\ S \\
5: & S & \rightarrow & \textbf{while}\ (B)\ S \\
6: & L & \rightarrow & L\ S \\
7: & L & \rightarrow & S \\
8: & E & \rightarrow & \textbf{id} \\
9: & E & \rightarrow & \textbf{num}
\end{array}
$$

Attributes for Control Construct

$S.nextlist$: – List of (indices of) quads having dangling **exit**s for statement S

$L.nextlist$: – List of (indices of) quads having dangling **exit**s for (list of) statements L

Back-patching Control Construct Grammar

1:	S	$\rightarrow$	$\{\ L\ \}$
2:	S	$\rightarrow$	**id** **=** E **;**
3:	S	$\rightarrow$	**if** $(B)\ M\ S_1$
4:	S	$\rightarrow$	**if** $(B)\ M_1\ S_1\ N$ **else** $M_2\ S_2$
5:	S	$\rightarrow$	**while** $M_1\ (B)\ M_2\ S_1$
6:	L	$\rightarrow$	$L_1\ M\ S$
7:	L	$\rightarrow$	S
8:	E	$\rightarrow$	**id**
9:	E	$\rightarrow$	**num**
10:	M	$\rightarrow$	ϵ // Marker rule
11:	N	$\rightarrow$	ϵ // Fall-through Guard rule

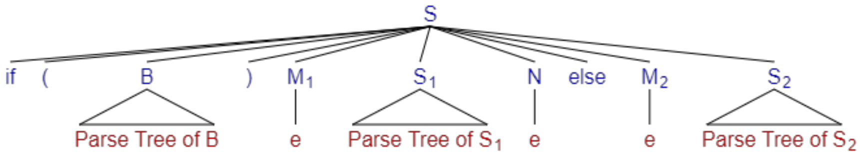
Back-patching Control Construct Grammar with Actions

1: $S \rightarrow \{ \; L \; \}$ $\quad \{ \; S.nextlist = L.nextlist; \; \}$

2: $S \rightarrow \textbf{id} = \; E \; ;$ $\quad \{ \; S.nextlist = null;$
$\quad emit(\textbf{id}.loc, \; " = ", \; E.loc); \; \}$

3: $S \rightarrow \textbf{if} \; (B) \; M \; S_1$ $\quad \{ \; backpatch(B.truelist, M.instr);$
$\quad S.nextlist = merge(B.falselist, S_1.nextlist); \; \}$

4: $S \rightarrow \textbf{if} \; (B) \; M_1 \; S_1 \; N \; \textbf{else} \; M_2 \; S_2$
$\quad \{ \; backpatch(B.truelist, M_1.instr);$
$\quad backpatch(B.falselist, M_2.instr);$
$\quad temp = merge(S_1.nextlist, N.nextlist); \; \}$
$\quad S.nextlist = merge(temp, S_2.nextlist); \; \}$

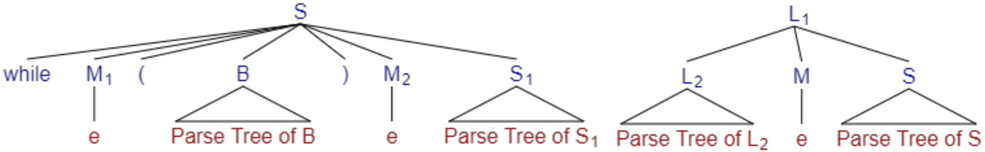


Back-patching Control Construct Grammar with Actions

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

6: $L \rightarrow L_1 \ M \ S$ $\{$ $backpatch(L_1.nextlist, M.instr);$
$L.nextlist = S.nextlist;$ $\}$

7: $L \rightarrow S$ $\{$ $L.nextlist = S.nextlist;$ $\}$



Back-patching Control Construct Grammar with Actions

8:	E	$\rightarrow$	**id**	$\{\ E.loc = \mathbf{id}.loc;\ \}$
9:	E	$\rightarrow$	**num**	$\{\ E.loc = gentemp();$ $emit(E.loc,\ ''=\!'',\ num.val);\ \}$
10:	M	$\rightarrow$	ϵ	$\{\ M.instr = nextinstr;\ \}$
11:	N	$\rightarrow$	ϵ	$\{\ N.nextlist = makelist(nextinstr);$ $emit(''goto'',\ ''.....'');\ \}$

Example: $S \rightarrow$ **if** $(B)\ M_1\ S_1\ N$ **else** $M_2\ S_2$

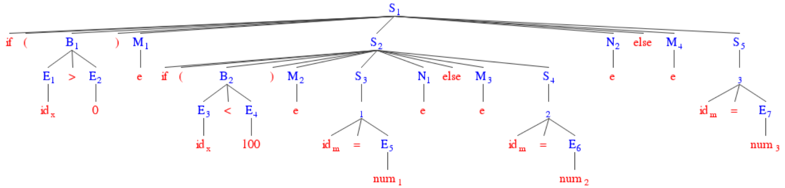
```
if (x > 0) if (x < 100) m = 1; else m = 2; else m = 3;
nextinstr = 100
```

Order of Reductions

S#	Production
01:	$B_1 \rightarrow E_1$ `relop` E_2
02:	$M_1 \rightarrow \epsilon$
03:	$B_2 \rightarrow E_3$ `relop` E_4
04:	$M_2 \rightarrow \epsilon$
05:	$S_3 \rightarrow id_m = E_5$
06:	$N_1 \rightarrow \epsilon$
07:	$M_3 \rightarrow \epsilon$
08:	$S_4 \rightarrow id_m = E_6$
09:	$S_2 \rightarrow$ **if** $(B_2)\ M_2\ S_3\ N_1$ **else** $M_3\ S_4$
10:	$N_2 \rightarrow \epsilon$
11:	$M_4 \rightarrow \epsilon$
12:	$S_5 \rightarrow id_m = E_7$
13:	$S_1 \rightarrow$ **if** $(B_1)\ M_1\ S_2\ N_2$ **else** $M_4\ S_5$

```
[01] 100: if x > 0 goto ? 102   // [13] BP(B1.TL, M1.I)
[01] 101: goto ? 108            // [13] BP(B1.FL, M4.I)
[03] 102: if x < 100 goto ? 104 // [09] BP(B2.TL, M2.I)
[03] 103: goto ? 106            // [09] BP(B2.FL, M3.I)
[05] 104: m = 1
[06] 105: goto ?
[08] 106: m = 2
[10] 107: goto ?
[12] 108: m = 3
```

```
[01] B1.TL= {100} // NI = 100
[01] B1.FL= {101}
[02] M1.I = 102
[03] B2.TL= {102} // NI = 102
[03] B2.FL= {103}
[04] M2.I = 104
[05] S3.NL= {}    // NI = 104
[06] N1.NL= {105} // NI = 105
[07] M3.I = 106
[08] S4.NL= {}                             // NI = 106
[09] S2.NL= S3.NL U N1.NL U S4.NL= {105}
[10] N2.NL= {107}                          // NI = 107
[11] M4.I = 108
[12] S5.NL= {}                             // NI = 108
[13] S1.NL= S2.NL U N2.NL U S5.NL= {105, 107}
                                           // NI = 109
```



Practice Exercise 1: Control Construct

Translate the following expressions starting from `quad` location `100`

[1]

```
a = b = c = 7;
if (a + b > c) {
    c = a + b;
    d = 5;
}
```

[2]

```
c = 1;
d = 9;
while (c < d) {
    c =  c - 1;
    d = d - 1;
}
```

Practice Exercise 2: Control Construct

Extend the control construct grammar to support `do-while` and `for` loops as:

$$S \rightarrow \textbf{do } S_1 \textbf{ while } (\ B\ );$$
$$S \rightarrow \textbf{for } (\ E_1\ ;\ B\ ;\ E_2\ )\ S_1$$

[1] Modify the rules suitably for translation.

[2] Write the semantic action for your modified rules.

[3] Translate the following code segment starting from `quad` location `100`

```
n = 10;
for(i = 0; i < n; i = i + 1) {
    j = i;
    do
        m = m + 1;
        j = j - 1;
    while (j > 0);
}
```

Control Construct Grammar: Extended: Solution

1:	S	$\rightarrow$	$\{\ L\ \}$
2:	S	$\rightarrow$	$\textbf{id} = E\ \textbf{;}$
3:	S	$\rightarrow$	$\textbf{if}\ (B)\ M\ S_1$
4:	S	$\rightarrow$	$\textbf{if}\ (B)\ M_1\ S_1\ N\ \textbf{else}\ M_2\ S_2$
5:	S	$\rightarrow$	$\textbf{while}\ M_1\ (B)\ M_2\ S_1$
6:	S	$\rightarrow$	$\textbf{do}\ M_1\ S_1\ M_2\ \textbf{while}\ \textbf{(}\ B\ \textbf{);}$
7:	S	$\rightarrow$	$\textbf{for}\ \textbf{(}\ E_1\ \textbf{;}\ M_1\ B\ \textbf{;}\ M_2\ E_2\ N\ \textbf{)}\ M_3\ S_1$
8:	L	$\rightarrow$	$L_1\ M\ S$
9:	L	$\rightarrow$	S
10:	E	$\rightarrow$	$\textbf{id}$
11:	E	$\rightarrow$	$\textbf{num}$
12:	M	$\rightarrow$	ϵ // Marker rule
13:	N	$\rightarrow$	ϵ // Fall-through Guard rule

Control Construct Grammar: Extended: Solution

6: $S \rightarrow$ **do** $M_1\ S_1\ M_2$ **while (** B **);**

$\{\ backpatch(B.truelist, M_1.instr);$
$\quad backpatch(S_1.nextlist, M_2.instr);$
$\quad S.nextlist = B.falselist;\ \}$

7: $S \rightarrow$ **for (** E_1 **;** $M_1\ B$ **;** $M_2\ E_2\ N$ **)** $M_3\ S_1$

$\{\ backpatch(B.truelist, M_3.instr);$
$\quad backpatch(N.nextlist, M_1.instr);$
$\quad backpatch(S_1.nextlist, M_2.instr);$
$\quad emit(\text{"}goto\text{"}\ \ M_2.instr);$
$\quad S.nextlist = B.falselist;\ \}$

Handling **goto**

Maintain a Label Table having the following information and lookup(Label) method:

- ID of Label – This will be entered to Label Table either when a label is defined or it is used as a target for a **goto** before being defined. So if this ID exists in the table, it has been encountered already
- ADDR, Address of Label (index of quad) – This is set from the definition of a label. Hence it will be null as long as a label has been encountered in one or more **goto**'s but not defined yet
- LST, List of dangling **goto**'s for this label – This will be null if ADDR is not null

```
L1: ...       // If L1 exists in Label Table
              //    if (ADDR = null)
              //        ADDR = nextinstr
              //        backpatch LST with ADDR
              //        LST = null
              //    else
              //        duplicate definition of label L1 - an error
              // If L1 does not exist, make an entry
              //    ADDR = nextinstr
              //    LST = null
```

Handling goto

```
goto L1;  // If L1 exists in Label Table
          //    if (ADDR = null) // Forward jump already seen
          //        LST = merge(LST, makelist(nextinstr));
          //    else // Target crossed - a backward jump
          //        use ADDR
          // If L1 does not exist, make an entry
          //    ADDR = null // New forward jump
          //    LST = makelist(nextinstr);
```

Handling switch-case

$S \rightarrow$ **switch (** E **)** S_1
$S \rightarrow$ **case num:** S_1
$S \rightarrow$ **default:** S_1

Using Mutually Exclusive "case" Clauses - Unlike C

Synthesized Attributes		Inherited Attributes	
	Code to Evaluate E into **t**		Code to Evaluate E into **t**
	goto test		**if t !=** V_1 **goto** L_1
L_1:	Code for S_1		Code for S_1
	goto next		**goto next**
L_2:	Code for S_2	L_1:	**if t !=** V_2 **goto** L_2
	goto next		Code for S_2
	...		**goto next**
L_{n-1}:	Code for S_{n-1}	L_2:	
	goto next		...
L_n:	Code for S_n	L_{n-2}:	**if t !=** V_{n-1} **goto** L_{n-1}
	goto next		Code for S_{n-1}
test:	**if t =** V_1 **goto** L_1		**goto next**
	if t = V_2 **goto** L_2	L_{n-1}:	Code for S_n
	...	**next**:	
	if t = V_{n-1} **goto** L_{n-1}		
	goto L_n		
next:			

Handling `break`, `continue`

Design suitable schemes to translate **break** and **continue** statements:

$$
\begin{array}{lcl}
S & \rightarrow & \textbf{break;} \\
S & \rightarrow & \textbf{continue;}
\end{array}
$$

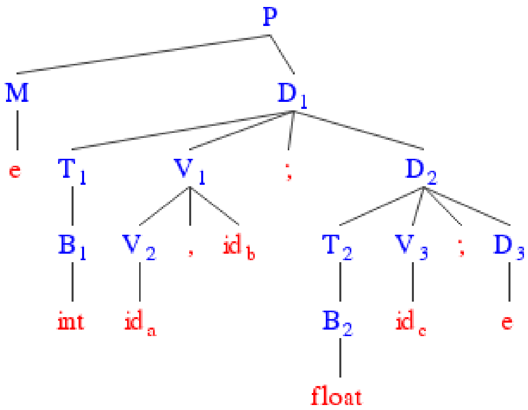
Types & Declarations

Declaration Grammar

$$
\begin{array}{llll}
0: & P & \rightarrow & M \; D \\
1: & D & \rightarrow & T \; V \; \textbf{;} \; D \\
2: & D & \rightarrow & \epsilon \\
3: & V & \rightarrow & V \; \textbf{,} \; \textbf{id} \\
4: & V & \rightarrow & \textbf{id} \\
5: & T & \rightarrow & B \\
6: & B & \rightarrow & \textbf{int} \\
7: & B & \rightarrow & \textbf{float} \\
8: & M & \rightarrow & \epsilon
\end{array}
$$

```
int a, b; float c;
```

Name	Type	Size	Offset
a	int	4	0
b	int	4	4
c	float	8	8



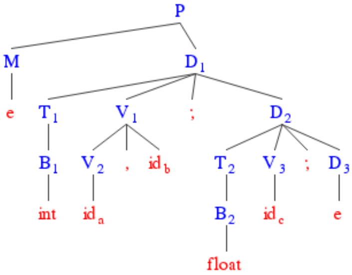
Inherited Attribute

Consider the following attributes for types:

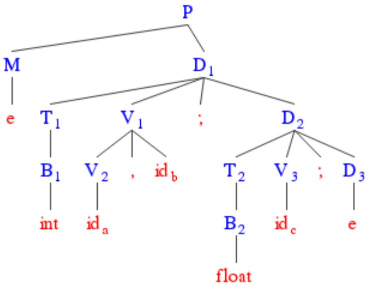
type: Type expression for B, T.

width: The width of a type (B, T), that is, the number of storage units (bytes) needed for objects of that type.It is integral for basic types.

In the context of `int a, b; float c;` when $V \rightarrow$ **id** (or $V \rightarrow V$ **, id**) is reduced, we need to set the type (size) for **id** in the symbol table. However, the type (size) is not available from the children of V as *Synthesized Attributes*. Rather, it is available in T ($T.type$ or $T.width$) which is a sibling of V. This is the situation of an *Inherited Attribute*.



Inherited Attribute



We can handle inherited attributes in one of following ways:

- **[Global]** When we reduce by $T \rightarrow B$, we can remember $T.type$ and $T.width$ in two global variables t and w and use them subsequently
- **[Lazy Action]** Accumulate the list of variables generated from V in a list $V.list$ and the set the type from $T.type$ while reducing with $D \rightarrow T\ V\ \mathbf{;}\ D_1$
- **[Bison Stack]** Use $0, $-1 etc. to extract the inherited attribute during reduction of $V \rightarrow \mathbf{id}$ (or $V \rightarrow V\ \mathbf{,}\ \mathbf{id}$)
- **[Grammar Rewrite]** Rewrite the grammar so that the inherited attributes become synthesized

Attributes for Types: Using Global

type: Type expression for B, T. This is an inherited attribute.

width: The width of a type (B, T), that is, the number of storage units (bytes) needed for objects of that type. It is integral for basic types. This is an inherited attribute.

t: Global to pass the *type* information from a B node to the node for production $V \rightarrow \textbf{id}$.

w: Global to pass the *width* information from a B node to the node for production $V \rightarrow \textbf{id}$.

offset: Global marker for Symbol Table fill-up.

Semantic Actions using Global: Inherited Attributes

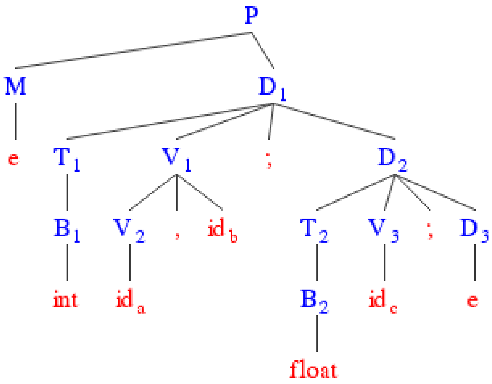
0:	P	$\rightarrow$		$\{\ offset = 0;\ \}$
			D	
1:	D	$\rightarrow$	$T\ V\ ;\ D_1$	
2:	D	$\rightarrow$	ϵ	
3:	V	$\rightarrow$	$V\ ,\ \mathbf{id}$	$\{\ update(\mathbf{id}.loc, t, w, offset);$ $offset = offset + w;\ \}$
4:	V	$\rightarrow$	$\mathbf{id}$	$\{\ update(\mathbf{id}.loc, t, w, offset);$ $offset = offset + w;\ \}$
5:	T	$\rightarrow$	B	$\{\ t = B.type; w = B.width;$ $T.type = B.type;$ $T.width = B.width;\ \}$
6:	B	$\rightarrow$	$\mathbf{int}$	$\{\ B.type = integer; B.width = 4;\ \}$
7:	B	$\rightarrow$	$\mathbf{float}$	$\{\ B.type = float; B.width = 8;\ \}$

- `update(<SymbolTableEntry>, <type>, <width>, <offset>)` updates the symbol table entry for type, width and offset.

Example: Using Global

```
int a, b;     offset = 0
float c;      B1.type = integer
              B1.width = 4
              T1.type = integer
              T1.width = 4
              t = integer
              w = 4
              // id_a updated
              offset = 4
              // id_b updated
              offset = 8
              B2.type = float
              B2.width = 8
              T2.type = float
              T2.width = 8
              t = float
              w = 8
              // id_c updated
              offset = 16
```

Name	Type	Size	Offset
a	integer	4	0
b	integer	4	4
c	float	8	8



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0: $P \rightarrow M\ D$

1: $D \rightarrow T\ V\ \mathbf{;}\ D$

2: $D \rightarrow \epsilon$

3: $V \rightarrow V\ \mathbf{,}\ \mathbf{id}$

4: $V \rightarrow \mathbf{id}$

5: $T \rightarrow B$

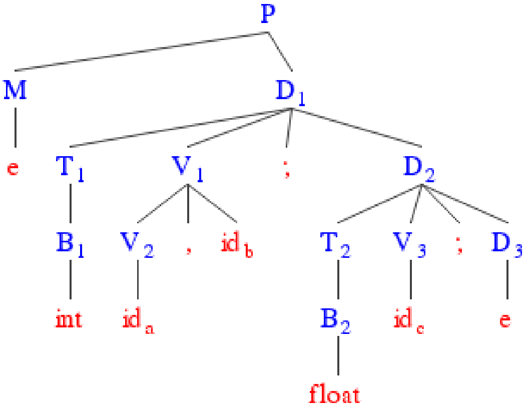
6: $B \rightarrow \mathbf{int}$

7: $B \rightarrow \mathbf{float}$

8: $M \rightarrow \epsilon$

```
int a, b; float c;
```

Name	Type	Size	Offset
a	int	4	0
b	int	4	4
c	float	8	8



Attributes for Types: Lazy Action

type: Type expression for B, T. This an is inherited (synthesized) attribute.

width: The width of a type (B, T), that is, the number of storage units (bytes) needed for objects of that type. It is integral for basic types. This is an inherited (synthesized) attribute.

list: List of variables generated from V. This is a synthesized attribute.

offset: Global marker for Symbol Table fill-up.

Semantic Actions using Lazy Action: Inherited Attributes

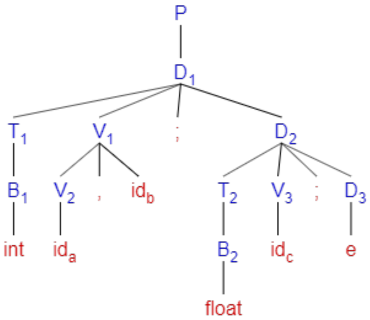
$$
\begin{array}{llcll}
0: & P & \rightarrow & D & \{\ offset = 0;\ update\_offset();\ \} \\
1: & D & \rightarrow & T\ \ V\ \ ;\ D_1 & \{\ update(V.list, T.type, T.width);\ \} \\
2: & D & \rightarrow & \epsilon & \\
3: & V & \rightarrow & V_1\ \ ,\ \mathbf{id} & \{\ l = makelist(\mathbf{id}.loc); \\
 & & & & \quad V.list = merge(V_1.list, l);\ \} \\
4: & V & \rightarrow & \mathbf{id} & \{\ V.list = makelist(\mathbf{id}.loc);\ \} \\
5: & T & \rightarrow & B & \{\ T.type = B.type; \\
 & & & & \quad T.width = B.width;\ \} \\
6: & B & \rightarrow & \mathbf{int} & \{\ B.type = integer; B.width = 4;\ \} \\
7: & B & \rightarrow & \mathbf{float} & \{\ B.type = float; B.width = 8;\ \}
\end{array}
$$

- `update(<ListOfSymbolTableEntry>, <type>, <width>)` updates the symbol table entry for type and width.
- `update_offset()` updates the offset for all entries in the symbol table

Example: Using Lazy Actions

```
int a, b;
float c;
```

```
B1.type = integer
B1.width = 4
T1.type = integer
T1.width = 4
V2.list = {ST[0]} = {id_a}
V1.list = {ST[0], ST[1]} = {id_a, id_b}
B2.type = float
B2.width = 8
T2.type = float
T2.width = 8
V3.list = {ST[2]} = {id_c}
offset = 0
```



States of Symbol Table ST

lists created

	Name	Type	Size	Offset
0	a	?	?	?
1	b	?	?	?
2	c	?	?	?

V3.list resolved

	Name	Type	Size	Offset
0	a	?	?	?
1	b	?	?	?
2	c	float	8	?

V1.list resolved

	Name	Type	Size	Offset
0	a	integer	4	?
1	b	integer	4	?
2	c	float	8	?

offsets updated

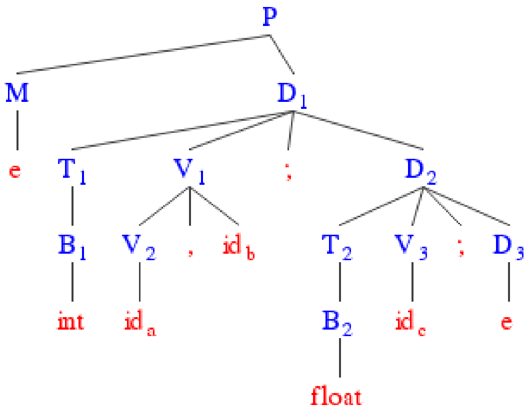
	Name	Type	Size	Offset
0	a	integer	4	0
1	b	integer	4	4
2	c	float	8	8

Declaration Grammar

$$
\begin{array}{llll}
0: & P & \rightarrow & M\ D \\
1: & D & \rightarrow & T\ V\ \mathbf{;}\ D \\
2: & D & \rightarrow & \epsilon \\
3: & V & \rightarrow & V\ \mathbf{,\ id} \\
4: & V & \rightarrow & \mathbf{id} \\
5: & T & \rightarrow & B \\
6: & B & \rightarrow & \mathbf{int} \\
7: & B & \rightarrow & \mathbf{float} \\
8: & M & \rightarrow & \epsilon
\end{array}
$$

```
int a, b; float c;
```

Name	Type	Size	Offset
a	int	4	0
b	int	4	4
c	float	8	8



Attributes for Types: Bison Stack

type: Type expression for B, T. This an inherited attribute.

width: The width of a type (B, T), that is, the number of storage units (bytes) needed for objects of that type. It is integral for basic types. This an inherited attribute.

offset: Global marker for Symbol Table fill-up.

Bison Stack

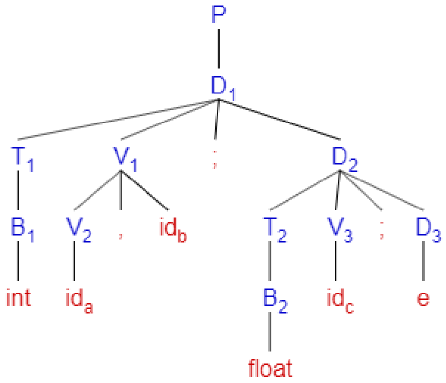
In the context of `int a, b; float c;`, when $V \rightarrow$ **id** or $V \rightarrow V$ **, id** is reduced, the stack is as follows:

id	\$1
T	\$0
...	\$-1
...	\$-2
...	

$V \rightarrow$ **id**

id	\$3
,	\$2
V	\$1
T	\$0
...	\$-1
...	\$-2
...	

$V \rightarrow V$ **, id**



Semantic Actions using Bison Stack: Inherited Attributes

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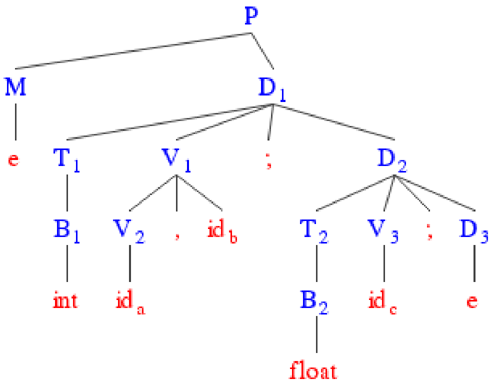
0:	P	$\rightarrow$		$\{\ offset = 0;\ \}$
			D	
1:	D	$\rightarrow$	$T\ V\ ;\ D_1$	
2:	D	$\rightarrow$	ϵ	
3:	V	$\rightarrow$	$V\ ,\ \textbf{id}$	$\{\ update(\textbf{id}.loc, \$0.type, \$0.width, offset);$
				$offset = offset + \$0.width;\ \}$
4:	V	$\rightarrow$	$\textbf{id}$	$\{\ update(\textbf{id}.loc, \$0.type, \$0.width, offset);$
				$offset = offset + \$0.width;\ \}$
5:	T	$\rightarrow$	B	$\{\ T.type = B.type; T.width = B.width;\ \}$
6:	B	$\rightarrow$	$\textbf{int}$	$\{\ B.type = integer; B.width = 4;\ \}$
7:	B	$\rightarrow$	$\textbf{float}$	$\{\ B.type = float; B.width = 8;\ \}$

- `update(<SymbolTableEntry>, <type>, <width>, <offset>)` updates the symbol table entry for type and width.

Example: Using Bison Stack

```
int a, b;     offset = 0
float c;      B1.type = integer
              B1.width = 4
              T1.type = integer
              T1.width = 4
              // id_a updated with $0 = T1
              // $0.type = integer, $0.width = 4
              // id_b updated with $0 = T1
              // $0.type = integer, $0.width = 4
              B2.type = float
              B2.width = 8
              T2.type = float
              T2.width = 8
              // id_c updated with $0 = T2
              // $0.type = float, $0.width = 8
```

Name	Type	Size	Offset
a	integer	4	0
b	integer	4	4
c	float	8	8

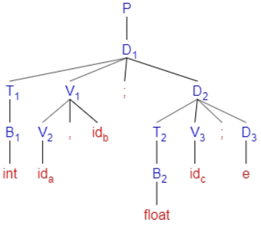


Declaration Grammar

Inherited Attribute	Synthesized Attribute	

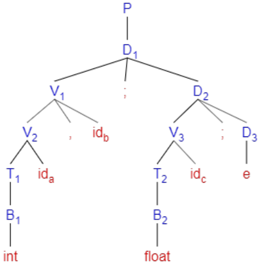
Inherited Attribute

0:	P	$\rightarrow$	D
1:	D	$\rightarrow$	$T\ V\ ;\ D$
2:	D	$\rightarrow$	ϵ
3:	V	$\rightarrow$	V , **id**
4:	V	$\rightarrow$	**id**
5:	T	$\rightarrow$	B
6:	B	$\rightarrow$	**int**
7:	B	$\rightarrow$	**float**



Synthesized Attribute

0:	P	$\rightarrow$	D
1:	D	$\rightarrow$	$V\ ;\ D$
2:	D	$\rightarrow$	ϵ
3:	V	$\rightarrow$	V , **id**
4:	V	$\rightarrow$	T **id**
5:	T	$\rightarrow$	B
6:	B	$\rightarrow$	**int**
7:	B	$\rightarrow$	**float**




```
int a, b; float c;
```

Name	Type	Size	Offset
a	int	4	0
b	int	4	4
c	float	8	8

Attributes for Types: Grammar Rewrite (Synthesized Attributes)

type: Type expression for B, T, and V. This a synthesized attribute.

width: The width of a type (B, T) or a variable (V), that is, the number of storage units (bytes) needed for objects of that type. It is integral for basic types. This a synthesized attribute.

offset: Global marker for Symbol Table fill-up.

Semantic Actions using Grammar Rewrite: Synthesized Attributes

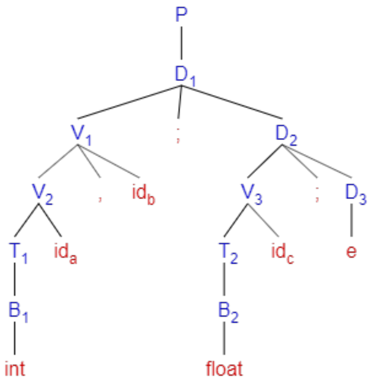
$$
\begin{array}{llll}
0: & P & \rightarrow & \{\ offset = 0;\ \} \\
 & & & D \\
1: & D & \rightarrow & V\ \mathbf{;}\ D_1 \\
2: & D & \rightarrow & \epsilon \\
3: & V & \rightarrow & V_1\ \mathbf{,}\ \mathbf{id} \\
 & & & \{\ update(\mathbf{id}.loc, V_1.type, V_1.width, offset); \\
 & & & \quad offset = offset + V_1.width; \\
 & & & \quad V.type = V_1.type;\ V.width = V_1.width;\ \} \\
4: & V & \rightarrow & T\ \mathbf{id} \\
 & & & \{\ update(\mathbf{id}.loc, T.type, T.width, offset); \\
 & & & \quad offset = offset + T.width; \\
 & & & \quad V.type = T.type;\ V.width = T.width;\ \} \\
5: & T & \rightarrow & B \\
 & & & \{\ T.type = B.type;\ T.width = B.width;\ \} \\
6: & B & \rightarrow & \mathbf{int}\ \{\ B.type = integer; B.width = 4;\ \} \\
7: & B & \rightarrow & \mathbf{float}\ \{\ B.type = float; B.width = 8;\ \}
\end{array}
$$

- `update(<SymbolTableEntry>, <type>, <width>, <offset>)` updates the symbol table entry for type and width.

Example: Grammar Rewrite: Synthesized Attributes

```
int a, b;     offset = 0
float c;      B1.type = integer
              B1.width = 4
              T1.type = integer
              T1.width = 4
              V2.type = integer
              V2.width = 4
              V1.type = integer
              V1.width = 4
              B2.type = float
              B2.width = 8
              T2.type = float
              T2.width = 8
              V3.type = float
              V3.width = 8
```

Name	Type	Size	Offset
a	integer	4	0
b	integer	4	4
c	float	8	8



Practice Exercise 1: Variable Declarations

Translate the following declarations to populate the symbol with the respective types, sizes, and offsets:

[1]

```
double c, d;
int a;
int b;
```

[2]

```
int i;
bool b;
float f;
double d;
```

In each case, draw the parse tree and show the actions with attribute computations while you use the following schemes:

[1] Global Attribute
[2] Lazy Actions
[3] Bison Stack
[4] Rewritten grammar for synthesized attributes

Practice Exercise 2: Variable Declarations

The scheme discussed so far works for declarations (without initialization) within a single block placed before the first executable statement. Extend the scheme with the following features:

- Initialization with constant literals (no expression in initializing value)
- Nested blocks
- Alternating sequences of declarations and executable statements (use assignment statement only)

For the above extensions design the following (assume types `int` and `double` only):

- Extended grammar
- Set of attributes. Highlight inherited attributes.
- Semantic actions using the Bison stack

Test your translation scheme with the following code snippet:

```
{ // Function scope
    double a, b = 2.0;
    a = b + 1.0;
    { // Nested scope
        int a = 5;
        a = a + 2;
    }
    double c;
    c = a + b;
}
```

Discuss the pros and cons of rewriting the grammar so that all attributes may be synthesized.

Practice Exercise 3: Sub-scripted Variable Declarations

The scheme discussed so far works for declarations work for simple variables. Extend the scheme for declarations of sub-scripted variables.

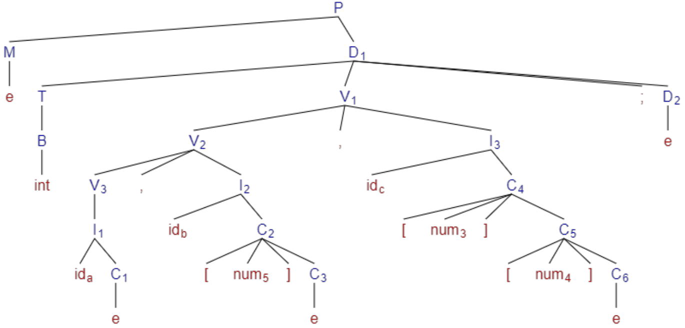
- Extended grammar
- Set of attributes. Highlight inherited attributes.
- Semantic actions using the Bison stack

Test your translation scheme with the following code snippet:

```
int a[5], b;
int c[3][4];
```

Practice Exercise 3: Sub-scripted Variable Declarations: Grammar

0:	P	$\rightarrow$	$M\ D$
1:	D	$\rightarrow$	$T\ V$ **;** D
2:	D	$\rightarrow$	ϵ
3:	V	$\rightarrow$	V **,** I
4:	V	$\rightarrow$	I
5:	I	$\rightarrow$	**id** C
6:	C	$\rightarrow$	**[num]** C
7:	C	$\rightarrow$	ϵ
8:	T	$\rightarrow$	B
9:	B	$\rightarrow$	**int**
10:	B	$\rightarrow$	**float**
11:	M	$\rightarrow$	ϵ




```
int a, b[5], c[3][4];
```

Name	Type	Size	Offset
a	int	4	0
b	T1	4	4
c	T2	8	8

T1 = array(5, int). T2' = array(4, int)
T2 = array(3, T2') = array(3, array(4, int))
T1.width = 5 * int.width = 5 * 4 = 20
T2'.width = 4 * int.width = 4 * 4 = 16
T2.width = 3 * T1'.width = 3 * 16 = 48

Translation by Type

Use of type in Translation

- **Implicit Conversion**
  - *Safe*
    - Usually smaller type converted to larger type, called *Type Promotion*
    - No data loss
    - Conversions on Type Hierarchy in C:

      ```
      bool -> char -> short int -> int -> unsigned int ->
      long -> unsigned -> long long ->
      float -> double -> long double
      ```
    - Array – Pointer Duality
    - Integer interpreted as Boolean in context
  - *Unsafe*
    - Usually larger type converted to smaller type
    - Potential data loss
- **Explicit Conversion**
  - Using cast operators
  - `void* --> int`, `int --> void*`
- **Type Errors**
  - Between incompatible types

Use of type in Translation: `int` $\leftrightarrow$ `double`

Grammar:

$E \rightarrow E_1 + E_2$
$E \rightarrow \textbf{id}$

Translation:

`int a, b, c;`
`a = b + c;`
	`int a, b; double c;`
	`a = b + c; // warning C4244: '=' : conversion from 'double' to 'int',`
	`           // possible loss of data`

`100: t1 = b + c`
`101: a = t1`
	`100: t1 = int2dbl(b)  // Small to Large: Okay`
	`101: t2 = t1 + c`
	`102: t3 = dbl2int(t2) // Large to Small: Data loss`
	`103: a = t3`

Use of type in Translation: `int` $\leftrightarrow$ `double`

$$
\begin{array}{lcll}
E & \rightarrow & E_1 + E_2 & \{\ E.loc = gentemp(); \\
 & & & \quad if\ \ (E_1.type\ != E_2.type) \\
 & & & \qquad E.type = \text{double}; \\
 & & & \qquad t = gentemp(); \\
 & & & \qquad update(t, \text{double}, \text{sizeof(double)}, offset); \\
 & & & \qquad if(E_1.type == \text{integer})\ //\ E_2.type == \text{double} \\
 & & & \qquad\quad emit(t\ '='\ \text{int2dbl}(E_1.loc)); \\
 & & & \qquad\quad emit(E.loc\ '='\ t\ '+'\ E_2.loc); \\
 & & & \qquad else\ //\ E_2.type == \text{integer} \\
 & & & \qquad\quad emit(t\ '='\ \text{int2dbl}(E_2.loc)); \\
 & & & \qquad\quad emit(E.loc\ '='\ E_1.loc\ '+'\ t); \\
 & & & \qquad endif \\
 & & & \quad else \\
 & & & \qquad E.type = E_1.type;\ //\ = E_2.type \\
 & & & \qquad emit(E.loc\ '='\ E_1.loc\ '+'\ E_2.loc); \\
 & & & \quad endif \\
 & & & \quad update(E.loc, E.type, \text{sizeof}(E.type), offset); \\
 & & & \} \\
E & \rightarrow & \textbf{id} & \{\ E.loc = \textbf{id}.loc; \\
 & & & \quad E.type = \textbf{id}.type; \\
 & & & \}
\end{array}
$$

Use of type in Translation: `int` $\rightarrow$ `bool`

Grammar:

$E \rightarrow E_1$!= E_2

$E \rightarrow E_1\ N_1$ **?** $M_1\ E_2\ N_2$ **:** $M_2\ E_3$

$M \rightarrow \epsilon$

$N \rightarrow \epsilon$

Translation:

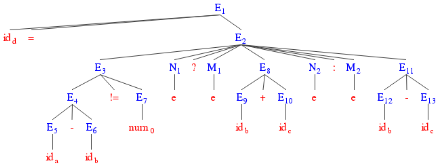
```
int a, b, c, d;
d = a - b != 0 ? b + c : b - c;

100: t1 = a - b
101: t2 = 0
102: if t1 != t2 goto 105
103: goto 107
104: goto 111
105: t3 = b + c
106: goto 110
107: t4 = b - c
108: t5 = t4
109: goto 111
110: t5 = t3
111: d = t5
```

```
int a, b, c, d;
d = a - b ? b + c : b - c;

100: t1 = a - b
101: goto 107
102: t2 = b + c
103: goto 109
104: t3 = b - c
105: t4 = t3
106: goto 110
107: if t1 = 0 goto 104
108: goto 102
109: t4 = t2
110: d = t4
```

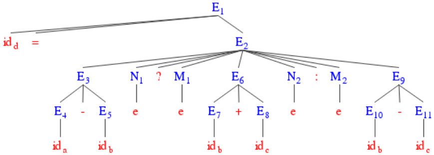
Use of type in Translation: `int` $\rightarrow$ `bool`

$E \rightarrow E_1 \texttt{ != } E_2 \mid E_1\ N_1 \texttt{ ? } M_1\ E_2\ N_2 \texttt{ : } M_2\ E_3$
$M \rightarrow \epsilon$
$N \rightarrow \epsilon$

```
int a, b, c, d; d = a - b != 0 ? b + c : b - c;
```



```
int a, b, c, d; d = a - b ? b + c : b - c;
```



Use of type in Translation: `int` $\rightarrow$ `bool`

$convInt2Bool(E)$:

If $E.type$ is integer ($E.loc$ is valid and $E.truelist$ & $E.falselist$ are invalid), it converts $E.type$ to boolean and generates the required codes for it. Now $E.truelist$ and $E.falselist$ become valid and $E.loc$ becomes invalid. Outline of this method is:

if ($E.type ==$ integer)
  $E.falselist = makelist(nextinstr)$;
  $emit($if $E.loc$ '$=$' 0 goto .... $)$;
  $E.truelist = makelist(nextinstr)$;
  $emit($goto .... $)$;
endif

Use of type in Translation: `int` $\rightarrow$ `bool`

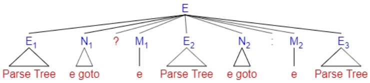
$$E \quad \rightarrow \quad E_1\ N_1\ \mathbf{?}\ M_1\ E_2\ N_2\ \mathbf{:}\ M_2\ E_3$$

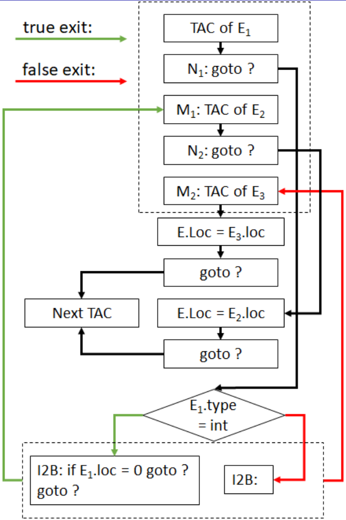
$\{\ E.loc = gentemp();$
$\quad E.type = E_2.type;$ // Assume $E_2.type = E_3.type$
$\quad emit(E.loc\ \text{'='}\ E_3.loc);$ // Control gets here by fall-through
$\quad l = makelist(nextinstr);$
$\quad emit(\text{goto ....}\ );$
$\quad backpatch(N_2.nextlist, nextinstr);$
$\quad emit(E.loc\ \text{'='}\ E_2.loc);$
$\quad l = merge(l, makelist(nextinstr));$
$\quad emit(\text{goto ....}\ );$
$\quad backpatch(N_1.nextlist, nextinstr);$
$\quad convInt2Bool(E_1);$
$\quad backpatch(E_1.truelist, M_1.instr);$
$\quad backpatch(E_1.falselist, M_2.instr);$
$\quad backpatch(l, nextinstr);$
$\}$

Use of type in Translation: int → bool, bool

$E \rightarrow E_1\ N_1\ ?\ M_1\ E_2\ N_2 : M_2\ E_3$

{
  $E.loc = gentemp();$
  // Assume $E_2.type = E_3.type$
  $E.type = E_2.type;$
  // Control gets here by fall-through
  $emit(E.loc$ '=' $E_3.loc);$
  $l = makelist(nextinstr);$
  $emit($goto .... $);$
  $backpatch(N_2.nextlist, nextinstr);$
  $emit(E.loc$ '=' $E_2.loc);$
  $l = merge(l, makelist(nextinstr));$
  $emit($goto .... $);$
  $backpatch(N_1.nextlist, nextinstr);$
  $convInt2Bool(E_1);$
  $backpatch(E_1.truelist, M_1.instr);$
  $backpatch(E_1.falselist, M_2.instr);$
  $backpatch(l, nextinstr);$
}





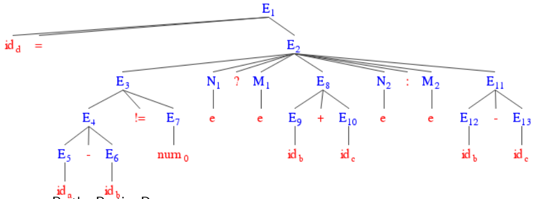
Translation of ?: for bool Condition

```
int a, b, c, d; d = a - b != 0 ? b + c : b - c;
```

```
E5.loc = a, E5.type = int
E6.loc = b, E6.type = int
E4.loc = t1, E4.type = int
E7.loc = t2, E7.type = int
E3.type = bool
E3.truelist = {102}
E3.falselist = {103}
N1.nextlist = {104}
M1.instr = 105
E9.loc = b, E9.type = int
E10.loc = c, E10.type = int
E8.loc = t3, E8.type = int
N2.nextlist = {106}
M2.instr = 107
E12.loc = b, E12.type = int
E13.loc = c, E13.type = int
E11.loc = t4, E11.type = int
E2.loc = t5, E2.type = int
E1.loc = t6, E1.type = int
```

```
100: t1 = a - b
101: t2 = 0
102: if t1 != t2 goto 105
103: goto 107
104: goto 112
105: t3 = b + c
106: goto 110
107: t4 = b - c
108: t5 = t4
109: goto 112
110: t5 = t3
111: goto 112
112: d = t5
113: t6 = t5
```

Name	Type	Size	Offset
a	int	4	0
b	int	4	4
c	int	4	8
d	int	4	12
t1	int	4	16
t2	int	4	20
t3	int	4	24
t4	int	4	28
t5	int	4	32
t6	int	4	36



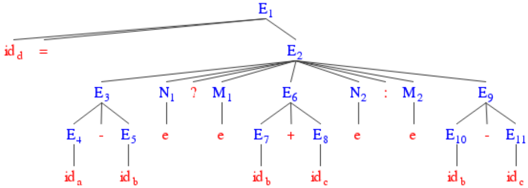
Translation of `?:` for `int` Condition

```
int a, b, c, d; d = a - b ? b + c : b - c;
```

```
E4.loc = a, E4.type = int
E5.loc = b, E5.type = int
E3.loc = t1, E3.type = int
N1.nextlist = {101}
M1.instr = 102
E7.loc = b, E7.type = int
E8.loc = c, E8.type = int
E6.loc = t2, E6.type = int
N2.nextlist = {103}
M2.instr = 104
E10.loc = b, E10.type = int
E11.loc = c, E11.type = int
E9.loc = t3, E9.type = int
E2.loc = t4, E2.type = int
E3.type = bool // Changed
E3.falselist = {109}
E3.truelist = {110}
E1.loc = t5, E1.type = int
```

```
100: t1 = a - b
101: goto 109
102: t2 = b + c
103: goto 107
104: t3 = b - c
105: t4 = t3
106: goto 111
107: t4 = t2
108: goto 111
109: if t1 = 0 goto 104
110: goto 102
111: d = t4
112: t5 = t4
```

Name	Type	Size	Offset
a	int	4	0
b	int	4	4
c	int	4	8
d	int	4	12
t1	int	4	16
t2	int	4	20
t3	int	4	24
t4	int	4	28
t5	int	4	32



Use of type in Translation

for:

```
int i;

for(i = 10; i != 0; --i) { ... } // No conv.

for(i = 10; i; --i) { ... }      // i --> i != 0
```

Grammar / Translation So Far ...

00:	P	$\rightarrow O\ D\ S$
01:	D	$\rightarrow V\ \textbf{;}\ D$
02:	D	$\rightarrow \epsilon$
03:	V	$\rightarrow V\ \textbf{,}\ \textbf{id}$
04:	V	$\rightarrow T\ \textbf{id}$
05:	T	$\rightarrow B$
06:	B	$\rightarrow \textbf{int}$
07:	B	$\rightarrow \textbf{float}$
08:	S	$\rightarrow \{\ L\ \}$
09:	S	$\rightarrow \textbf{if}\ (E)\ M\ S_1$
10:	S	$\rightarrow \textbf{if}\ (E)\ M_1\ S_1\ N\ \textbf{else}\ M_2\ S_2$
11:	S	$\rightarrow \textbf{while}\ M_1\ (E)\ M_2\ S_1$
12:	S	$\rightarrow \textbf{do}\ M_1\ S_1\ M_2\ \textbf{while}\ \textbf{(}\ E\ \textbf{);}$
13:	S	$\rightarrow \textbf{for}\ \textbf{(}\ E_1\ \textbf{;}\ M_1\ E\ \textbf{;}\ M_2\ E_2\ N\ \textbf{)}\ M_3\ S_1$
14:	S	$\rightarrow E\ \textbf{;}$
15:	L	$\rightarrow L_1\ M\ S$
16:	L	$\rightarrow S$
17:	E	$\rightarrow E_1\ N_1\ \textbf{?}\ M_1\ E_2\ N_2\ \textbf{:}\ M_2\ E_3$
18:	E	$\rightarrow E_1 = E_2$
19:	E	$\rightarrow E_1\ \vert\vert\ M\ E_2$
20:	E	$\rightarrow E_1\ \&\&\ M\ E_2$
21:	E	$\rightarrow\ !E_1$
22:	E	$\rightarrow E_1\ \texttt{relop}\ E_2$
23:	E	$\rightarrow E_1 + E_2$
24:	E	$\rightarrow E_1 - E_2$
25:	E	$\rightarrow E_1 * E_2$
26:	E	$\rightarrow E_1\ /\ E_2$
27:	E	$\rightarrow (E_1)$
28:	E	$\rightarrow -\ E_1$
29:	E	$\rightarrow \textbf{id}$
30:	E	$\rightarrow \textbf{num}$
31:	E	$\rightarrow \textbf{true}$
32:	E	$\rightarrow \textbf{false}$
33:	O	$\rightarrow \epsilon$
34:	M	$\rightarrow \epsilon$
35:	N	$\rightarrow \epsilon$

Attributes

- E: $E.type$, $E.width$, $E.loc$ ($E.type =$ **int**), $E.truelist$ ($E.type =$ **bool**), $E.falselist$ ($E.type =$ **bool**)
- S: $S.nextlist$
- N: $N.nextlist$
- T: $T.type$, $T.width$
- M: $M.instr$
- **num**: **num**.val
- L: $L.nextlist$
- V: $V.type$, $V.width$
- B: $B.type$, $B.width$
- **id**: **id**.loc

Arrays in Expression

Translation of Array Expression

array:

```
int a[10], b, i;

b = a[i]; // a[i] --> a + i * sizeof(int)
```

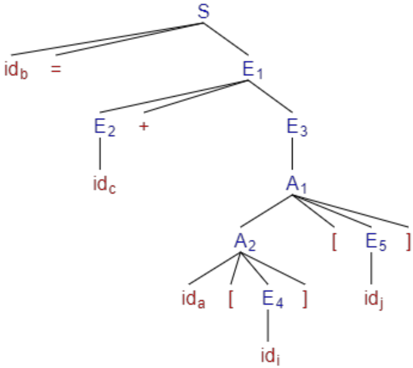
Translation:

```
t1 = i * 4
t2 = a[t1]
b = t2
```

Expression Grammar with Arrays

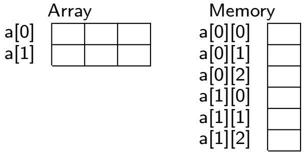
$$
\begin{array}{llll}
1: & S & \rightarrow & \textbf{id} = E \,; \\
2: & S & \rightarrow & A = E \,; \\
3: & E & \rightarrow & E_1 + E_2 \\
4: & E & \rightarrow & \textbf{id} \\
5: & E & \rightarrow & A \\
6: & A & \rightarrow & \textbf{id}\ [\ E\ ] \\
7: & A & \rightarrow & A_1\ [\ E\ ]
\end{array}
$$

ob **is** [**and** cb **is**]



Input:

```
int a[2][3], b, c;

b = c + a[i][j];
```



Output:

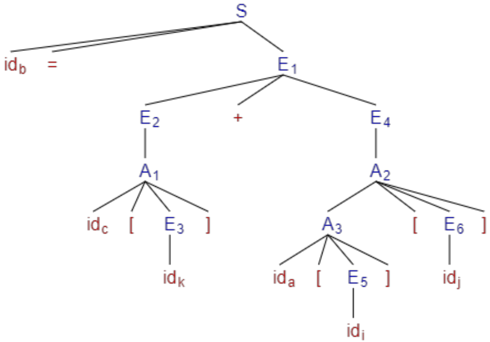
```
t1 = i * 12
t2 = j * 4
t3 = t1 + t2
t4 = a[t3]
t5 = c + t4
b = t5
```

Parse Tree of Array Expression

1:	S	$\rightarrow$	**id** $= E$;	5:	E	$\rightarrow$	A
2:	S	$\rightarrow$	$A = E$;	6:	A	$\rightarrow$	**id [** E **]**
3:	E	$\rightarrow$	$E_1 + E_2$	7:	A	$\rightarrow$	A_1 **[** E **]**
4:	E	$\rightarrow$	**id**				

`ob` **is** [**and** `cb` **is**]

```
int a[2][3], b, c[5]; int i, j, k;

b = c[k] + a[i][j];
```



Attributes for Arrays

A.loc: Temporary used for computing the offset for the array reference by summing the terms $i_j \times W_j$.

A.array: Pointer to the symbol-table entry for the array name. This has *base* and *type*.
The base address of the array, say, $A.array.base$ is used to determine the actual *l*-value of an array reference after all the index expressions are analysed.

A.type: Type of the sub-array generated by A. For any type t, the width is given by $t.width$. We use types as attributes, rather than widths, since types are needed anyway for type checking. For any array type t, suppose that $t.elem$ gives the element type.

Expression Grammar with Arrays

1:	S	$\rightarrow$	$\textbf{id} = E\ \textbf{;}$	$\{\ emit(\textbf{id}.loc\ \text{'='}\ E.loc);\ \}$
2:	S	$\rightarrow$	$A = E\ \textbf{;}$	$\{\ emit(A.array.base\ \text{'['}\ A.loc\ \text{']'}\ \text{'='}\ E.loc);\ \}$
3:	E	$\rightarrow$	$E_1 + E_2$	$\{\ E.loc = gentemp(); E.type = E_1.type;$ $emit(E.loc\ \text{'='}\ E_1.loc\ \text{'+'}\ E_2.loc);\ \}$
4:	E	$\rightarrow$	$\textbf{id}$	$\{\ E.loc = \textbf{id}.loc;\ E.type = \textbf{id}.type;\}$
5:	E	$\rightarrow$	A	$\{\ E.loc = gentemp(); E.type = A.type;$ $emit(E.loc\ \text{'='}\ A.array.base\ \text{'['}\ A.loc\ \text{']'});\ \}$
6:	A	$\rightarrow$	$\textbf{id}\ \textbf{[}\ E\ \textbf{]}$	$\{\ A.array = lookup(\textbf{id});$ $A.type = A.array.type.elem;$ $A.loc = gentemp();$ $emit(A.loc\ \text{'='}\ E.loc\ \text{'*'}\ A.type.width);\ \}$
7:	A	$\rightarrow$	$A_1\ \textbf{[}\ E\ \textbf{]}$	$\{\ A.array = A_1.array;$ $A.type = A_1.type.elem;$ $t = gentemp();$ $A.loc = gentemp();$ $emit(t\ \text{'='}\ E.loc\ \text{'*'}\ A.type.width);$ $emit(A.loc\ \text{'='}\ A_1.loc\ \text{'+'}\ t);\ \}$

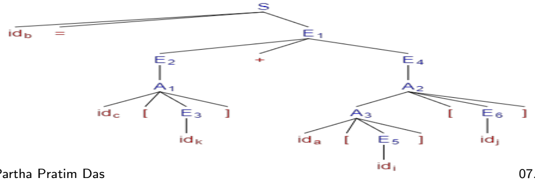
Translation of Array Expression

```
int a[2][3], b, c[5]; int i, j, k;
b = c[k] + a[i][j];

  E3.loc = k, E3.type = int   // E_3 -> id_k
  A1.array = ST[02]           // A_1 -> id_c [ E_3 ]
  A1.type = T2.elem = int
  A1.loc = t1
  A1.loc.type = E3.type = int
  E2.loc = t2, E2.type = int  // E_2 -> A_1
  E5.loc = i, E5.type = int   // E_5 -> id_i
  A3.array = ST[00]           // A_3 -> id_a [ E_5 ]
  A3.type = T1.elem = T1'
  A3.loc = t3
  A3.loc.type = E5.type = int
  E6.loc = j, E6.type = int   // E_6 -> id_j
  A2.array = ST[00]           // A_2 -> A_3 [ E_6 ]
  A2.type = T1'.elem = int
  A2.loc = t5
  A2.loc.type = E6.type = int

  E4.loc = t6, E4.type = int  // E_4 -> A_2
  E1.loc = t7, E1.type = int  // E_1 -> E_2 + E_4
```

```
.
.
.
.
100: t1 = k * 4
101: t2 = c[t1]
.
.
.
.
102: t3 = i * 12
.
.
.
.
103: t4 = j * 4
104: t5 = t3 + t4
105: t6 = a[t5]
106: t7 = t2 + t6
107: b = t7
```

No.	Name	Type	Size	Offset
00	a	T1	24	0
01	b	int	4	24
02	c	T2	20	28
03	i	int	4	48
04	j	int	4	52
05	k	int	4	56
06	t1	int	4	16
07	t2	int	4	20
08	t3	int	4	24
09	t4	int	4	28
10	t5	int	4	32
11	t6	int	4	36
12	t7	int	4	36

T1 = array(2, array(3, int)) = array(2, T1')
T1' = array(3, int). T2 = array(5, int)
T1'.width = 3 * int.width = 3 * 4 = 12
T1.width = 2 * T1'.width = 2 * 12 = 24
T2.width = 5 * int.width = 5 * 4 = 20



Expression Grammar with Arrays

Input:

```
int a[2][3], b, c[5];
int i, j, k;

b = c[k] + a[i][j];
```

Output:

```
t1 = k * 4
t2 = c[t1]
t3 = i * 12
t4 = j * 4
t5 = t3 + t4
t6 = a[t5]
t7 = t2 + t6
b = t7
```

Name	Type	Size	Offset
a	array(2, array(3, int))	24	0
b	int	4	24
c	array(5, int)	20	28
i	int	4	48
j	int	4	52
k	int	4	56

Practice Exercise 1: Arrays in Expressions

In the context of

```
int a, b, i, j, k;
int c[6];
int d[4][3], e;
```

Translate the following:

```
a = c[i];
b = d[j][k];
c[e] = b;
c[2] = c[1] + c[0];
d[2][1] = c[3] + a;
```

Type Expressions

Declaration Grammar (Inherited Attributes)

Without Array				With Array			
0:	P	$\rightarrow$	D	0:	P	$\rightarrow$	D
1:	D	$\rightarrow$	$T\ V\ ;\ D_1$	1:	D	$\rightarrow$	$T\ V\ ;\ D_1$
2:	D	$\rightarrow$	ϵ	2:	D	$\rightarrow$	ϵ
3:	V	$\rightarrow$	V_1 **, id**	3:	V	$\rightarrow$	V_1 **, id** C
4:	V	$\rightarrow$	**id**	4:	V	$\rightarrow$	**id** C
5:	T	$\rightarrow$	B	5:	T	$\rightarrow$	B
6:	B	$\rightarrow$	**int**	6:	B	$\rightarrow$	**int**
7:	B	$\rightarrow$	**float**	7:	B	$\rightarrow$	**float**
				8:	C	$\rightarrow$	**[num]** C_1
				9:	C	$\rightarrow$	ϵ

Why the rule of C is right-recursive?

- Since the information (of type) needs to flow from the innermost dimension of an array to its outer dimensions (right-to-left), the right recursion is natural in $C \rightarrow$ **[num]** C.
- However, while making a reference to that array in an expression, we need to start with its type expression and parse down (left-to-right). Hence, left recursion is natural in $A \rightarrow A$ **[** E **]**.

Symbol Table

Example:
```
int a, b;
int x, y[10], z;
double w[5];
```

Name	**Type**	**Size**	**Offset**
a	int	4	0
b	int	4	4
x	int	4	8
y	array(10, int)	40	12
z	int	4	52
w	array(5, double)	40	56

sizeof(int) $= 4$
sizeof(double) $= 8$

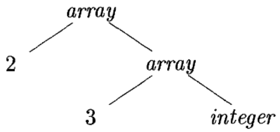
Type Expressions

Applications of types can be grouped under:

- *Type Checking*
  - Logical rules to reason about the behaviour of a program at run time.
  - The types of the operands should match the type expected by an operator. For example, the && operator in Java expects its two operands to be boolean; the result is also of type boolean
- *Translation Applications*
  - Determine the storage that will be needed for that name at run time,
  - Calculate the address denoted by an array reference,
  - Insert explicit type conversions,
  - Choose the right version of an arithmetic operator, ...

Type Expressions

- A *type expression* is either
  - a basic type or
  - formed by applying a *type constructor* operator to a type expression.
- The sets of basic types and constructors depend on the language to be checked.
- *Example*: Type expression of **int[2][3]** (*array of 2 arrays of 3 integers each*) is $array(2, array(3, integer))$



Operator *array* takes two parameters, a *number* and a *type*.

Type Expressions

- *Basic Types*
  - A basic type like **bool**, **char**, **int**, **float**, **double**, or **void** is a type expression. **void** denotes *the absence of a value*.
- *Type Name*
  - A type name is a type expression.
- *Cartesian Product*
  - For two type expressions s and t, we write the Cartesian product type expression $s \times t$ to represent a list or tuple of types (like function parameters). $\times$ associates to the left and has precedence over $\rightarrow$.
- *Type Variables*
  - Type expressions may contain variables whose values are type expressions. Compiler-generated type variables are also possible.

Type Expressions

- *Type Constructor*
  - A type expression can be formed by applying the *array* type constructor to a number and a type expression.

    ```
    int a[10][5];
    ```

    Type ≡ array(10, array (5, int))
  - A **struct** (or record) is a data structure with named fields. A type expression can be formed by applying the *record* type constructor to the field names and their types.

    ```
    struct _ {
        char name[20];
        int height;
    }
    ```

    Type ≡ record{name: char[20], height: int}

struct Type Expression

```
#include <iostream>
using namespace std;

typedef struct {    // record{ name: array (20, char), weight: int}
    char name[20];
    int weight;
} Person;

typedef struct {    // record{ name: array (20, char), weight: int}
    char s_name[20];
    int height;
} Student;

int main() {
    Person p = { "Partha", 80 };
    Student s = { "Arjun", 150 }, t = { "Priyanvada", 120 };

    cout << p.name << " " << p.weight << endl;
    cout << s.s_name << " " << s.height << endl;
    cout << t.s_name << " " << t.height << endl;

    // s = p; // Incompatible types
    s = t; // Compatible types

    cout << s.s_name << " " << s.height << endl;
}
```

Type Expressions

- *Type Constructor*
  - For two type expressions s and t, we write type expression $s \rightarrow t$ for *function from type s to type t*, where $\rightarrow$ is a function type constructor.

    ```
    int f(int);
    ```

    $\text{Type} \equiv \text{int} \rightarrow \text{int}$

    ```
    int add(int, int);
    ```

    $\text{Type} \equiv \text{int} \times \text{int} \rightarrow \text{int}$

    ```
    int main(int argc, char *argv[]);
    ```

    $\text{Type} \equiv \text{int} \times \text{array}(*, \text{char}*) \rightarrow \text{int}$
  - For a type expression t, address(t) is the expression for its pointer / address type

    ```
    int *p;
    ```

    $\text{Type} \equiv \text{address}(\text{int})$

Type Equivalence

- *If two type expressions are equal then return a certain type else error.*

```
typedef int * IntPtr;           // IntPtr = address(int)
typedef IntPtr IntPtrArray[10]; // IntPtrArray = array(10, IntPtr)
                                //     = array(10, address(int))
typedef int * IPtrArray[10];    // IPtrArray = array(10, address(int))

IntPtrArray x; // IntPtrArray
IPtrArray y;   // IPtrArray
int *z[10];    // T = array(10, address(int))

So, IntPtrArray = IPtrArray = T = array(10, address(int))
```

Further,

```
typedef int (*fptr)(int, int);
int f(int, int);

fptr = address(int X int --> int)
T1 = Type(&f) = address(int X int --> int)}
T2 = Type(f) = int X int --> int

So, fptr = T1, and T2 considered equivalent as well
```

- When type expressions are represented by graphs, two types are structurally equivalent if and only if:
  - They are the same basic type, or
  - They are formed by applying the same constructor to structurally equivalent types, or
  - One is a type name that denotes the other.

Declaration Grammar (Inherited Attributes)

With Array

$$
\begin{array}{llll}
0: & P & \rightarrow & D \\
1: & D & \rightarrow & T\ \textbf{id}\ \ C\ \textbf{;}\ D_1 \\
2: & D & \rightarrow & \epsilon \\
5: & T & \rightarrow & B \\
6: & B & \rightarrow & \textbf{int} \\
7: & B & \rightarrow & \textbf{float} \\
8: & C & \rightarrow & \textbf{[}\ \textbf{num}\ \textbf{]}\ C_1 \\
9: & C & \rightarrow & \epsilon
\end{array}
$$

For simplicity list of variables in a single declaration has been omitted here.

Attributes for Types

type: – Type expression for B, C, and T.
– This a synthesized attribute for B & C, and an inherited attribute for T.

width: – The width of a type (B, C, or T), that is, the number of storage units (bytes) needed for objects of that type. $width = type.width$. It is integral for basic types.
– This a synthesized attribute for B & C, and an inherited attribute for T.

t: – Global variable to pass the *type* information from a B node to the node for production $C \rightarrow \epsilon$.
– This is for handling inherited attribute.

w: – Global variable to pass the *width* information from a B node to the node for production $C \rightarrow \epsilon$. $w = t.width$
– This is for handling inherited attribute.

Sequence of Declarations

$$
\begin{array}{llll}
0: & P & \rightarrow & \{\ \text{offset} = 0;\ \} \\
 & & & D \\
1: & D & \rightarrow & T\ \textbf{id}\ C\ \textbf{;}\quad \{\ T.type = C.type; \\
 & & & \quad T.width = C.width; \\
 & & & \quad update(\textbf{id}.lexeme, T.type, offset); \\
 & & & \quad offset = offset + T.width;\ \} \\
 & & & D_1 \\
2: & D & \rightarrow & \epsilon
\end{array}
$$

Computing Types and their Widths

5: $T \rightarrow B$ $\{\ t = B.type;\ w = B.width;\ \}$

6: $B \rightarrow$ **int** $\{\ B.type = integer;\ B.width = 4;\ \}$

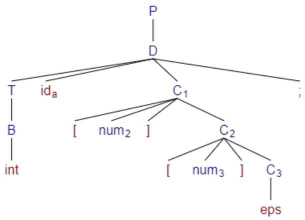
7: $B \rightarrow$ **float** $\{\ B.type = float;\ B.width = 8;\ \}$

8: $C \rightarrow$ **[num]** C_1
$\{\ C.type = array(\mathbf{num}.value, C_1.type);$
$C.width = \mathbf{num}.value \times C_1.width);\ \}$

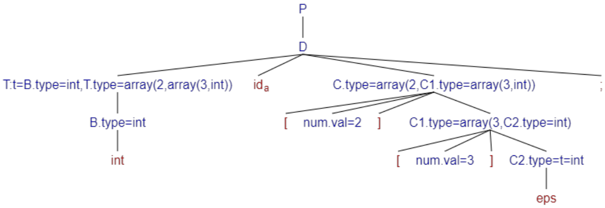
9: $C \rightarrow \epsilon$ $\{\ C.type = t;\ C.width = w;\ \}$

Array Declaration Example

Consider the array declaration: `int a[2][3];`



The parse tree is annotated with the attributes computed by the semantic actions. Note how `t` is set in node T and is used in node $C2$.



Declaration Grammar (Inherited Attributes): Dragon Book

The following grammar and actions are taken from Dragon Book which presents a little different treatment

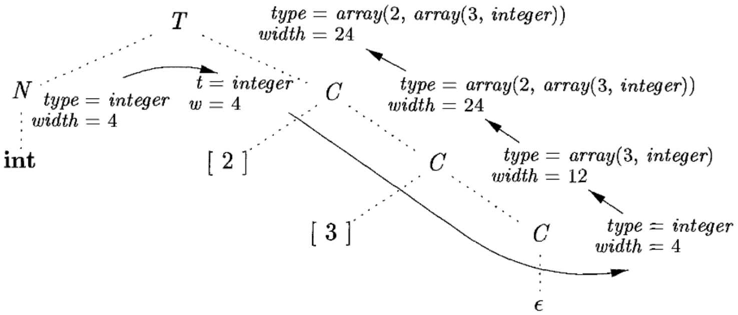
$$
\begin{array}{llll}
0: & P & \rightarrow & D \\
1: & D & \rightarrow & T \ \mathbf{id} \ \mathbf{;} \ D_1 \\
2: & D & \rightarrow & \epsilon \\
3: & T & \rightarrow & B \ C \\
4: & T & \rightarrow & \mathbf{struct} \ \{ \ D \ \} \\
5: & B & \rightarrow & \mathbf{int} \\
6: & B & \rightarrow & \mathbf{float} \\
7: & C & \rightarrow & \mathbf{[\ num \ ]} \ C_1 \\
8: & C & \rightarrow & \epsilon
\end{array}
$$

For simplicity list of variables in a single declaration has been omitted here.

Computing Types and their Widths: Dragon Book

$$
\begin{array}{llll}
3: & T & \rightarrow & B \quad \{\ t = B.type;\ w = B.width;\ \} \\
 & & & C \quad \{\ T.type = C.type;\ T.width = C.width;\ \} \\
5: & B & \rightarrow & \textbf{int} \quad \{\ B.type = integer;\ B.width = 4;\ \} \\
6: & B & \rightarrow & \textbf{float} \quad \{\ B.type = float;\ B.width = 8;\ \} \\
7: & C & \rightarrow & [\ \textbf{num}\ ]\ C_1 \\
 & & & \quad \{\ C.type = array(\textbf{num}.value, C_1.type); \\
 & & & \quad\ \ C.width = \textbf{num}.value \times C_1.width);\ \} \\
8: & C & \rightarrow & \epsilon \quad \{\ C.type = t;\ C.width = w;\ \}
\end{array}
$$

Computing Types and their Widths: Dragon Book



Computing Type for int[2][3]

The above diagram is taken from the Dragon Book.

Please read the non-terminal N as non-terminal B in our grammar.

Sequence of Declarations: Dragon Book

$$
\begin{array}{llll}
0: & P & \rightarrow & \{\ \text{offset} = 0;\ \} \\
 & & & D \\
1: & D & \rightarrow & T\ \mathbf{id}\ ; \quad \{\ update(\mathbf{id}.lexeme, T.type, offset); \\
 & & & \qquad offset = offset + T.width;\ \} \\
 & & & D_1 \\
2: & D & \rightarrow & \epsilon
\end{array}
$$

Declaration Grammar (Synthesized Attributes)

The translations discussed so far use inherited attributes. We may want to re-write the grammar to use *only* synthesized attributes and in the earlier style design something like:

Inherited Attributes

0:	P	$\rightarrow$	D
1:	D	$\rightarrow$	$T\ V\ ;\ D_1$
2:	D	$\rightarrow$	ϵ
3:	V	$\rightarrow$	$V_1\ ,\ \mathbf{id}\ \ C$
4:	V	$\rightarrow$	$\mathbf{id}\ \ C$
5:	T	$\rightarrow$	B
6:	B	$\rightarrow$	**int**
7:	B	$\rightarrow$	**float**
8:	C	$\rightarrow$	$[\ \mathbf{num}\ ]\ C_1$
9:	C	$\rightarrow$	ϵ

Synthesized Attributes

0:	P	$\rightarrow$	D
1:	D	$\rightarrow$	$V\ ;\ D_1$
2:	D	$\rightarrow$	ϵ
3:	V	$\rightarrow$	$V_1\ ,\ \mathbf{id}\ \ C$
4:	V	$\rightarrow$	$T\ \mathbf{id}\ \ C$
5:	T	$\rightarrow$	B
6:	B	$\rightarrow$	**int**
7:	B	$\rightarrow$	**float**
8:	C	$\rightarrow$	$[\ \mathbf{num}\ ]\ C_1$
9:	C	$\rightarrow$	ϵ

Declaration Grammar (Synthesized Attributes)

- It may be noted that this design is faulty because it still needs inherited attributes to compute the type of C in $C \rightarrow \epsilon$.
- It is rather non-trivial to re-write this grammar for synthesized attributes *only*. This is due to the right-recursive structure of the rules for handling array dimensions. For synthesis, the information naturally flows from left to right while for right recursion the information flows in the reverse order.
- Of course, it is possible to pass this type information through Symbol Table with using explicit global. But that does neither offer an elegant solution.

Functions

Function Declaration Grammar

1:	D	$\rightarrow$	T **id** (F_{opt})**;**	$\{$ $insert(ST_{gbl}$, **id**, $T.type$, function, $F_{opt}.ST)$; $insert(F_{opt}.ST$, `__retval`, $T.type, 0)$; $\}$
2:	F_{opt}	$\rightarrow$	F	$\{ F_{opt}.ST = F.ST; \}$
3:	F_{opt}	$\rightarrow$	ϵ	$\{ F_{opt}.ST = CreateSymbolTable(); \}$
4:	F	$\rightarrow$	F_1 **,** T **id**	$\{ F.ST = F_1.ST;$ $insert(F.ST$, **id**, $T.type, 0); \}$
5:	F	$\rightarrow$	T **id**	$\{ F.ST = CreateSymbolTable();$ $insert(F.ST$, **id**, $T.type, 0); \}$
6:	T	$\rightarrow$	**int**	$\{ T.type =$ int $\}$
7:	T	$\rightarrow$	**double**	$\{ T.type =$ double $\}$
8:	T	$\rightarrow$	**void**	$\{ T.type =$ void $\}$

```
int func(int i, double d);
```

ST(global) *This is the Symbol Table for global symbols*

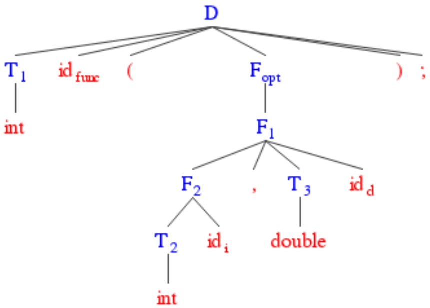
Name	Type	Init. Val.	Size	Offset	Nested Table
func	*function*	null	0	...	ptr-to-ST(func)

ST(func) *This is the Symbol Table for function* `func`

Name	Type	Init. Val.	Size	Offset	Nested Table
i	**int**	null	4	0	null
d	**double**	null	8	4	null
__retVal	**int**	null	4	12	null

Function Declaration Example

```
int func(int i, double d);

T1.type = int        // T_1 -> int
T2.type = int        // T_2 -> int
F2.ST = ST(func)     // T_2 -> T_2 id_i
T3.type = dbl        // T_3 -> double
F1.ST = ST(func)     // F_1 -> F_2 , T_3 id_d
F_opt.ST = ST(func)  // F_opt -> F_1
```



ST(global)

Name	Type	Size	Offset	Nested Table
func	int × dbl → int	0	...	ST(func)

ST(func)

Name	Type	Size	Offset	Nested Table
i	**int**	4	0	null
d	**dbl**	8	4	null
_ _ rv	**int**	4	12	null

Function Invocation Grammar

0:	D	$\rightarrow$	T **id** (F_{opt}) { L }	
1 | 2:	L	$\rightarrow$	$L_1\ S \mid S$	
3:	S	$\rightarrow$	**return** E ;	{ Check if function.*type* matches $E.type$; *emit*(**return** $E.loc$); }
4:	E	$\rightarrow$	**id** (A_{opt})	{ $ST = lookup(ST_{gbl}, \textbf{id}).symtab$; For every param p in $A_{opt}.list$; Match $p.type$ with param type in ST; *emit*(**param** $p.loc$); $E.loc = gentemp(lookup(ST_{gbl}, \textbf{id}).type)$; $emit(E.loc = \textbf{call id}, length(A_{opt}.list))$; }
5:	A_{opt}	$\rightarrow$	A	{ $A_{opt}.list = A.list$; }
6:	A_{opt}	$\rightarrow$	ϵ	{ $A_{opt}.list = 0$; }
7:	A	$\rightarrow$	A_1 , E	{ $A.list = Merge(A_1.list, Makelist(E.loc, E.type))$; }
8:	A	$\rightarrow$	E	{ $A.list = Makelist(E.loc, E.type)$; }

```
int a, b, c;
double d, e;
...
a = func(b + c, d * e);
return a;
```

List of Params

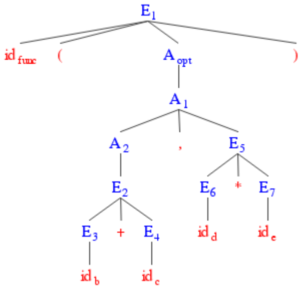
t1	int
t2	double

```
t1 = b + c
t2 = d * e
param t1
param t2
t3 = call func, 2
a = t3
```

Function Invocation Example

```
int a, b, c;
double d, e;
...
a = func(b + c, d * e);
return a;

------------------------

t1 = b + c
t2 = d * e
param t1
param t2
t3 = call func, 2
```

```
E3.loc = b, E3.type = int
E4.loc = c, E4.type = int
E2.loc = t1, E2.type = int
A2.list = {t1}
E6.loc = d, E6.type = dbl
E7.loc = e, E7.type = dbl
E5.loc = t2, E5.type = dbl
A1.list = {t1, t2}
A_opt.list = {t1, t2}
E1.loc = t3, E1.type = int
```



ST(global)

Name	Type	Size	Offset	Nested Table
func	int × dbl → int	0	...	ST(func)

ST(func)

Name	Type	Size	Offset	Nested Table
i	**int**	4	0	null
d	**dbl**	8	4	null
_rv	**int**	4	12	null

ST(?)

Name	Type	Size	Offset	Nested Table
a	**int**	4	0	null
b	**int**	4	4	null
c	**int**	4	8	null
d	**dbl**	8	16	null
e	**dbl**	8	24	null
t1	**int**	4	28	null
t2	**dbl**	8	32	null
t3	**int**	4	40	null

Practice Exercise 1: Function Declaration and Invocation

[1] Consider the following function prototypes:

```
int min(int a, int b);
int max(int a, int b);
int main();
```

Using the grammar and actions for function declaration, translate the above snippets. Show the parse tree, the working of the translation with the computation of attribute values, and the populated global symbol table and symbol tables of respective functions.

[2] Consider that the above functions are defined as follows later in the code:

```
int min(int a, int b) { return 0; }
int max(int a, int b) { return 0; }
int main() { return 0; }
```

Perform the translation again. Show the parse tree, the working of the translation with the computation of attribute values, and the populated global symbol table and symbol tables of respective functions.

Practice Exercise 2: Function Declaration and Invocation

[1] Next consider that the above functions are defined with meaningful body as follows:

```
int min(int a, int b) {
    int t;
    if (a < b) t = a; else t = b;
    return t;
}
int max(int a, int b) {
    int t;
    if (a > b) t = a; else t = b;
    return t;
}
int main() {
    int x, y, z;
    x = 3;
    y = 5;
    z = min(x, y) + max(x, y);
    return 0;
}
```

Perform the translation again. Show the parse tree, the working of the translation with the computation of attribute values, the populated global symbol table and symbol tables of respective functions, and the sequence of quads for every function.

Lexical Scope Management

Grammar for Global, Function and Nested Block Scopes

0:	Pgm	$\rightarrow$	TU	$\{$ $UpdateOffset(ST_{gbl})$; $\}$ // End of TAC Translate
1:	TU	$\rightarrow$	$TU_1\ P$	
2:	TU	$\rightarrow$	$M\ P$	
3:	M	$\rightarrow$	ϵ	$\{$ $ST_{gbl} = CreateSymbolTable()$; $ST_{gbl}.parent = 0$; $cST = ST_{gbl}$; $\}$
4:	P	$\rightarrow$	VD	// Variable Declaration
5:	P	$\rightarrow$	PD	// Function Prototype Declaration
6:	P	$\rightarrow$	FD	// Function Definition
7:	VD	$\rightarrow$	$T\ V$ **;**	$\{$ $type_{gbl} = null$; $width_{gbl} = 0$; $\}$
8:	V	$\rightarrow$	V_1 **, id** C	$\{$ $Name = lookup(cST, \textbf{id})$; $Name.category = (cST == ST_{gbl})$? global: local; $Name.type = C.type$; $Name.size = C.width$; $\}$
9:	V	$\rightarrow$	**id** C	$\{$ $Name = lookup(cST, \textbf{id})$; $Name.category = (cST == ST_{gbl})$? global: local; $Name.type = C.type$; $Name.size = C.width$; $\}$
10:	C	$\rightarrow$	**[num]** C_1	$\{$ $C.type = array(\textbf{num}.value, C_1.type)$; $C.width = \textbf{num}.value \times C_1.width)$; $\}$
11:	C	$\rightarrow$	ϵ	$\{$ $C.type = type_{gbl}$; $C.width = width_{gbl}$; $\}$
12:	T	$\rightarrow$	B	$\{$ $type_{gbl} = T.type = B.type$; $width_{gbl} = T.width = B.width$; $\}$
13:	B	$\rightarrow$	**int**	$\{$ $B.type =$ int; $B.width =$ sizeof$(B.type)$; $\}$
14:	B	$\rightarrow$	**double**	$\{$ $B.type =$ double; $B.width =$ sizeof$(B.type)$; $\}$
15:	B	$\rightarrow$	**void**	$\{$ $B.type =$ void; $B.width =$ sizeof$(B.type)$; $\}$

Grammar for Global, Function and Nested Block Scopes

16:	PD	$\rightarrow$	$T\ FN\ \textbf{(}\ FP_{opt}\ \textbf{);}$	$\{\ UpdateOffset(cST);\ cST = cST.parent;\ \}$
17:	FD	$\rightarrow$	$T\ FN\ \textbf{(}\ FP_{opt}\ \textbf{)}\ CS$	$\{\ UpdateOffset(cST);\ cST = cST.parent;\ \}$

18:	FN	$\rightarrow$	$\textbf{id}$	$\{\ Name = lookup(ST_{gbl}, \textbf{id});\ ST = Name.symtab;$
				if (ST is $null$)
				$ST = CreateSymbolTable();\ ST.parent = ST_{gbl};$
				$Name.category =$ function; $Name.symtab = ST;$
				endif
				$cST = ST;\ \}$

19:	FP_{opt}	$\rightarrow$	FP	
20:	FP_{opt}	$\rightarrow$	ϵ	
21:	FP	$\rightarrow$	$FP_1\ \textbf{,}\ T\ \textbf{id}$	$\{\ Name = lookup(cST, \textbf{id});\ Name.category =$ param; $Name.type = T.type;\ Name.size = T.width;\ \}$
22:	FP	$\rightarrow$	$T\ \textbf{id}$	$\{\ Name = lookup(cST, \textbf{id});\ Name.category =$ param; $Name.type = T.type;\ Name.size = T.width;\ \}$
23:	CS	$\rightarrow$	$\{\ N\ L\ \}$	$\{\ UpdateOffset(cST);\ cST = cST.parent;\ \}$
24:	N	$\rightarrow$	ϵ	$\{$ if ($cST.parent$ is not ST_{gbl}) // Not a function scope $N.ST = CreateSymbolTable();$ $N.ST.parent = cST;\ cST = N.ST;$ endif $\}$
25:	L	$\rightarrow$	$L_1\ S$	// List of Statements – Statement actions not shown
26:	L	$\rightarrow$	LD	
27:	LD	$\rightarrow$	$LD_1\ VD$	// List of Declarations
28:	LD	$\rightarrow$	ϵ	

Grammar for Global, Function and Nested Block Scopes

29:	S	$\rightarrow$	CS	
30:	S	$\rightarrow$	E **;**	
31:	S	$\rightarrow$	**return** E **;**	$\{$ $emit($**return** $E.loc)$; $\}$
32:	S	$\rightarrow$	**return ;**	$\{$ $emit($**return**$)$; $\}$
33:	E	$\rightarrow$	$E_1 = E_2$	$\{$ $E.loc = gentemp()$; $emit(E_1.loc$ '=' $E_2.loc)$; $emit(E.loc$ '=' $E_1.loc)$; $\}$
34:	E	$\rightarrow$	**id**	$\{$ $E.loc =$**id**$.loc$; $\}$
35:	E	$\rightarrow$	**num**	$\{$ $E.loc = gentemp()$; $emit(E.loc =$ **num**$.val)$; $\}$
36:	E	$\rightarrow$	AR	$\{$ $E.loc = gentemp()$; $emit(E.loc$ '=' $AR.array.base$ '[' $AR.loc$ ']'$)$; $\}$
37:	AR	$\rightarrow$	**id [** E **]**	$\{$ $AR.array = lookup(cST,$ **id**$)$; $AR.type = AR.array.type.elem$; $AR.loc = gentemp()$; $emit(AR.loc$ '=' $E.loc$ '*' $AR.type.width)$; $\}$
38:	AR	$\rightarrow$	AR_1 **[** E **]**	$\{$ $AR.array = AR_1.array$; $AR.type = AR_1.type.elem$; $t = gentemp()$; $AR.loc = gentemp()$; $emit(t$ '=' $E.loc$ '*' $AR.type.width)$; $emit(AR.loc$ '=' $AR_1.loc$ '+' $t)$; $\}$

Grammar for Global, Function and Nested Block Scopes

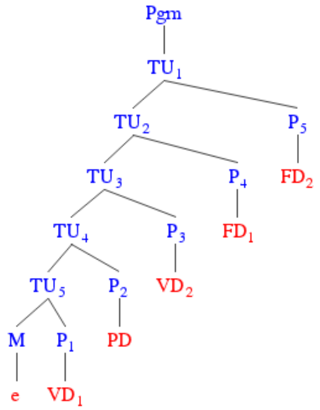
39:	E	$\rightarrow$	**id** (AP_{opt})	{ $ST = lookup(ST_{gbl}, \textbf{id}).symtab$; For every param p in $AP_{opt}.list$; Match $p.type$ with param type in ST; $emit(\textbf{param}\ p.loc)$; $E.loc = gentemp(lookup(ST_{gbl}, \textbf{id}).type)$; $emit(E.loc = \textbf{call id}, length(AP_{opt}.list))$; }
40:	AP_{opt}	$\rightarrow$	AP	{ $AP_{opt}.list = AP.list$; }
41:	AP_{opt}	$\rightarrow$	ϵ	{ $AP_{opt}.list = 0$; }
42:	AP	$\rightarrow$	AP_1 , E	{ $AP.list = Merge(AP_1.list,$ $Makelist((E.loc, E.type))$; }
43:	AP	$\rightarrow$	E	{ $AP.list = Makelist((E.loc, E.type))$; }

Example 1: Global & Function Scope: main() & add(): Source

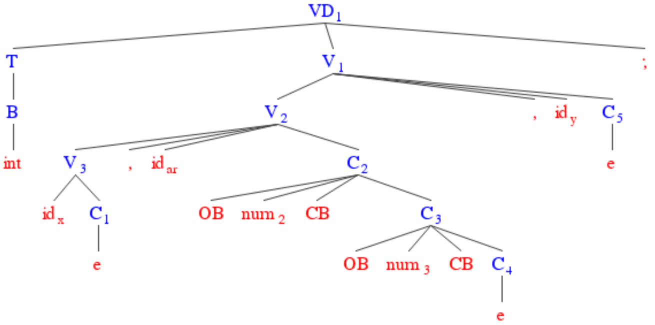

```
int x, ar[2][3], y;
int add(int x, int y);
double a, b;
int add(int x, int y) {
    int t;
    t = x + y;
    return t;
}
void main() {
    int c;
    x = 1;
    y = ar[x][x];
    c = add(x, y);
    return;
}
```

Example 1: Global & Function Scope: Parse Tree (Pgm)


```
                                // M
int x, ar[2][3], y;             // VD_1
int add(int x, int y);          // PD
double a, b;                    // VD_2
int add(int x, int y) {         // FD_1
    int t;
    t = x + y;
    return t;
}
void main() {                   // FD_2
    int c;
    x = 1;
    y = ar[x][x];
    c = add(x, y);
    return;
}
----
cST = ST.glb
```



Example 1: Global & Function Scope: Parse Tree (VD_1)




```
int x, ar[2][3], y;      // VD_1
```

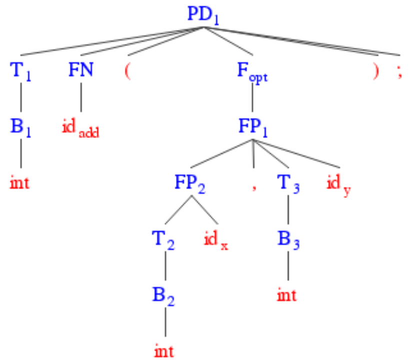
ST.gbl: ST.gbl.parent = null					
x	int	global	4	0	null
ar	array(2, array(3, int))				
		global	24	4	null
y	int	global	4	28	null

Columns: Name, Type, Category, Size, Offset, & Symtab

```
//cST = ST.glb
B.type = int, B.width = 4
T.type = int, T.width = 4
type_glb = int, width_glb = 4
C1.type = int, C1.width = 4
C4.type = int, C4.width = 4
C3.type = array(3, int), C3.width = 12
C2.type = array(2, array(3, int)), C4.width = 24
C5.type = int, C5.width = 4
```

Example 1: Global & Function Scope: Parse Tree (PD_1)


```
//cST = ST.glb
B1.type = int, B1.width = 4
T1.type = int, T1.width = 4
type_glb = int, width_glb = 4
cST = ST.add // FN -> id
B2.type = int, B2.width = 4
T2.type = int, T2.width = 4
type_glb = int, width_glb = 4
B3.type = int, B3.width = 4
T3.type = int, T3.width = 4
type_glb = int, width_glb = 4
cST = ST.glb // PD -> T FN ( F_opt ) ;
```



`int add(int x, int y);    // PD`

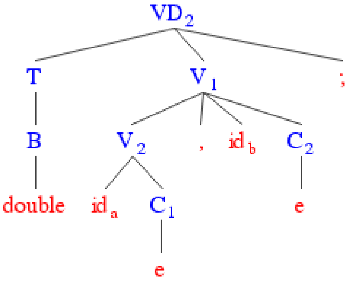
ST.gbl: ST.gbl.parent = null					
x	int	global	4	0	null
ar	array(2, array(3, int))	global	24	4	null
y	int	global	4	28	null
add	int $\times$ int $\rightarrow$ int	func	0	32	ST.add()

Columns: Name, Type, Category, Size, Offset, & Symtab

ST.add(): ST.add.parent = ST.gbl				
x	int	param	4	0
y	int	param	4	4

Example 1: Global & Function Scope: Parse Tree (VD_2)

```
//cST = ST.glb
B.type = double, B.width = 8
T.type = double, T.width = 8
type_glb = double, width_glb = 8
C1.type = double, C1.width = 8
C2.type = double, C2.width = 8
```




```
double a, b;                // VD_2
```

ST.gbl: ST.gbl.parent = null

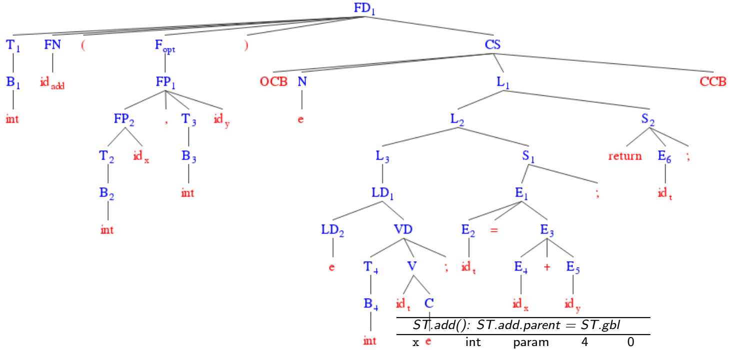
x	int	global	4	0	null
ar	array(2, array(3, int))	global	24	4	null
y	int	global	4	28	null
add	int $\times$ int $\rightarrow$ int	func	0	32	ST.add()
a	double	global	8	32	null
b	double	global	8	40	null

Columns: Name, Type, Category, Size, Offset, & Symtab

ST.add(): ST.add.parent = ST.gbl

x	int	param	4	0
y	int	param	4	4

Example 1: Global & Function Scope: Parse Tree (FD_1)



ST.gbl: ST.gbl.parent = null

x	int	global	4	0	null
ar	array(2, array(3, int))				
		global	24	4	null
y	int	global	4	28	null
add	int × int → int				
		func	0	32	ST.add()
a	double	global	8	32	null
b	double	global	8	40	null

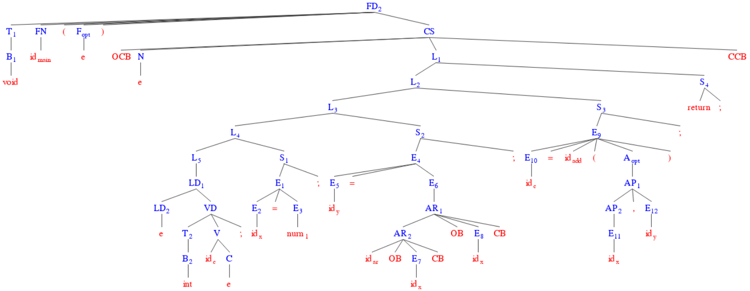
Columns: Name, Type, Category, Size, Offset, & Symtab

ST.add(): ST.add.parent = ST.gbl

x	int	param	4	0
y	int	param	4	4
t	int	local	4	8
t#1	int	temp	4	12

```
int add(int x, int y) {  // FD_1
    int t;
    t = x + y;
    return t;
}
```

Example 1: Global & Function Scope: Parse Tree (FD_2)



ST.gbl: ST.gbl.parent = null

x	int	global	4	0	null
ar	array(2, array(3, int)) global		24	4	null
y	int	global	4	28	null
add	int × int → int func		0	32	ST.add()
a	double	global	8	32	null
b	double	global	8	40	null
main	void → void func		0	48	ST.main()

Columns: Name, Type, Category, Size, Offset, & Symtab

ST.add(): ST.add.parent = ST.gbl

x	int	param	4	0
y	int	param	4	4
t	int	local	4	8
t#1	int	temp	4	12

ST.main(): ST.main.parent = ST.gbl

c	int	local	4	0
t#1	int	temp	4	4
t#2	int	temp	4	8
t#3	int	temp	4	12
t#4	int	temp	4	16

Example 1: Global & Function Scope: main() & add(): Source & TAC


```
int x, ar[2][3], y;
int add(int x, int y);
double a, b;
int add(int x, int y) {
    int t;
    t = x + y;
    return t;
}
void main() {
    int c;
    x = 1;
    y = ar[x][x];
    c = add(x, y);
    return;
}
```

```
add:    t#1 = x + y
        t = t#1
        return t

main:   t#1 = 1
        x = t#1
        t#2 = x * 12
        t#3 = x * 4
        t#4 = t#2 + t#3
        y = ar[t#4]
        param x
        param y
        c = call add, 2
        return
```

ST.gbl: ST.gbl.parent = null

x	int	global	4	0	null
ar	array(2, array(3, int))				
		global	24	4	null
y	int	global	4	28	null
add	int × int → int				
		func	0	32	ST.add()
a	double	global	8	32	null
b	double	global	8	40	null
main	void → void				
		func	0	48	ST.main()

Columns: Name, Type, Category, Size, Offset, & Symtab

ST.add(): ST.add.parent = ST.gbl

x	int	param	4	0
y	int	param	4	4
t	int	local	4	8
t#1	int	temp	4	12

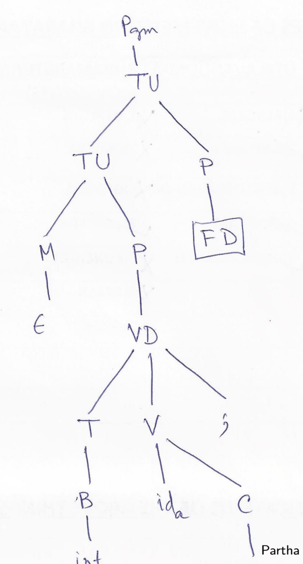
ST.main(): ST.main.parent = ST.gbl

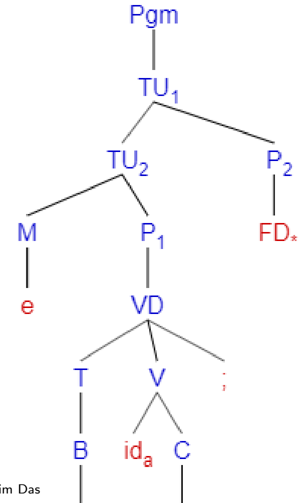
c	int	local	4	0
t#1	int	temp	4	4
t#2	int	temp	4	8
t#3	int	temp	4	12
t#4	int	temp	4	16

Example 2: Nested Blocks: Source

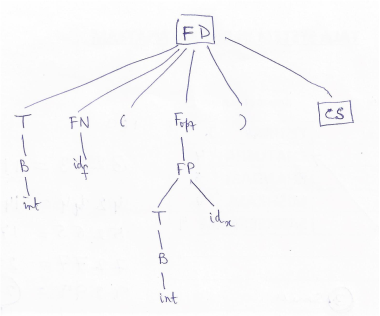
```
int a;
int f(int x) { // function scope f
    int t, u;
    t = x; // t in f, x in f
    { // un-named block scope f_1
         int p, q, t;
         p = a; // p in f_1, a in global
         t = 4; // t in f_1, hides t in f
         { // un-named block scope f_1_1
             int p;
             p = 5; // p in f_1_1, hides p in f_1
         }
         q = p; // q in f_1, p in f_1
    }
    return u = t; // u in f, t in f
}
```

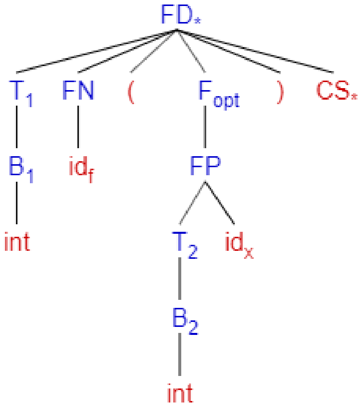
Example 2: Nested Blocks: Parse Tree (Pgm)



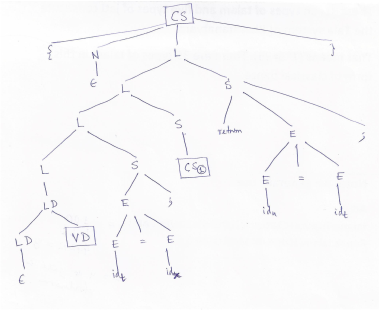


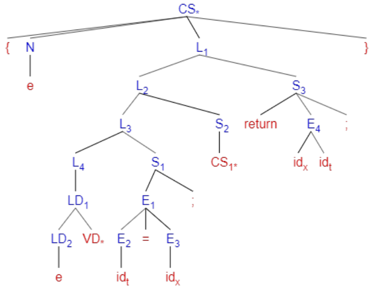
Example 2: Nested Blocks: Parse Tree (FD)



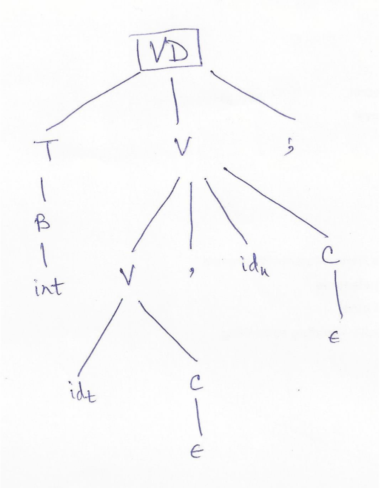


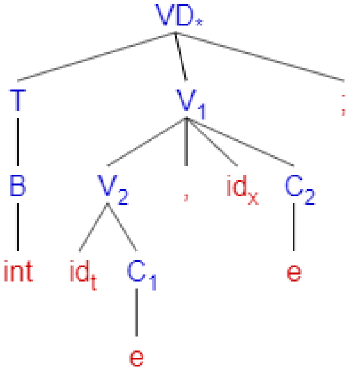
Example 2: Nested Blocks: Parse Tree (CS)



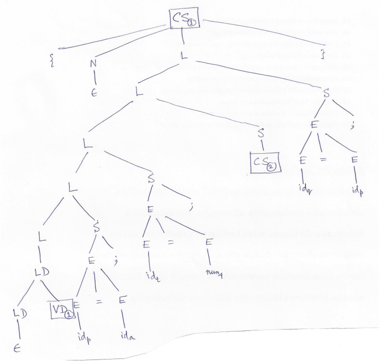


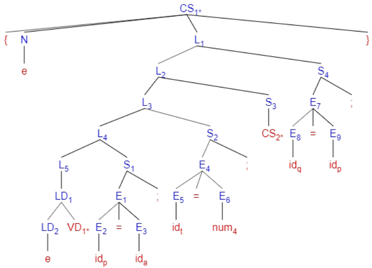
Example 2: Nested Blocks: Parse Tree (VD)



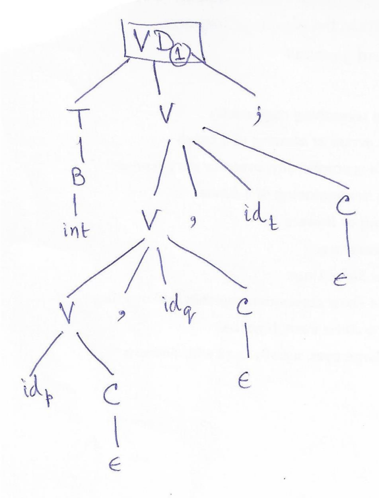


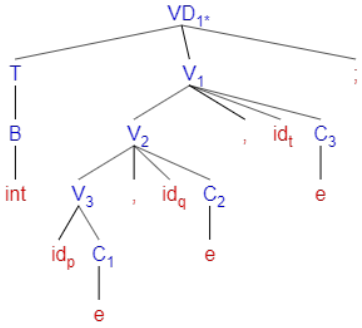
Example 2: Nested Blocks: Parse Tree (CS_1)



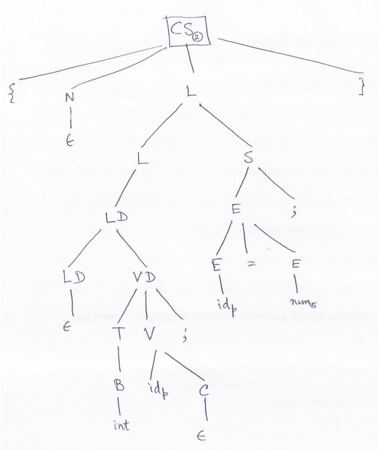


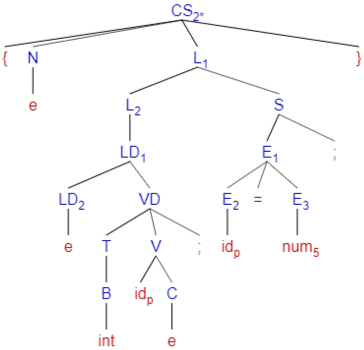
Example 2: Nested Blocks: Parse Tree (VD_1)



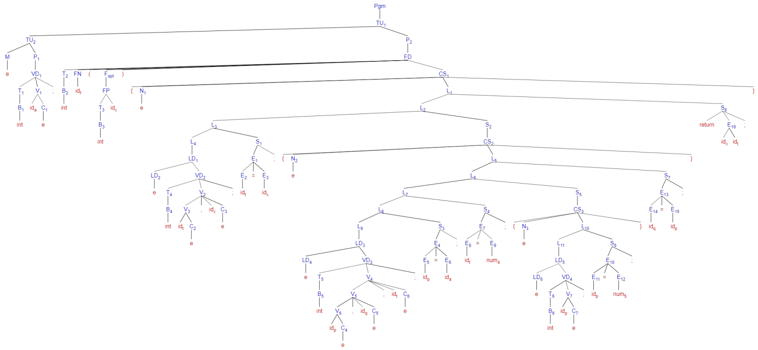


Example 2: Nested Blocks: Parse Tree (CS_2)





Example 2: Nested Blocks: Parse Tree (Pgm Whole)



Example 2: Nested Blocks: Source & TAC

```
int a;
int f(int x) { // function scope f
    int t, u;
    t = x; // t in f, x in f
    { // un-named block scope f_1
         int p, q, t;
         p = a; // p in f_1, a in global
         t = 4; // t in f_1, hides t in f
         { // un-named block scope f_1_1
             int p;
             p = 5; // p in f_1_1, hides p in f_1
         }
         q = p; // q in f_1, p in f_1
    }
    return u = t; // u in f, t in f
}
```

```
f: // function scope f
   // t in f, x in f
   t = x
   // p in f_1, a in global
   p@f_1 = a@gbl
   // t in f_1, hides t in f
   t@f_1 = 4
   // p in f_1_1, hides p in f_1
   p@f_1_1 = 5
   // q in f_1, p in f_1
   q@f_1 = p@f_1
   // u in f, t in f
   u = t
```

ST.gbl: ST.gbl.parent = null					
a	int	global	4	0	null
f	int → int				
		func	0	0	ST.f

ST.f(): ST.f.parent = ST.gbl					
x	int	param	4	0	null
t	int	local	4	4	null
u	int	local	4	8	null
f_1	null	block	–		ST.f_1

ST.f_1: ST.f_1.parent = ST.f					
p	int	local	4	0	null
q	int	local	4	4	null
t	int	local	4	8	null
f_1_1	null	block	–		ST.f_1_1

ST.f_1_1: ST.f_1_1.parent = ST.f_1					
p	int	local	4	0	null

Columns: Name, Type, Category, Size, Offset, & Symtab

Example 2: Nested Blocks Flattened

```
f: // function scope f
   // t in f, x in f
   t = x
   // p in f_1, a in global
   p@f_1 = a@gbl
   // t in f_1, hides t in f
   t@f_1 = 4
   // p in f_1_1, hides p in f_1
   p@f_1_1 = 5
   // q in f_1, p in f_1
   q@f_1 = p@f_1
   // u in f, t in f
   u = t
```

ST.f(): ST.f.parent = ST.gbl					
x	int	param	4	0	null
t	int	local	4	4	null
u	int	local	4	8	null
f_1	null	block	–		ST.f_1

ST.f_1: ST.f_1.parent = ST.f					
p	int	local	4	0	null
q	int	local	4	4	null
t	int	local	4	8	null
f_1_1	null	block	–		ST.f_1_1

ST.f_1_1: ST.f_1_1.parent = ST.f_1					
p	int	local	4	0	null

Columns: Name, Type, Category, Size, Offset, & Symtab

```
f: // function scope f
   // t in f, x in f
   t = x
   // p in f_1, a in global
   p#1 = a@gbl
   // t in f_1, hides t in f
   t#3 = 4
   // p in f_1_1, hides p in f_1
   p#4 = 5
   // q in f_1, p in f_1
   q#2 = p#1
   // u in f, t in f
   u = t
```

ST.f(): ST.f.parent = ST.gbl					
x	int	param	4	0	null
t	int	local	4	4	null
u	int	local	4	8	null
p#1	int	blk-local	4	0	null
q#2	int	blk-local	4	4	null
t#3	int	blk-local	4	8	null
p#4	int	blk-local	4	0	null

Additional Features

Additional Features

- Handling Structures in Expression
- Handling of directives in C Pre-Processor (CPP)
- Handling of `class` definitions and instantiation
- Handling Inheritance
  - Static
  - Dynamic
- Handling `templates`