

# COMPILER CONSTRUCTION

## A Simple Compiler

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# Chapter 2

# Design of a Simple Compiler



# Overview

- In this chapter, we will describe:
  - a simple programming language, **adding calculator** (*ac*), &
  - a simple compiler for *ac*

- The *ac* compiler translates the *ac* program into the corresponding **desk calculator** (*dc*) program
  - which is a **stack-based** calculator
  - Stack-based languages commonly serve as targets of translation
    - They lend themselves to compact representation
    - Examples: Java → Java Virtual Machine, ActionScript → AVM2 for Flash media, printable documents → PostScript



# Key Concepts for the *ac* Compiler

- Regular expressions
  - For basic symbols of ac
- Context-free grammar (CFG)
  - For syntax of ac
- Parse tree
- Scanning
- Parsing
- Abstract Syntax Trees
- Semantic Analysis
- Code generation



# Token

- Token
  - A string with an assigned and identified meaning
  - Serves as the basic unit during compilation process
- Regular Expression for **Token**
  - A regular expression is use to identify a **terminal symbol** (called **token**) from within the actual input characters; it is covered in Ch.3
- For example:
  - **assign** symbol is a terminal, which appears in the input stream as "=" character
  - The terminal **id (identifier)** could be *any alphabetic character*
    - Note **f**, **i**, and **p** are reserved for special use in ***ac***
    - It is specified as [a-e] | [g-h] | [j-o] | [q-z]



# Token (Cont'd)

- Recognize tokens via regular expression rules
- Examples:
  - Reserved keywords: f, i, and p
  - '|' is used to specify the union of four sets for **id**
  - One or more decimal digits for **inum**

| Terminal | Regular Expression |
|---|---|
| floatdcl | "f" |
| intdcl | "i" |
| print | "p" |
| id | [a − e] \| [g − h] \| [j − o] \| [q − z] |
| assign | "=" |
| plus | "+" |
| minus | "-" |
| inum | $[0-9]^+$ |
| fnum | $[0-9]^+.[0-9]^+$ |
| blank | (" ")$^+$ |

Figure 2.3: Formal definition of ac tokens.



# Syntax for *ac*

- A **context-free grammar** (CFG) specifies the **syntax of a language**
  - CFG is used to describe the **acceptable statements** for the language
  - CFG is further described in Ch.4

- Now, we can view a CFG simply as a set of **productions** (or **rewriting rules)**

Order matters!!!

```
1  Prog  → Dcls Stmts $
2  Dcls  → Dcl Dcls
3        | λ
4  Dcl   → floatdcl id
5        | intdcl id
6  Stmts → Stmt Stmts
7        | λ
8  Stmt  → id assign Val Expr
9        | print id
10 Expr  → plus Val Expr
11       | minus Val Expr
12       | λ
13 Val   → id
14       | inum
15       | fnum
```

Figure 2.1: Context-free grammar for ac.



# Syntax for *ac*: Stmt Example

Stmt → id assign Val Expr (1)

| print id (2)

- **Stmt** serves the same role in each of the productions separated by ' | '
- These productions indicate that a Stmt can be replaced by one of two strings of symbols:

  (1) **Stmt** is rewritten by symbols that represent **assignment to an identifier**

  (2) **Stmt** is rewritten by symbols that **print an identifier's value**



# Productions

- Two kinds of grammar symbols (in Productions):
  1. A **terminal** cannot be rewritten, a.k.a. **token**
     E.g., id, assign, and $ symbols have no productions
  2. A **non-terminal** can be rewritten by a production rule
     E.g., Val and Expr
- A special non-terminal is **start symbol**
  - which is usually the symbol on the **left-hand side (LHS)** of the grammar's first rule, e.g., **Prog**
- From the start symbol, we proceed to generate a program
  - by replacing (rewriting) a symbol on LHS with the **right-hand side (RHS)** of some production of that symbol



# Productions (Cont'd)

- A special symbol **λ** denotes **empty** or **null string**
  - which indicates that there are no symbols on a production's RHS
- The special symbol **$** represents the end of the input stream

```
1  Prog  → Dcls Stmts $
2  Dcls  → Dcl Dcls
3        | λ
4  Dcl   → floatdcl id
5        | intdcl id
6  Stmts → Stmt Stmts
7        | λ
8  Stmt  → id assign Val Expr
9        | print id
10 Expr  → plus Val Expr
11       | minus Val Expr
12       | λ
13 Val   → id
14       | inum
15       | fnum
```

Figure 2.1: Context-free grammar for ac.



# Productions (Cont'd)

- For an ac program, we continue **rewriting non-terminals by applying production rules** against CFG until none of non-terminals remains
  - Example shown in the next page
  - **Any string of terminals that can be produced in this manner is considered syntactically valid**
  - Any other string has a **syntax error** and would not be a legal program
- Notice that some productions in a grammar serve to generate an **unbounded list of symbols** from a nonterminal using **recursive rules**
  - E.g., **Stmts**→**Stmt Stmts** (Rule 6) allows an arbitrary number of Stmt symbols to be produced
  - The recursion is terminated by applying **Stmts**→λ (Rule 7)



# Example *ac* program

- Given the example ac program

```
f b i a  a = 5  b = a + 3.2  p b
```

- We apply the grammar rules in Fig. 2.1 to see if it is a valid program
  - by generating the string of terminals based on the grammar and comparing the string with the above program

# Example of the Derivation of One *ac* Program

**f b i a  a = 5  b = a + 3.2  p b**

| Step | Sentential Form | Production Number |
|---|---|---|
| 1 | ⟨Prog⟩ | |
| 2 | ⟨Dcls⟩ Stmts $ | 1 |
| 3 | ⟨Dcl⟩ Dcls Stmts $ | 2 |
| 4 | floatdcl id ⟨Dcls⟩ Stmts $ | 4 |
| 5 | floatdcl id ⟨Dcl⟩ Dcls Stmts $ | 2 |
| 6 | floatdcl id intdcl id ⟨Dcls⟩ Stmts $ | 5 |
| 7 | floatdcl id intdcl id ⟨Stmts⟩ $ | 3 |
| 8 | floatdcl id intdcl id ⟨Stmt⟩ Stmts $ | 6 |
| 9 | floatdcl id intdcl id id assign ⟨Val⟩ Expr Stmts $ | 8 |
| 10 | floatdcl id intdcl id id assign inum ⟨Expr⟩ Stmts $ | 14 |
| 11 | floatdcl id intdcl id id assign inum ⟨Stmts⟩ $ | 12 |
| 12 | floatdcl id intdcl id id assign inum ⟨Stmt⟩ Stmts $ | 6 |
| 13 | floatdcl id intdcl id id assign inum id assign ⟨Val⟩ Expr Stmts $ | 8 |
| 14 | floatdcl id intdcl id id assign inum id assign id ⟨Expr⟩ Stmts $ | 13 |
| 15 | floatdcl id intdcl id id assign inum id assign id plus ⟨Val⟩ Expr Stmts $ | 10 |
| 16 | floatdcl id intdcl id id assign inum id assign id plus fnum ⟨Expr⟩ Stmts $ | 15 |
| 17 | floatdcl id intdcl id id assign inum id assign id plus fnum ⟨Stmts⟩ $ | 12 |
| 18 | floatdcl id intdcl id id assign inum id assign id plus fnum ⟨Stmt⟩ Stmts $ | 6 |
| 19 | floatdcl id intdcl id id assign inum id assign id plus fnum print id ⟨Stmts⟩ $ | 9 |
| 20 | floatdcl id intdcl id id assign inum id assign id plus fnum print id $ | 7 |

Figure 2.2: Derivation of an ac program using the grammar in Figure 2.1.

```
1  Prog  → Dcls Stmts $
2  Dcls  → Dcl Dcls
3        | λ
4  Dcl   → floatdcl id
5        | intdcl id
6  Stmts → Stmt Stmts
7        | λ
8  Stmt  → id assign Val Expr
9        | print id
10 Expr  → plus Val Expr
11       | minus Val Expr
12       | λ
13 Val   → id
14       | inum
15       | fnum
```

Figure 2.1: Context-free grammar for ac.



# Parse Tree of the *ac* Program

- The **derivation** shown textually in previous page can be represented as a derivation (or parse) tree shown here
- Yes. The ac program is valid

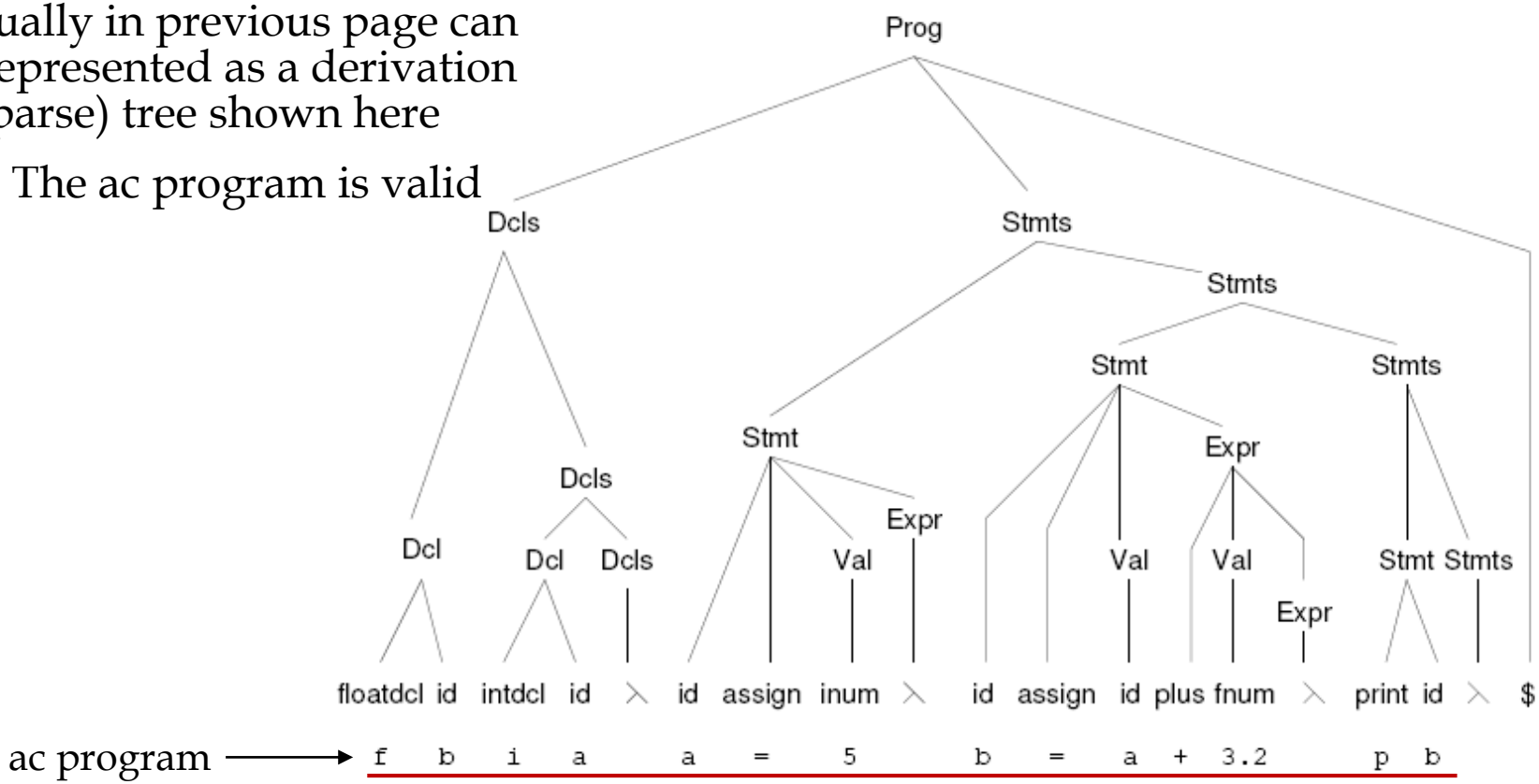



Figure 2.4: An ac program and its parse tree.



# Parse Tree of the *ac* Program (Cont'd)

1 ⟨Prog⟩
2 ⟨Dcls⟩ Stmts $
3 ⟨Dcl⟩ Dcls Stmts $
4 floatdcl id ⟨Dcls⟩ Stmts $
5 floatdcl id ⟨Dcl⟩ Dcls Stmts $
6 floatdcl id intdcl id ⟨Dcls⟩ Stmts $
7 floatdcl id intdcl id ⟨Stmts⟩ $
8 floatdcl id intdcl id ⟨Stmt⟩ Stmts $
9 floatdcl id intdcl id id assign ⟨Val⟩ Expr Stmts $
10 floatdcl id intdcl id id assign inum ⟨Expr⟩ Stmts $
11 floatdcl id intdcl id id assign inum ⟨Stmts⟩ $
12 floatdcl id intdcl id id assign inum ⟨Stmt⟩ Stmts $
13 floatdcl id intdcl id id assign inum id assign ⟨Val⟩ Expr Stmts $
14 floatdcl id intdcl id id assign inum id assign id ⟨Expr⟩ Stmts $
15 floatdcl id intdcl id id assign inum id assign id plus ⟨Val⟩ Expr Stmts $
16 floatdcl id intdcl id id assign inum id assign id plus fnum ⟨Expr⟩ Stmts $
17 floatdcl id intdcl id id assign inum id assign id plus fnum ⟨Stmts⟩ $
18 floatdcl id intdcl id id assign inum id assign id plus fnum ⟨Stmt⟩ Stmts $
19 floatdcl id intdcl id id assign inum id assign id plus fnum print id ⟨Stmts⟩ $
20 floatdcl id intdcl id id assign inum id assign id plus fnum print id $

Figure 2.2: Derivation of an ac program using the grammar in Figure 2.1.

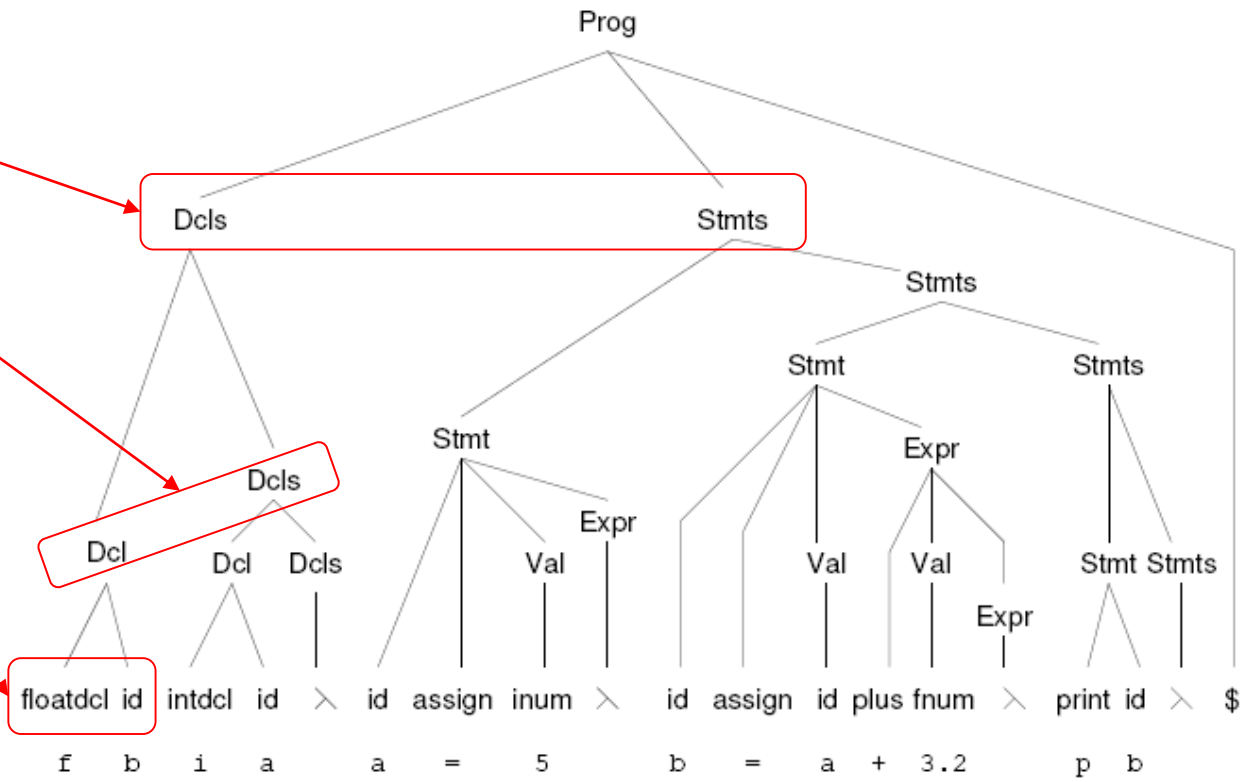



Figure 2.4: An ac program and its parse tree.



# Phases of the *ac* Compiler

- Regular expressions
  - for basic symbols of ac
- Context-free grammar (CFG)
  - For syntax of ac
- Parse tree
- Scanning
- Parsing
- Abstract Syntax Trees
- Semantic Analysis
- Code generation

# An *Informal* Definition of *ac*



- **Types**
  - Most programming languages offer a significant number of predefined data types, with the ability to extend existing types or specify new data types
  - In ***ac***, there are only **two data types: integer and float**
  - An **integer type** is a sequence of decimal numerals, as found in most programming languages
  - A **float type** allows five fractional digits after the decimal point
- **Keywords**
  - Most programming languages have a number of **reserved keywords**, such as *if* and *while*, which would otherwise serve as variable names
  - In ***ac***, there are three reserved keywords, each limited for simplicity to a single letter:
    - **f** (declares a float variable), **i** (declares an integer variable), and **p** (prints the value of a variable)
- **Variables**
  - Some programming languages insist that a variable is declared by specifying the variable's type prior to using the variable's name
  - The ***ac*** language offers only **23 possible variable names**, drawn from the lowercase Roman alphabet and excluding the three reserved keywords f, i, and p
  - Variables must be declared prior to using them
- Check Figure. 2.3 for formal definition of ***ac*** tokens



# Scanning

- The **scanner** reads a source ***ac*** program as a text file and produces a stream of tokens

- Each token has the two components:
  **1)Token type** explains the token's category, e.g., **id**
  **2)Token value** provides the string value of the token, e.g., "**b**"

- Methods:
  - **PEEK**(): a single character of lookahead
  - **ADVANCE**(): the scanner is moved to the next input character (using advance), which suffices to determine the next token

# Scanner for *ac*

- The figure shows a scanner that finds all tokens for ***ac***
- Pseudo code for ***ac*** scanner
  - A big case-switch to choose the type for the character of the input stream
  - Referencing the token definition below

| Terminal | Regular Expression |
|---|---|
| floatdcl | "f" |
| intdcl | "i" |
| print | "p" |
| id | [a – e] \| [g – h] \| [j – o] \| [q – z] |
| assign | "=" |
| plus | "+" |
| minus | "-" |
| inum | $[0-9]^+$ |
| fnum | $[0-9]^+.[0-9]^+$ |
| blank | (" ")$^+$ |

```
function SCANNER( ) returns Token
    while s.PEEK( ) = blank do call s.ADVANCE( )
    if s.EOF( )
    then ans.type ← $
    else
        if s.PEEK( ) ∈ {0, 1, . . . , 9}
        then ans ← SCANDIGITS( )
        else
            ch ← s.ADVANCE( )
            switch (ch)
                case {a, b, . . . , z} – {i, f, p}
                    ans.type ← id
                    ans.val ← ch
                case f
                    ans.type ← floatdcl
                case i
                    ans.type ← intdcl
                case p
                    ans.type ← print
                case =
                    ans.type ← assign
                case +
                    ans.type ← plus
                case -
                    ans.type ← minus
                case default
                    call LEXICALERROR( )
    return (ans)
end
```

Figure 2.5: Scanner for the ac language. The variable $s$ is an input stream of characters.



# Scanner for *ac*

- Given the input stream:
  - **i a a = 32 p a**
- We show how scanner to get the token **i**

| Terminal | Regular Expression |
|---|---|
| floatdcl | `"f"` |
| intdcl | `"i"` |
| print | `"p"` |
| id | `[a – e] \| [g – h] \| [j – o] \| [q – z]` |
| assign | `"="` |
| plus | `"+"` |
| minus | `"-"` |
| inum | $[0-9]^+$ |
| fnum | $[0-9]^+.[0-9]^+$ |
| blank | $(" ")^+$ |

```
function SCANNER( ) returns Token
    while s.PEEK( ) = blank do call s.ADVANCE( )
    if s.EOF( )
    then ans.type ← $
    else
        if s.PEEK( ) ∈ {0, 1, . . . , 9}
        then ans ← SCANDIGITS( )
        else
            ch ← s.ADVANCE( )
            switch (ch)
                case {a, b, . . . , z} – {i, f, p}
                    ans.type ← id
                    ans.val ← ch
                case f
                    ans.type ← floatdcl
                case i
                    ans.type ← intdcl
                case p
                    ans.type ← print
                case =
                    ans.type ← assign
                case +
                    ans.type ← plus
                case -
                    ans.type ← minus
                case default
                    call LEXICALERROR( )
    return (ans)
end
```

Input stream:
**i a a = 32 p a**

s

Figure 2.5: Scanner for the ac language. The variable *s* is an input stream of characters.



# Scanner for *ac*

- Given the input stream:
  - **i a a = 32 p a**
- We are at **i**, and we show how scanner
  - skip the **blank** and
  - recognizes **id** (**a**)

| Terminal | Regular Expression |
|---|---|
| floatdcl | `"f"` |
| intdcl | `"i"` |
| print | `"p"` |
| id | `[a – e] \| [g – h] \| [j – o] \| [q – z]` |
| assign | `"="` |
| plus | `"+"` |
| minus | `"-"` |
| inum | $[0-9]^+$ |
| fnum | $[0-9]^+.[0-9]^+$ |
| blank | $(" ")^+$ |

```
function SCANNER( ) returns Token
    while s.PEEK( ) = blank do call s.ADVANCE( )
    if s.EOF( )
    then ans.type ← $
    else
        if s.PEEK( ) ∈ {0, 1, . . . , 9}
        then ans ← SCANDIGITS( )
        else
            ch ← s.ADVANCE( )
            switch (ch)
                case {a, b, . . . , z} – {i, f, p}
                    ans.type ← id
                    ans.val ← ch
                case f
                    ans.type ← floatdcl
                case i
                    ans.type ← intdcl
                case p
                    ans.type ← print
                case =
                    ans.type ← assign
                case +
                    ans.type ← plus
                case -
                    ans.type ← minus
                case default
                    call LEXICALERROR( )
    return (ans)
end
```

Input stream:

**i a a = 32 p a**

s s

Figure 2.5: Scanner for the ac language. The variable *s* is an input stream of characters.



# Scanner for *ac* (Numbers)

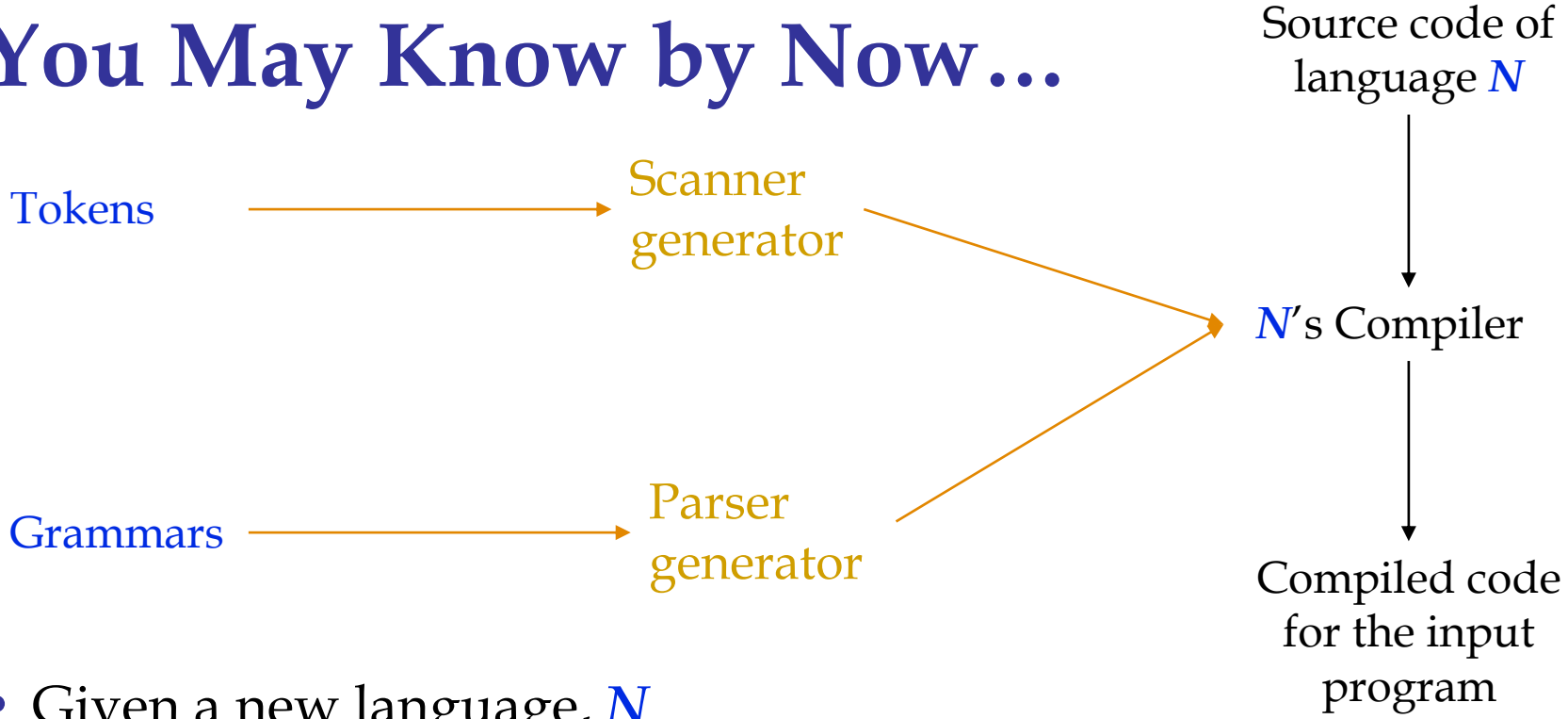
- The figure shows scanning a number token
- Handle a number
  - **Type**:
    - Integer
    - Float
  - Its **Value**

```
function ScanDigits( ) returns token
    tok.val ← " "
    while s.peek( ) ∈ {0, 1, . . . , 9} do
        tok.val ← tok.val + s.advance( )
    if s.peek( ) ≠ "."
    then tok.type ← inum
    else
        tok.type ← fnum
        tok.val ← tok.val + s.advance( )
        while s.peek( ) ∈ {0, 1, . . . , 9} do
            tok.val ← tok.val + s.advance( )
    return (tok)
end
```

| Terminal | Regular Expression |
|---|---|
| floatdcl | `"f"` |
| intdcl | `"i"` |
| print | `"p"` |
| id | `[a – e] \| [g – h] \| [j – o] \| [q – z]` |
| assign | `"="` |
| plus | `"+"` |
| minus | `"-"` |
| inum | $[0-9]^+$ |
| fnum | $[0-9]^+.[0-9]^+$ |
| blank | $(" ")^+$ |

Figure 2.6: Finding inum or fnum tokens for the ac language.

# You May Know by Now…




- Given a new language, ***N***
  - The figure shows the flow of constructing a compiler for ***N***
  - →Define the ***Tokens*** and ***Grammars*** for ***N***, and
  - →build ***N's*** scanner and parser with the ***Tokens*** and ***Grammars***, which produce ***N's*** compiler
- You can build the compiler for L
  - by given the tokens and grammars of another language, ***L***



# Parsing

- **Parser**
  - processes tokens produced by the scanner,
  - determines the syntactic validity of the token stream, &
  - creates an **abstract syntax tree (AST)** for subsequent phases
- In most compilers, the **grammar** serves
  - not only to define the **syntax of a programming language**,
  - but also to guide the **automatic construction of a parser**



# Parsing Technique

- **Recursive descent** is one simple parsing technique used in practical compilers
  - The name is taken from the **mutually recursive parsing routines** that descend through a derivation tree
  - In recursive-descent parsing, **each nonterminal in the grammar has an associated *parsing procedure***
    - that is responsible for determining if the token stream contains a sequence of tokens derivable from that nonterminal



# Actually, Mutual Recursion Refers to …

- **Mutual recursion** is a form of recursion
  - where two mathematical or computational objects are **defined in terms of each other**
  - such as functions or data types
- Example
  - Determine whether a non-negative number is even or odd?
  - It is done by defining **two separate functions that call each other**, decrementing each time

```
bool is_even(unsigned int n)
{
    if (n == 0)
        return true;
    else
        return is_odd(n - 1);
}
bool is_odd(unsigned int n) {
    if (n == 0)
        return false;
    else
        return is_even(n - 1);
}
```

Courtesy of https://en.wikipedia.org/wiki/Mutual_recursion



# Recursive-Descent Parsing

- Each parsing procedure examines the next input token to **predict** which production to apply
- Example:
  The parsing procedure for **Stmt** shown in Fig. 2.7

  **Stmt → id assign Val Expr**

  **Stmt → print id**

```
procedure STMT( )
    if ts.PEEK( ) = id                                  (1)
    then
        call MATCH(ts, id)                              (2)
        call MATCH(ts, assign)                          (3)
        call VAL( )                                     (4)
        call EXPR( )                                    (5)
    else
        if ts.PEEK( ) = print                           (6)
        then
            call MATCH(ts, print)
            call MATCH(ts, id)
        else
            call ERROR( )                               (7)
end
```

Figure 2.7: Recursive-descent parsing procedure for Stmt. The variable *ts* is an input stream of tokens.



# Recursive-descent Parsing (Cont'd)

- If **id** is the next input token, the parse proceeds with the production:

  **Stmt → id assign Val Expr**

  and the **predict set** for the production is {id}

- If **print** is the next, the parse proceeds with:

  **Stmt → print id**

  the **predict set** for the production is {print}

- If the next input token is neither **id** nor **print**, neither rule can be applied; it calls **ERROR**

```
procedure STMT( )
    if ts.PEEK( ) = id                          (1)
    then
        call MATCH(ts, id)                      (2)
        call MATCH(ts, assign)                  (3)
        call VAL( )                             (4)
        call EXPR( )                            (5)
    else
        if ts.PEEK( ) = print                   (6)
        then
            call MATCH(ts, print)
            call MATCH(ts, id)
        else
            call ERROR( )                       (7)
end
```

Figure 2.7: Recursive-descent parsing procedure for Stmt. The variable *ts* is an input stream of tokens.



# Recursive-descent Parsing (Cont'd)

- Computing the predict sets used in **Stmt** is relatively easy
  - since each production for Stmt **begins with a distinct terminal symbol: id or print**



# Recursive-descent Parsing (Cont'd)

- Consider the productions for **Stmts**:

  **Stmts** → **Stmt Stmts**

  **Stmts** → λ

  - The predict sets for **Stmts** can be computed by inspecting the following:
  - **Stmts** → **Stmt Stmts** begins with the non-terminal **Stmt**
    - → Find those symbols that predict **any** rule for **Stmt** (i.e., **first** symbols in **Stmt**)
    - → Check for **id** or **print** as the next token
  - **Stmts** → λ derives no symbols
    - → Look for what symbol(s) could occur **following** such a production
    - → In this case, it is **$** (→ Rule 1 in Fig. 2.1)

```
procedure STMTS( )
    if ts.PEEK( ) = id or ts.PEEK( ) = print                    (8)
    then
        call STMT( )                                            (9)
        call STMTS( )                                           (10)
    else
        if ts.PEEK( ) = $                                       (11)
        then
            /*   do nothing for λ-production                    */ (12)
        else   call ERROR( )
end
```

Figure 2.8: Recursive-descent parsing procedure for Stmts.

**The analysis required to compute predict sets in general is covered in Ch.4 and Ch.5**



# Recursive-descent Parsing (Cont'd)

- When a terminal such as **id** is encountered, a call to **MATCH(ts, id)** is placed into the code
  - The **MATCH** procedure simply consumes the expected token **id** if it is indeed the next token in the input stream
  - The next call to **MATCH(ts, assign)** tries to match **assign**
- The last two symbols in **Stmt→id assign Val Expr** are nonterminals
  - Later, calls to **Val()** and **Expr()** are performed
- You may try to think about how **Stmts** is parsed (Check Sec. 2.5.2)

```
procedure STMT( )
    if ts.PEEK( ) = id                          (1)
    then
        call MATCH(ts, id)                      (2)
        call MATCH(ts, assign)                  (3)
        call VAL( )                             (4)
        call EXPR( )                            (5)
    else
        if ts.PEEK( ) = print                   (6)
        then
            call MATCH(ts, print)
            call MATCH(ts, id)
        else
            call ERROR( )                       (7)
end
```

Figure 2.7: Recursive-descent parsing procedure for Stmt. The variable *ts* is an input stream of tokens.

```
procedure MATCH(ts, token)
    if ts.PEEK( ) = token
    then call ts.ADVANCE( )
    else call ERROR(Expected token)
end
```

Figure 5.5: Utility for matching tokens in an input stream.



# Abstract Syntax Tree (AST)

- The **scanner** and **parser** together
  - accomplish the syntax analysis phase of a compiler
  - ensure that the compiler's input conforms to a language's token and CFG specifications
- **Parse tree**
  - might be considered as the structure that survives syntax analysis and is used for the remaining phases
  - However, such trees can be rather large and unnecessarily detailed, even for very simple grammars and inputs



# Abstract Syntax Tree (AST) (Cont'd)

- **Abstract syntax tree**
  - contains the **essential information from a parse tree**,
  - but inessential punctuation and delimiters (braces, semicolons, parentheses, etc.) are not included
- It serves as **a representation of a program** for all phases after syntax analysis
  - It is actually the **data structure kept in memory** to represent the program code during compilation
  - Such phases may make use of information in the AST, decorate the AST with more information, or transform the AST

# Abstract Syntax Tree (AST) (Cont'd)

- Consider the expression **a+3.2**
  - 8 nodes for parse tree (Fig. 2.4)
  - 3 nodes for AST (Fig. 2.9)
  - Check Sec. 2.6 for rules to translate from parse tree to AST

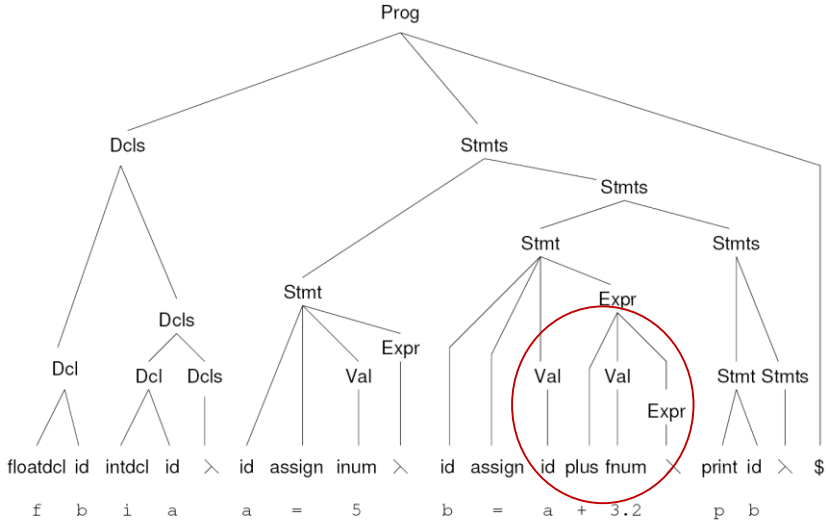



Figure 2.4: An ac program and its parse tree.

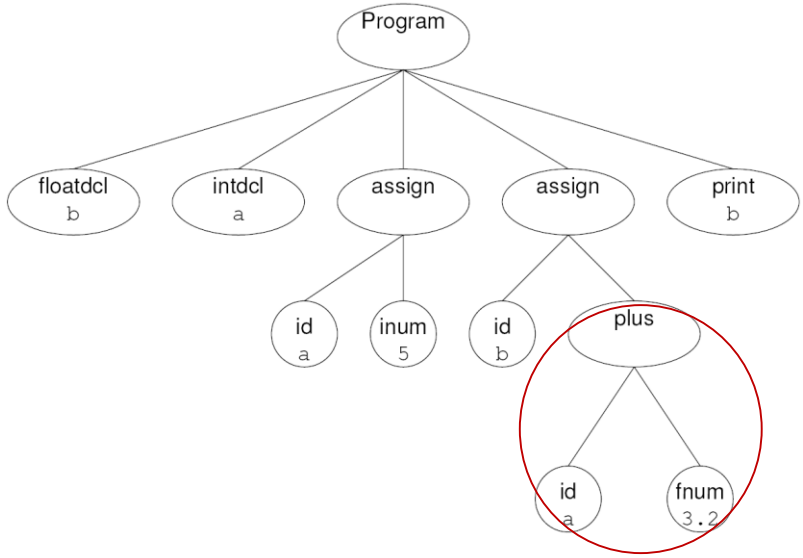



Figure 2.9: An abstract syntax tree for the ac program shown in Figure 2.4.



# Semantic Analysis

- Is a catchall term for any post-parsing processing
  - that enforces aspects of a language's definition **that are not easily accommodated by syntax analysis**
- Examples (Two examples are introduced below):
  1. Declarations and name scopes are processed to construct a **symbol table**, so that declarations and uses of identifiers can be properly coordinated
  2. Language- and user-defined **types** are examined for consistency
  - Operations and storage references are processed so that type-dependent behavior can become explicit in the program representation



# Semantic Analysis Example: Symbol Table

- Symbol-table construction is a semantic processing activity
  - that **traverses the AST to record all identifiers and their types** in a symbol table
- In ***ac,*** identifiers must be declared prior to use
  - but this requirement is not easily enforced during syntax analysis

```
/* Visitor methods */
procedure VISIT(SymDeclaring n)
    if n.GETTYPE() = floatdcl
    then call ENTERSYMBOL(n.GETID(), float)
    else call ENTERSYMBOL(n.GETID(), integer)
end

/* Symbol table management */
procedure ENTERSYMBOL(name, type)
    if SymbolTable[name] = null
    then SymbolTable[name] ← type
    else call ERROR("duplicate declaration")
end

function LOOKUPSYMBOL(name) returns type
    return (SymbolTable[name])
end
```

Figure 2.10: Symbol table construction for ac.

f b i c α = 5 p b ← Syntactically correct, but something goes wrong.

→ A separate pass to build the table



# Build Symbol Table for *ac*

- We traverse the AST
  - counting on the presence of a **symbol-declaring node** to trigger appropriate effects on the symbol table
  - Correspondingly, nodes such as **floatdcl** and **intdcl** implement an interface called **SymDeclaring**,
  - which implements a method to return the declared **identifier's type**
- In Fig. 2.10
  - **visit(SymDeclaring n)** shows the code to be applied at nodes that declare symbols
  - **EnterSymbol** checks that the given identifier has not been previously declared

```
/*    Visitor methods    */
procedure VISIT(SymDeclaring n)
    if n.GETTYPE( ) = floatdcl
    then call ENTERSYMBOL(n.GETID( ), float)
    else call ENTERSYMBOL(n.GETID( ), integer)
end

/*    Symbol table management    */
procedure ENTERSYMBOL(name, type)
    if SymbolTable[name] = null
    then SymbolTable[name] ← type
    else call ERROR("duplicate declaration")
end

function LOOKUPSYMBOL(name) returns type
    return (SymbolTable[name])
end
```

Figure 2.10: Symbol table construction for ac.



# Symbol Table for *ac*

- In *ac*, a program can mention at most 23 distinct identifiers
- The built symbol table for *ac*
  - with 23 entries
  - Each contains **symbol** and **type**
  - Type: integer, float, or unused (null)
- On the contrary
  - most languages have infinite potential identifiers
  - The type information may include other attributes
  - such as, the identifier's value, scope of visibility, storage class, and protection properties

| Symbol | Type | Symbol | Type | Symbol | Type |
|---|---|---|---|---|---|
| a | integer | k | **null** | t | **null** |
| b | float | l | **null** | u | **null** |
| c | **null** | m | **null** | v | **null** |
| d | **null** | n | **null** | w | **null** |
| e | **null** | o | **null** | x | **null** |
| g | **null** | q | **null** | y | **null** |
| h | **null** | r | **null** | z | **null** |
| j | **null** | s | **null** | | |

Figure 2.11: Symbol table for the ac program from Figure 2.4.



# Semantic Analysis Example: Type Checking

- Most programming language specifications include a **type hierarchy**
  - which compares the language's types in terms of their generality
- Example:
  A float type is considered **wider** (i.e., more general) than an integer (Java, C, and C++)
  - Every integer can be represented as a float
  - On the other hand, **narrowing** a float to an integer loses precision for some float values



# Type Checking

- Most languages allow **automatic widening of type**
  - →E.g., an integer can be converted to a float without the programmer having to specify this conversion explicitly

```
int a;
float b, c;
c = a+b; //(automatically type casting for a)
```

- On the other hand, a float cannot become an integer in most languages
  - unless the programmer explicitly calls for this conversion



# Type Checking for *ac*

- Two types defined in ***ac***
  - I.e., **integer** and **float**, and
  - all identifiers must be type-declared in a program before they can be used
- Once the symbol table has been constructed,
  - the declared type of each identifier is known, and
  - the executable statements of the program can be **checked for type consistency**

→**Type checking**
Refers to the process that walks the AST **bottom-up**, from its leaves toward its root

# Type Analysis for *ac*

- At each AST node, VISIT() is called:
  1. For **constants and symbol** references, the visitor methods simple set the supplied node's type based on the node's contents
     Constant: **IntConsting** & **FloatConsting**
     Symbol: **SymReferencing**
  2. For **nodes that compute value**, such as plus and minus, the appropriate type is computed by calling the utility methods
  3. For an **assignment operation**, the visitor makes certain that the value computed by the second child is of the same type as the assigned identifier (the first child)
     → n.child1 = n.child2

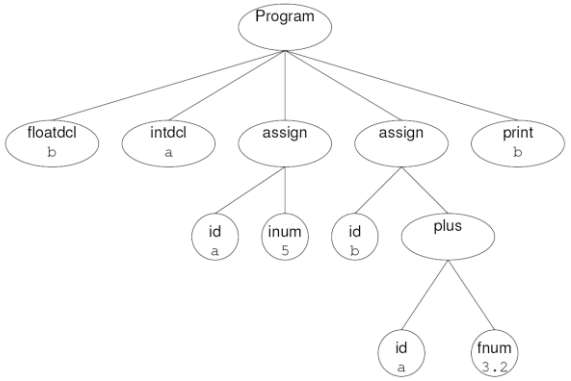



Figure 2.9: An abstract syntax tree for the ac program shown in Figure 2.4.

```
/*    Visitor methods                                              */
procedure VISIT( Computing n )
    n.type ← CONSISTENT(n.child1, n.child2)
end
procedure VISIT( Assigning n )
    n.type ← CONVERT(n.child2, n.child1.type)
end
procedure VISIT( SymReferencing n )
    n.type ← LOOKUPSYMBOL(n.id)
end
procedure VISIT( IntConsting n )
    n.type ← integer
end
procedure VISIT( FloatConsting n )
    n.type ← float
end
/*    Type-checking utilities                                      */
function CONSISTENT(c1, c2) returns type
    m ← GENERALIZE(c1.type, c2.type)
    call CONVERT(c1, m)
    call CONVERT(c2, m)
    return (m)
end
function GENERALIZE(t1, t2) returns type
    if t1 = float or t2 = float
    then ans ← float
    else ans ← integer
    return (ans)
end
procedure CONVERT(n, t)
    if n.type = float and t = integer
    then call ERROR("Illegal type conversion")
    else
        if n.type = integer and t = float
        then
            /*    replace node n by convert-to-float of node n    */
        else /* nothing needed */
end
```

Figure 2.12: Type analysis for ac.

# Type Analysis for *ac*

- **CONSISTENT()** is responsible for reconciling the type of a pair of AST nodes with the following steps:
  1. The **GENERALIZE()** function determines the least general (i.e., simplest) type that encompasses its supplied pair of types In *ac*, if either type is float, then float is the appropriate type; otherwise, integer will do
  2. The **CONVERT()** procedure checks whether conversion is necessary, possible, or impossible
- An important consequence occurs at **Marker 13** in Figure 2.12
  - If conversion is attempted from integer to float, then the **AST is transformed to represent this type conversion explicitly**
  - Subsequent compiler passes (particularly code generation) can then assume a type-consistent AST in which all operations are explicit

```
/*    Type-checking utilities                                          */
function CONSISTENT(c1, c2) returns type
    m ← GENERALIZE(c1.type, c2.type)
    call CONVERT(c1, m)
    call CONVERT(c2, m)
    return (m)
end
function GENERALIZE(t1, t2) returns type
    if t1 = float or t2 = float
    then ans ← float
    else ans ← integer
    return (ans)
end
procedure CONVERT(n, t)
    if n.type = float and t = integer
    then call ERROR("Illegal type conversion")
    else
        if n.type = integer and t = float
        then
            /*    replace node n by convert-to-float of node n          */ (13)
        else /* nothing needed */
end
```

Figure 2.12: Type analysis for ac.

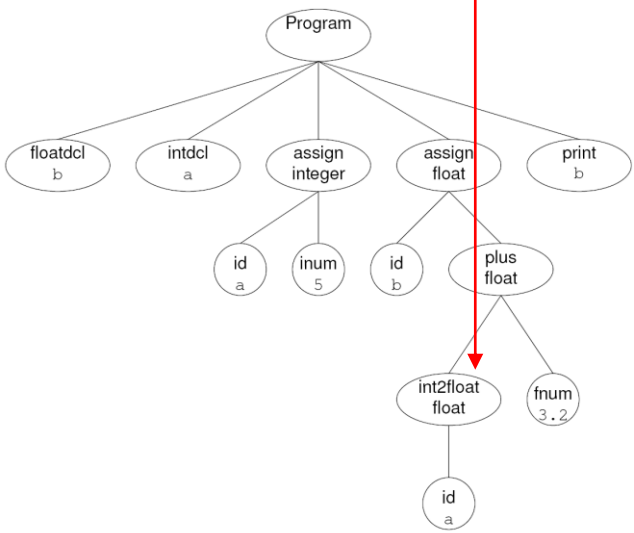



Figure 2.13: AST after semantic analysis.



# Code Generation

- The final task undertaken by a compiler

  → The formulation of **target-machine instructions** that faithfully represent the semantics (i.e.,meaning) of the source program

  - Translation exercise of the textbook consists of generating source code that is suitable for the ***dc*** program, which is a simple calculator based on a stack machine model

- In a **stack machine**, most instructions receive their input from the contents at or near the **top of an operand stack**

  - The result of most instructions is pushed on the stack
  - Programming languages such as C# and Java are frequently translated into a portable, stack machine representation
  - Check Ch.11 and Ch.13



# Code Generation (Cont'd)

- The AST was transformed and decorated with **type information** during semantic analysis
  - Such information is required for **selecting the proper instructions**
- The instruction set on most computers distinguishes between **float** and **integer** data types
  - ARM processors have the instructions
    - **VADD** for Floating-point Add
    - **VDIV** for Floating-point Divide
    - **ADD** for Integer Add
    - **SDIV** for Signed Divide



# Generating Code for *ac*

- Traverse the AST
  - starting at its root and working toward its leaves
- The code generator is called recursively
  - to generate code for the left and right subtrees
  - The resulting values will be at top-of-stack

- **VISIT(Computing n)**
  - generates code for **plus** and **minus**
  - The appropriate operator is then emitted (**Marker 15**) to perform the operation

```
procedure VISIT(Assigning n)
    call CODEGEN(n.child2)
    call EMIT("s")
    call EMIT(n.child1.id)
    call EMIT("0 k")                    (14)
end
procedure VISIT(Computing n)
    call CODEGEN(n.child1)
    call CODEGEN(n.child2)
    call EMIT(n.operation)              (15)
end
procedure VISIT(SymReferencing n)
    call EMIT("l")
    call EMIT(n.id)
end
procedure VISIT(Printing n)
    call EMIT("l")
    call EMIT(n.id)
    call EMIT("p")
    call EMIT("si")                     (16)
end
procedure VISIT(Converting n)
    call CODEGEN(n.child)
    call EMIT("5 k")                    (17)
end
procedure VISIT(Consting n)
    call EMIT(n.val)
end
```

Figure 2.14: Code generation for ac



# Generating Code for *ac* (Cont'd)

- **VISIT (Assigning n)**
  - E.g., the expression **a = 5** is evaluated
  - Code is then emitted to **store** the value in the appropriate **dc register, a**
  - The calculator's **precision** is then **reset** to integer by setting the fractional precision to zero (**Marker 14**)

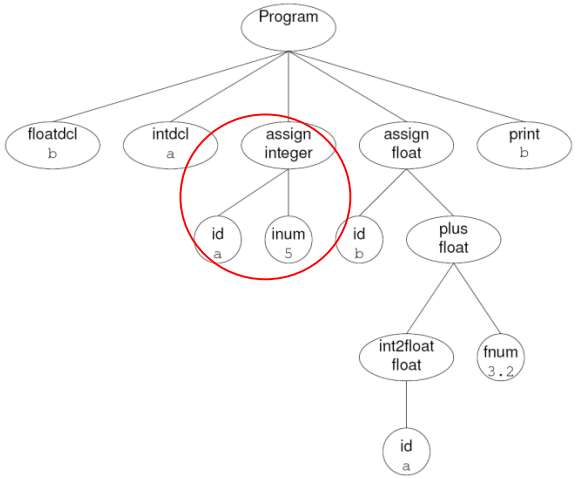



Figure 2.13: AST after semantic analysis.

| Code |
|---|
| 5 |
| sa |
| |
| 0 k |

```
procedure VISIT(Assigning n)
    call CODEGEN(n.child2)      5
    call EMIT("s")              s
    call EMIT(n.child1.id)      a
    call EMIT("0 k")            0k
end
```

Figure 2.14: Code generation for ac



# Generating Code for *ac*

- **VISIT (Computing n)**
  - generates code for the computation: **plus** or **minus**
  - The appropriate operator is then emitted (**Marker 15**) to perform the operation

```
procedure VISIT(Assigning n)
    call CODEGEN(n.child2)
    call EMIT("s")
    call EMIT(n.child1.id)
    call EMIT("0 k")                    (14)
end
procedure VISIT(Computing n)
    call CODEGEN(n.child1)
    call CODEGEN(n.child2)
    call EMIT(n.operation)              (15)
end
procedure VISIT(SymReferencing n)
    call EMIT("l")
    call EMIT(n.id)
end
procedure VISIT(Printing n)
    call EMIT("l")
    call EMIT(n.id)
    call EMIT("p")
    call EMIT("si")                     (16)
end
procedure VISIT(Converting n)
    call CODEGEN(n.child)
    call EMIT("5 k")                    (17)
end
procedure VISIT(Consting n)
    call EMIT(n.val)
end
```

Figure 2.14: Code generation for ac



# Generating Code for *ac* (Cont'd)

- **VISIT (SymReferencing n)**
  - causes a value to be retrieved from the appropriate ***dc*** **register** and **pushed onto the stack**
  - Push register
    → Load (**l**) symbol (**a**) to *dc* register
    → `**la**'

```
procedure VISIT(Assigning n)
    call CODEGEN(n.child2)
    call EMIT("s")
    call EMIT(n.child1.id)
    call EMIT("0 k")                    (14)
end
procedure VISIT(Computing n)
    call CODEGEN(n.child1)
    call CODEGEN(n.child2)
    call EMIT(n.operation)              (15)
end
procedure VISIT(SymReferencing n)
    call EMIT("l")
    call EMIT(n.id)
end
procedure VISIT(Printing n)
    call EMIT("l")
    call EMIT(n.id)
    call EMIT("p")
    call EMIT("si")                     (16)
end
procedure VISIT(Converting n)
    call CODEGEN(n.child)
    call EMIT("5 k")                    (17)
end
procedure VISIT(Consting n)
    call EMIT(n.val)
end
```

Figure 2.14: Code generation for ac



# Generating Code for *ac* (Cont'd)

- **VISIT (Printing n)**
  - is tricky because dc does not discard the value on top-of-stack after it is printed
  - The instruction sequence `**si**' is generated at **Marker 16**,
  - thereby popping the stack and storing the value in dc's **i** register
  - Conveniently, the ac language precludes a program from using this register because the **i** token is reserved for spelling the terminal symbol integer

```
procedure VISIT(Assigning n)
    call CODEGEN(n.child2)
    call EMIT("s")
    call EMIT(n.child1.id)
    call EMIT("0 k")                    (14)
end
procedure VISIT(Computing n)
    call CODEGEN(n.child1)
    call CODEGEN(n.child2)
    call EMIT(n.operation)              (15)
end
procedure VISIT(SymReferencing n)
    call EMIT("l")
    call EMIT(n.id)
end
procedure VISIT(Printing n)
    call EMIT("l")
    call EMIT(n.id)
    call EMIT("p")
    call EMIT("si")                     (16)
end
procedure VISIT(Converting n)
    call CODEGEN(n.child)
    call EMIT("5 k")                    (17)
end
procedure VISIT(Consting n)
    call EMIT(n.val)
end
```

Figure 2.14: Code generation for ac



# Generating Code for *ac* (Cont'd)

- **VISIT (Converting n)**
  - causes a change of type from integer to float at **Marker 17,**
  - which accomplished by setting *dc*'s precision to five fractional decimal digits → `**5 k**'

```
procedure VISIT(Assigning n)
    call CODEGEN(n.child2)
    call EMIT("s")
    call EMIT(n.child1.id)
    call EMIT("0 k")                    (14)
end
procedure VISIT(Computing n)
    call CODEGEN(n.child1)
    call CODEGEN(n.child2)
    call EMIT(n.operation)              (15)
end
procedure VISIT(SymReferencing n)
    call EMIT("l")
    call EMIT(n.id)
end
procedure VISIT(Printing n)
    call EMIT("l")
    call EMIT(n.id)
    call EMIT("p")
    call EMIT("si")                     (16)
end
procedure VISIT(Converting n)
    call CODEGEN(n.child)
    call EMIT("5 k")                    (17)
end
procedure VISIT(Consting n)
    call EMIT(n.val)
end
```

Figure 2.14: Code generation for ac



# Generating Code for *ac* (Cont'd)

| Code | Source | Comments |
|---|---|---|
| `5` | `a = 5` | Push 5 on stack |
| `sa` | | Pop the stack, storing (s) the popped value in register a |
| `0 k` | | Reset precision to integer |
| `la` | `b = a + 3.2` | Load (l) register a, pushing its value on stack |
| `5 k` | | Set precision to float |
| `3.2` | | Push 3.2 on stack |
| `+` | | Add: 5 and 3.2 are popped from the stack and their sum is pushed |
| `sb` | | Pop the stack, storing the result in register b |
| `0 k` | | Reset precision to integer |
| `lb` | `p b` | Push the value of the b register |
| `p` | | Print the top-of-stack value |
| `si` | | Pop the stack by storing into the i register |

Figure 2.15: Code generated for the AST shown in Figure 2.9.



# QUESTIONS?