Derivation

- Given a BNF grammar called G and a grammatical category called C.

- A derivation w.r.t G is a sequence:

  $C \Rightarrow C_1 \Rightarrow C_2 \Rightarrow \ldots$

  where each instance of $\Rightarrow$ denotes the application of a *single* rule of G.

  – One wants a derivation to **terminate** and the **last right hand** of a derivation to be composed of **terminals only**.

- **Example:** Consider the following BNF grammar:

  Integer $\rightarrow$ Digit | Integer Digit

  Digit $\rightarrow$ 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10

  Integer $\Rightarrow$ Integer Digit $\Rightarrow$ Digit Digit $\Rightarrow$ 3 Digit $\Rightarrow$ 32 is a derivation.

- Each string on the right of a $\Rightarrow$ is called a **sentential form**.

  Example: Integer Digit, Digit Digit, 3 Digit and 32 are sentential forms.

- A **left-most derivation** is a derivation in which the left-most nonterminal in the sentential form is replaced at each step.

  Example: Integer $\Rightarrow$ Integer Digit $\Rightarrow$ Digit Digit $\Rightarrow$ 3 Digit $\Rightarrow$ 32 is a left-most derivation.

- A **right-most derivation** is a derivation in which the right-most nonterminal in the sentential form is replaced at each step.

  Example: Integer $\Rightarrow$ Integer Digit $\Rightarrow$ Integer 2 $\Rightarrow$ Digit 2 $\Rightarrow$ 32 is a right-most derivation.

Parse tree

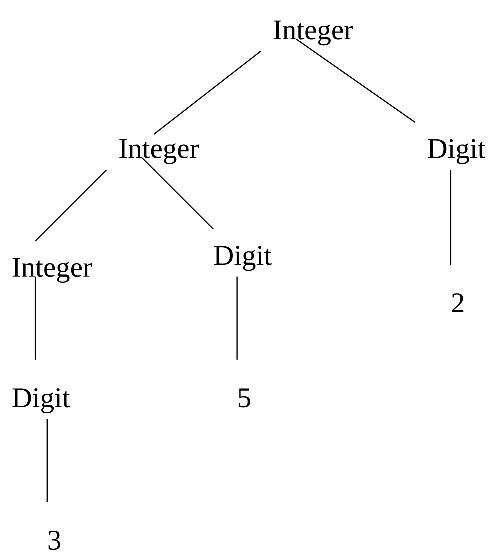
- A **parse tree** is a graphical representation of a derivation.

  – The root node of a parse tree is the particular grammatical category of interest (here C).

  – The internal nodes of a parse tree are grammatical categories (left hand sides of rules of G).

  – The leaves of a parse tree are terminals.

- The following tree is a parse tree:



Language

- Given a BNF grammar called G with start symbol called S.

- **Parsing** a string s to check if s is an instance of the grammatical category called C from G can be done:

  - Using a **derivation** (Is there a derivation $C \Rightarrow ... \Rightarrow s$?)

  - Using a **Parse tree** (Is there a parse tree with root C, such that reading the leaves from left to right reconstructs the string s?)

- The **Language** defined by a BNF grammar is that set of *all* strings that can be parsed or derived using the rules of the grammar (starting from S).

- **Property:** If s is a string of the language L described by G, there is a derivation:

  $S \Rightarrow ... \Rightarrow s$

  and a parse tree with root S and reading the leaves from left to right reconstructs s.

  The number of internal node of the parse tree is equal to the number steps needed to derived s from S.

Example

- BNF grammar:

  Integer $\rightarrow$ Digit | Integer Digit

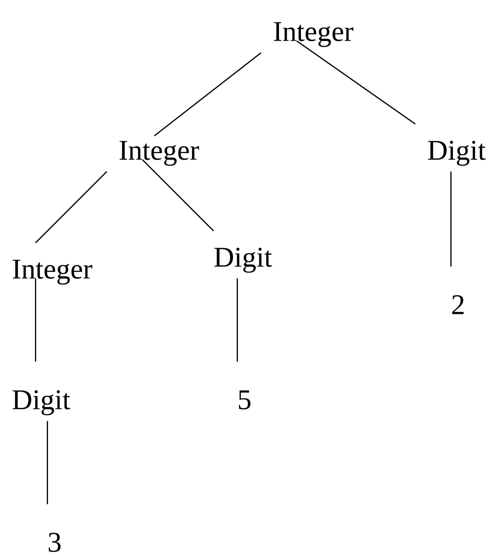
  Digit $\rightarrow$ 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10

- Justify that 352 is an $Integer$.

  – First method (left-most derivation): Integer $\Rightarrow$ Integer Digit $\Rightarrow$ Integer Digit Digit $\Rightarrow$ Digit Digit Digit $\Rightarrow$ 3 Digit Digit $\Rightarrow$ 3 5 Digit $\Rightarrow$ 352

  – Second method (right-most derivation): Integer $\Rightarrow$ Integer Digit $\Rightarrow$ Integer 2 $\Rightarrow$ Integer Digit 2 $\Rightarrow$ Integer 5 2 $\Rightarrow$ Digit 5 2 $\Rightarrow$ 352

  – Third method (Parse tree):



Ambiguity

- A grammar is said **ambiguous** if it permits a string in its language to be parsed into two or more parse trees.
  - Ambiguous grammars should be avoided.

- **Example 1:** The following grammar is ambiguous.

  Expression $\rightarrow$ 0 | 1 | Expression – Expression

  because 1 – 0 – 1 can be parsed into 2 parse trees.

- **Example 2: Dangling-else ambiguity**

  The following grammar is ambiguous.

  Statement $\rightarrow$ if Expression then Statement | if Expression then Statement else Statement

  Expression $\rightarrow$ ...

  if E1 then if E2 then S1 else S2 can be parsed in 2 parse trees.

- **Example 3:** The following grammar is ambiguous.

  Assignment $\rightarrow$ Variable = Expression

  Expression $\rightarrow$ variable | Expression + Expression

  Variable $\rightarrow$ x | y | z

  $x = x + y + z$ can be parsed in 2 parse trees.

Solving Ambiguity

- To solve the ambiguity:

  – Use an explicit and formal specification outside the BNF grammar considering the properties of some symbols of the grammar.

  Example: left-associativity, right-associativity, precedence (priority) on symbols ...

  – Use an explicit and non formal specification outside the BNF syntax.

  Example: The language designer can stipulate the extra-grammatical rule that every $else$ clause will be associated with the textually closest preceding if statement. If a different attachment is desired, the programmer can always make it clear (by inserting braces for example).

  – Redesign the BNF grammar.

- **Example 1:**

  Expression $\rightarrow$ 0 | 1 | Expression – Expression

  To solve ambiguity we use the fact that – is left-associative.

- **Example 2: Dangling Else**

  How is it solve in programming languages?

  – C and C++ stipulate the extra-grammatical rule that every $else$ clause will be associated with the textually closest preceding if statement.

  – SR and ADA provide a special keyword fi (end if).

  – JAVA expands the BNF grammar with the following rules:

  IfThenStatement $\rightarrow$ if (Expression) Statement

  IfThenStatementStatement $\rightarrow$ if (Expression) StatementNoShortIf else Statement

  – JAY has the following BNF grammar for conditionals:

  Statement $\rightarrow$; $|$ Block $|$ Assignment $|$ IfStatement $|$ WhileStatement

  Block $\rightarrow$ $\{$Statement$\}$

  IfStatement $\rightarrow$ if (Expression) Statement $|$ if (Expression) Statement else Statement

- **Example 3:**

  Assignment $\rightarrow$ Variable = Expression

  Expression $\rightarrow$ Variable $|$ Expression + Expression

  Variable $\rightarrow$ x $|$ y $|$ z

  To solve ambiguity we use the fact that + is left-associative.

Regular Expressions

- An alternative to BNF for specifying a language is the use of **regular expressions**.

- Conventions for Writing Regular Expressions:

Regular Expression	**Meaning**
`x`	A character (stands for itself)
`"xyz"`	A literal string (stands for itself)
`M	N`	M or N
`M N`	M followed by N (concatenation)
`M*`	Zero or more occurrences of M
`M+`	One or more occurrences of M
`M?`	Zero or one occurrence of M
`[a-zA-Z]`	Any alphabetic character
`[0-9]`	Any digit
`.`	Any single character

Examples

- "true" | "false" is a regular expression to describe Boolean values.

- $[a-zA-Z][a-zA-Z0-9]^*$ is a regular expression to describe Identifiers composed of letters and digits only. An Identifier begins with a letter.

- "//"$[a-zA-Z]^*(return)$ is a regular expression to describe Comments as a series of characters introduced by // and followed by a return.

- The language containing strings of the form a^nb^n cannot be generated by a regular expression.

  Can it be generated by a BNF grammar?

EBNF

- Extended BNF
- EBNF was introduced to simplify the specification of **recursion** in grammar rules and to introduce the idea of an optional part in a rule's right-hand side.
- EBNF uses Regular Expressions.
- **Example:** The following BNF rules:

  Expression $\rightarrow$ Term | Expression + Term | Expression $-$ Term

  Term $\rightarrow$ Factor | Term $*$ Factor | Term / Factor

  Factor $\rightarrow$ Identifier | Literal | (Expression)

  can be written equivalently using EBNF rules the following way:

  Expression $\rightarrow$ Term $\{[+ \mid -]$ Term$\}^*$

  Term $\rightarrow$ Factor{['*' | /]Factor}*

  Factor $\rightarrow$ Identifier | Literal | (Expression)

- EBNF definitions tend to be slightly clearer and briefer than BNF definitions.
- The star notation (*) in EBNF definitions suggests a loop rather recursion.

Example

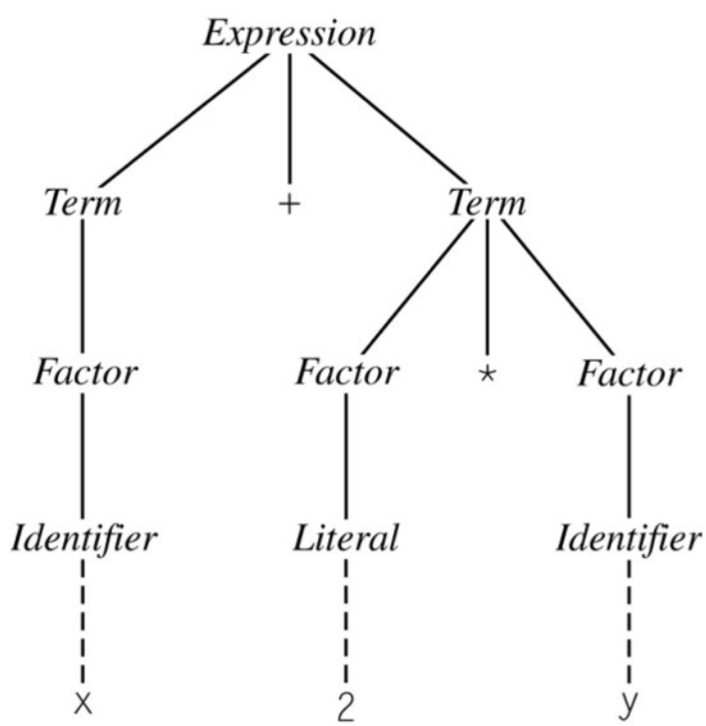
- Consider the following EBNF grammar:

  Expression $\rightarrow$ Term $\{[+ \mid -]$ Term$\}^*$

  Term $\rightarrow$ Factor$\{['*' \mid /]$Factor$\}^*$

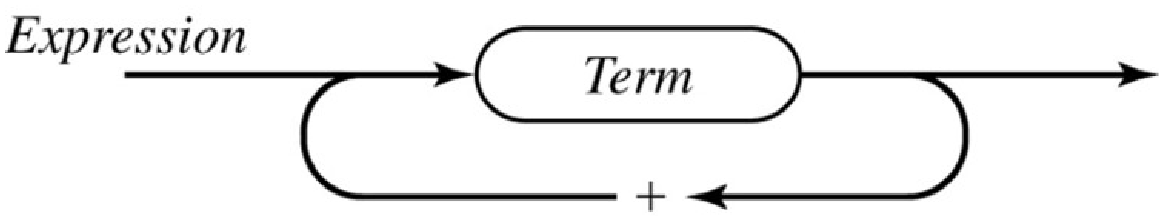
  Factor $\rightarrow$ Identifier $\mid$ Literal $\mid$ (Expression)

- EBNF-Based Parse tree for the expression $x + 2 * y$



Syntax diagrams

- **Syntax Diagrams** represent another alternative for specifying a language.
- This representation was famous because of PASCAL.
- Example:



Compilation Process

Compiler

- High-level languages must be translated to machine language prior to execution.
- This is done using a software called a **compiler**.
- **Compilers** are complex software to design and implement.
- Why?

  To one high-level language statement correspond many machine language or assembly language statements.

  High-level languages are **one-to-many**

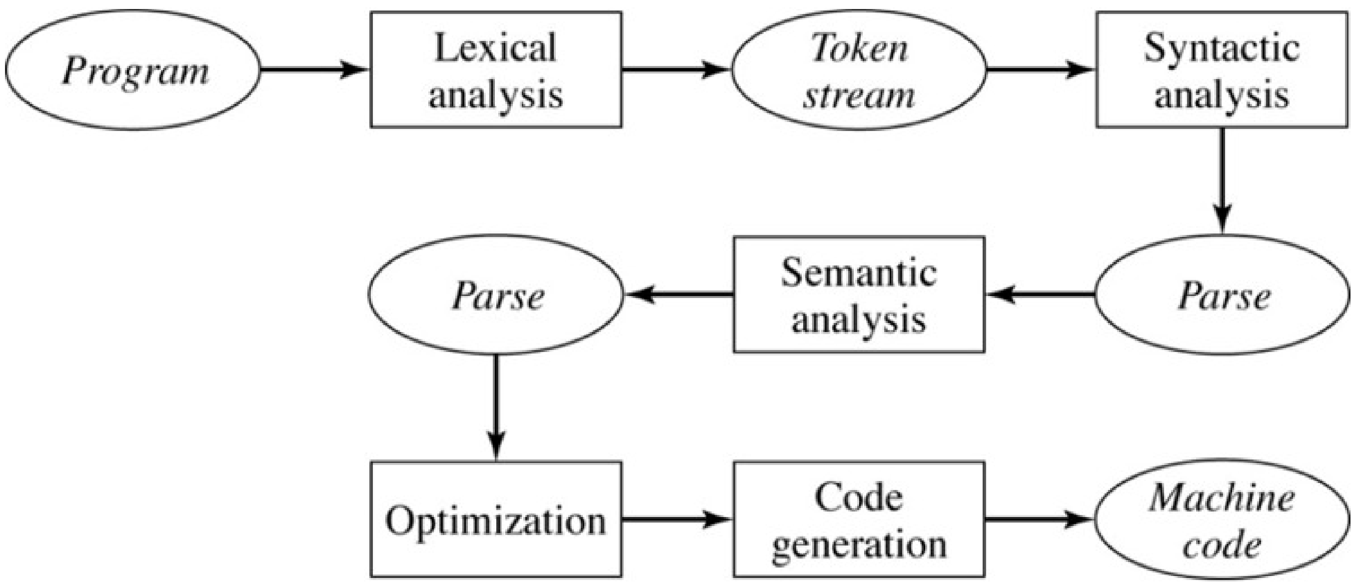
  Whereas:

  To one assembly language statement correspond one machine language statement.

  Assembly languages are **one-to-one**.
- Translation must be **correct**.

  The machine language program is a **correct** translation of the high-level language program. (They do the same thing).
- The translated code must be **efficient** and **concise** (speed and size of the compiled program).

Major Stages in the Compiling Process



Major Stages in the Compiling Process

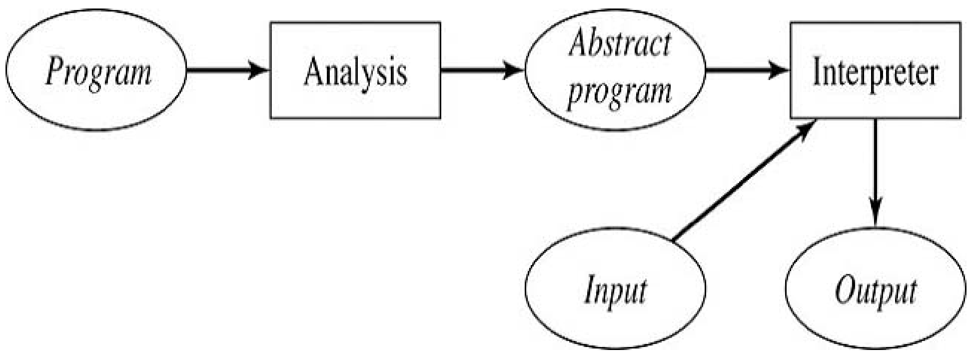
- **Lexical Analysis** translates the program text into a stream of **Tokens**, passing the individual tokens one-by-one to the syntactic analysis stage.

- **Syntactic Analysis** develops an abstract representation or **Parse** for the program, detecting syntactic errors along the way.

- Absent syntactic errors, the **semantic analysis and optimization** stages analyze the parse for semantic consistency and transform the parse so that it can efficiently utilize the architecture where the program will run.

- The **code generation** stage uses the resultant abstract representation as a basis for generating executable machine code and optimizes it.

Major Stages in the Interpreting Process



Lexical Analysis

Lexical Syntax

- The **Lexicon*** of a programming language is the set of all grammatical categories that define strings of nonblank characters, called **Tokens**, from which programs are written.

  – *Identifiers*, *Literals* (Example: integer numbers), Operators, Separators (;,.,{,},...) and Keywords (int, main...) are the tokens of most programming languages.

- A **Token** is described by a **type** (Identifier, Literal,...) and by a **value** (the string it represents).

  Example: The token t is an Identifier (its type) and its value is x.

- The **Lexical Syntax** of a programming language is defined by the lexicon of the programming language.

  – The lexical syntax of a programming language may be defined by a BNF grammar.

*Token class or Token category

Lexical Syntax of JAY

Appendix B on page 351

InputElement → *WhiteSpace* | *Comment* | *Token*
WhiteSpace → `space` | `\t` | `\r` | `\n` | `\f` | `\r\n`
Comment → // any sequence of characters followed by \r, \n, or \r\n
Token → *Identifier* | *Keyword* | *Literal* |
Separator | *Operator*
Identifier → *Letter* | *Identifier Letter* | *Identifier Digit*
Letter → `a` | `b` | . . . | `z` | `A` | `B` | . . . | `Z`
Digit → `0` | `1` | `2` | . . . | `9`
Keyword → `boolean` | `else` | `if` | `int` |
`main` | `void` | `while`
Literal → *Boolean* | *Integer*
Boolean → `true` | `false`
Integer → *Digit* | *Integer Digit*
Separator → `(` | `)` | `{` | `}` | `;` | `,`
Operator → `=` | `+` | `-` | `*` | `/` |
`<` | `<=` | `>` | `>=` | `==` | `!=` | `&&` | `||` | `!`

Note: Letter, Digit... can be described by **regular expressions**.

Lexical Syntax of JAVA

- The 5 lexical classes of JAY form the basis for JAVA's lexical syntax.
- JAVA identifiers are made up of *JavaLetters*, which include A-Z, a-z, _ and $.
- The JAVA keywords are 47 in all.
- JAVA literals falls into the following classes: Integer, Boolean, FloatingPoint, Character, String, and Null.
- See java.sun.com/docs/books/jls/second_edition/ html/j.title.doc.html

Lexical Analysis

- **Lexical analysis** transforms a program into a stream of tokens.

  Non essential strings (blanks, new lines, comments...) are discarded.

- **Example:**

  Consider the following JAY program.

```
// First JAY Program
void main(){
int n;
n=8;
}
```

  The following stream of tokens is associated to the JAY program above:

```
Type of the token 1: Keyword
Value of the token 1: void
Type of the token 2: Keyword
Value of the token 2: main
Type of the token 3: Separator
Value of the token 3: (
Type of the token 4: Separator
Value of the token 4: )
Type of the token 5: Separator
```

```
Value of the token 5: {
Type of the token 6: Keyword
Value of the token 6: int
Type of the token 7: Identifier
Value of the token 7: n
Type of the token 8: Separator
Value of the token 8: ;
Type of the token 9: Identifier
Value of the token 9: n
Type of the token 10: Operator
Value of the token 10: =
Type of the token 11: Literal
Value of the token 11: 8
Type of the token 12: Separator
Value of the token 12: ;
Type of the token 13: Separator
Value of the token 13: }
```

Lexical Analysis of JAY in JAVA

Token.java class:

```
class Token {
   public String type; // Token type: Identifier Keyword...
   public String value;// Token value
}
```

TokenStream.java:

```
public class TokenStream {

    private boolean isEof = false;
    // next character in input stream
    private char nextChar = ' ';
    private BufferedReader input;

    // Pass a filename for the program text as a source for
    // the TokenStream
    public TokenStream (String fileName) {
        try {
            input = new BufferedReader
            (new FileReader(fileName));
        }
        catch (FileNotFoundException e) {
            System.out.println("File not found: " +
            fileName);
            System.exit(1);
        }
    }
```

```
// Return next token type and value
public Token nextToken() {
    Token t = new Token();
    t.type = "Other";
    t.value = "";

    // first check for whitespace and bypass it
    while (isWhiteSpace(nextChar)) {
        nextChar = readChar();
    }

    // Then check for a comment, and bypass it
    // but remember that / is also a division operator
    if (nextChar=='/') {
        ...
    }

    // Then check for an Operator; recover 2-character
    // operators as well as 1-character ones
    if (isOperator(nextChar)) {
        t.type = "Operator";
        ...
    }

   // Then check for a Separator
    if (isSeparator(nextChar)) {
        t.type = "Separator";
        ...
    }
```

```
        // Then check for an Identifier,Keyword, or Literal
        if (isLetter(nextChar)) { // get an Identifier
            t.type = "Identifier";
            ...
        }

        // check for integers
        if (isDigit(nextChar)) {
            t.type = "Literal";
            ...
        }
        ...
        return t;
    }

...
}
```

$$\boxed{\textbf{Syntactic Analysis}}$$

Concrete Syntax

- The **Concrete Syntax** of a language defines the structure of all the parts of a program that occur above the lexical level, such as arithmetic expressions, assignments, loops, functions definitions... and programs themselves. It tells the programmer concretely what to write in order to have a valid program.

- A language's concrete syntax uses BNF as a primary tool to provide a precise definition. The definition of this BNF grammar is based on the use of the token classes of the lexical syntax.

- BNF concrete grammars should not be ambiguous.

- **Example:**

  Assignment $\to$ Identifier $=$ Expression ;

  Expression $\to$ Term $|$ Expression $+$ Term $|$ Expression $-$ Term

  Term $\to$ Factor $|$ Term $*$ Factor $|$ Term / Factor

  Factor $\to$ Identifier $|$ Literal $|$ (Expression)

Concrete Syntax for JAY

Appendix B on pages 351-352

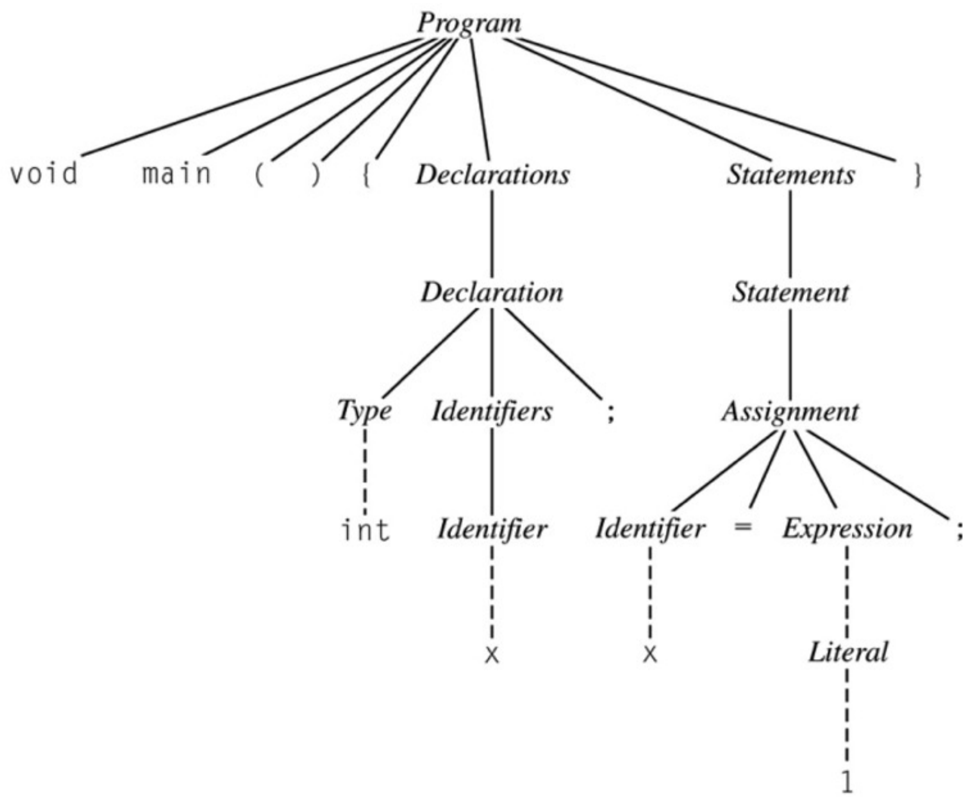
Syntactic Analysis

- The output of the lexical analysis (tokens) is used as a basis for defining the structure of all the different parts of a program.

- **Syntactic analysis** develops an abstract representation or **parse** for the program, detecting syntactic errors along the way.

- A program is **syntactically correct** if it can be parsed into a tree whose root is the start symbol of the concrete syntax.

Concrete Parse Tree



- This JAY program has 2 main parts: a Declaration part and a Statement part.

$$\boxed{\textbf{Linking Syntax and Semantics}}$$

Abstract Syntax

- The **Abstract Syntax** of a program describes the actual information that is carried by a program striping away syntactic sugar.

- **Example:**

  Consider following loop written in PASCAL:

  ```
  while i<n do begin {
  i:= i+1;
  }
  ```

  If we think about a loop abstractly the only essential elements are a $test$ expression for continuing a loop and the $body$ of the loop to be repeated.

- The **Abstract Syntax** of a programming language can be defined using a set of rules of the form, $Lhs = Rhs$ where:

  – Lhs is the name of an abstract syntactic class

  – Rhs is a list of essential components that define a member of that class. The components are separated by ;.

- Recursion naturally occurs among the definitions in the Abstract syntax (mutual recursion).

- **Example:**

  ```
  Loop = Expression test; Statement body
  ```

  The abstract class Loop has two components, a *test* which is a member of the abstract class Expression and a *body* which is a member of an abstract class Statement.

- **Example:**

  ```
  Statement = Assignment | Loop
  Assignement = Variable target; Expression source
  Loop = Expression test; Statement body
  Expression = Variable | Value | Binary
  Binary = Operator op; Expression term1, term2
  ```

- One immediate by-product of an abstract syntax is that it provides a basis for defining the abstract structure of a language as a set of classes.

- **Examples:**

```
class Loop extends Statement{
  Expression test;
  Statement body;
}

class Assignment extends Statement {
// Assignment = Variable target; Expression source
  Variable target;
  Expression source;
}
```

(See the AbstractSyntax.java file)

Abstract Syntax for JAY

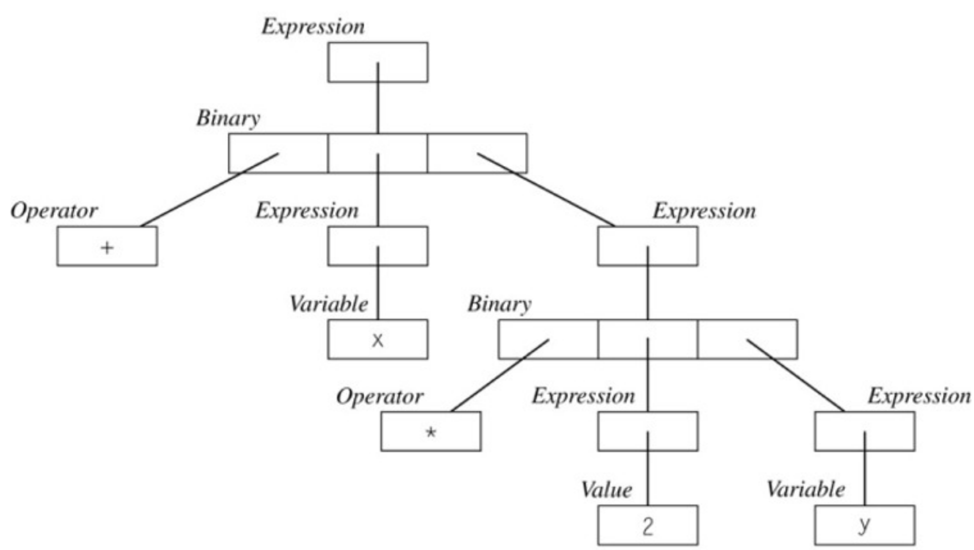
Appendix B on page 353

Abstract Syntax Tree

- An Abstract syntax tree can be built from the Abstract syntax.
- Consider the following abstract syntax:

```
Expression = Variable | Value | Binary
Binary = Operator op; Expression term1, term2
```

- The abstract syntax tree for the expression $x + 2 * y$ is the following:



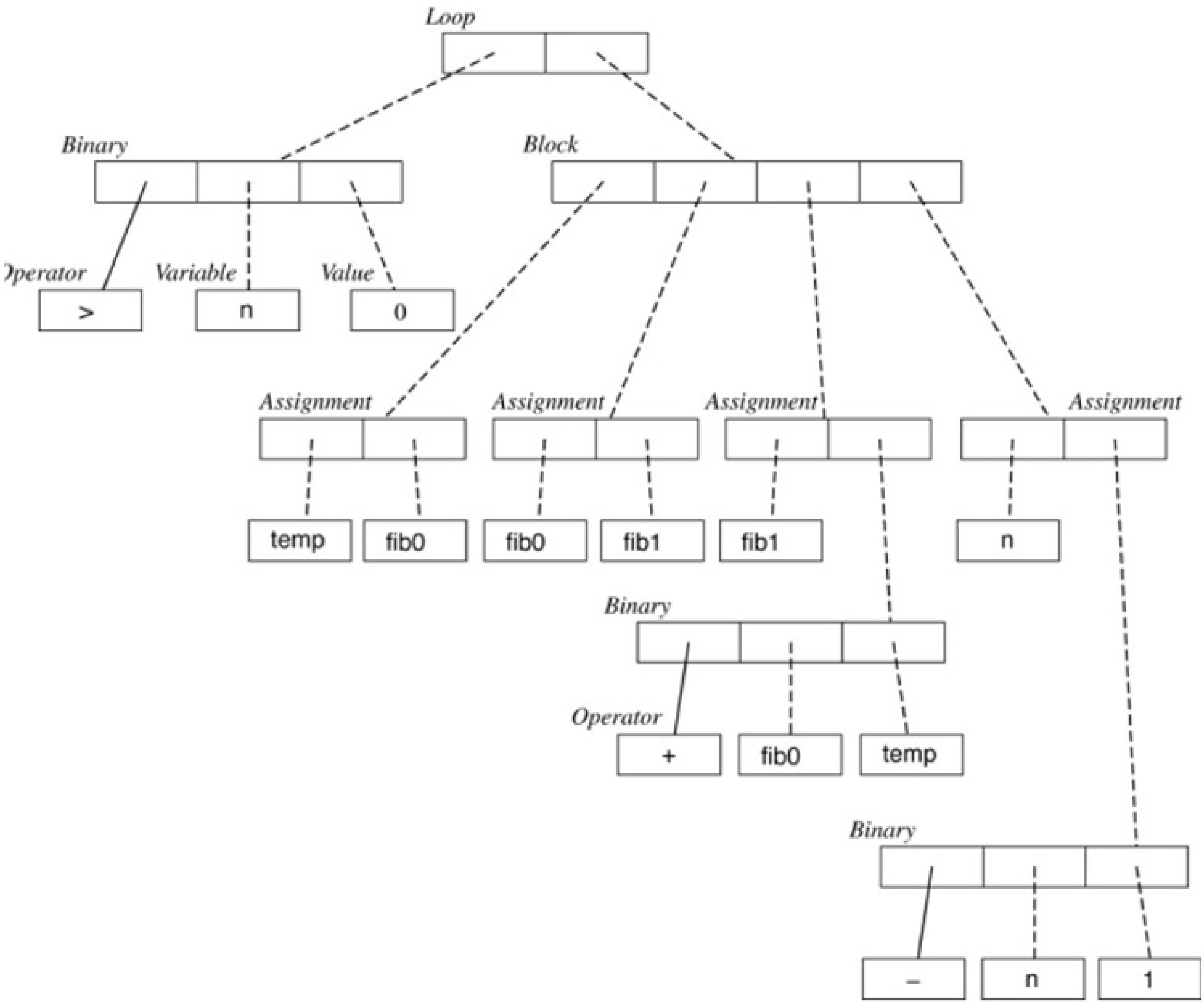
(b)

Example in JAY

Example of program

```
// compute result = the nth Fibonacci number
void main () {
  int n, fib0, fib1, temp, result;
  n = 8;
  fib0 = 0;
  fib1 = 1;
  while (n > 0) {
    temp = fib0;
    fib0 = fib1;
    fib1 = fib0 + temp;
    n = n - 1;
  }
   result = fib0;
}
```

Abstract syntax tree for the previous program



Concrete and Abstract Syntax

- The concrete syntax tells the programmer concretely what to write in order to have a valid program in a language X.

- The abstract syntax allows valid programs in language X and language Y to share common abstract representations.

- The concrete syntax provides a link between syntax and semantics.

- Concrete and Abstract syntax definitions are necessary.

Recursive Descent Parser

- Based on the lexical, concrete and abstract syntax and on the concrete and abstract parse tree representations.

- Algorithm that translates the input stream of tokens, which is the program, into an abstract syntax tree, which is the **parse**.

- The tree is generated top-down.

- Algorithm based on the use of an EBNF concrete syntax.

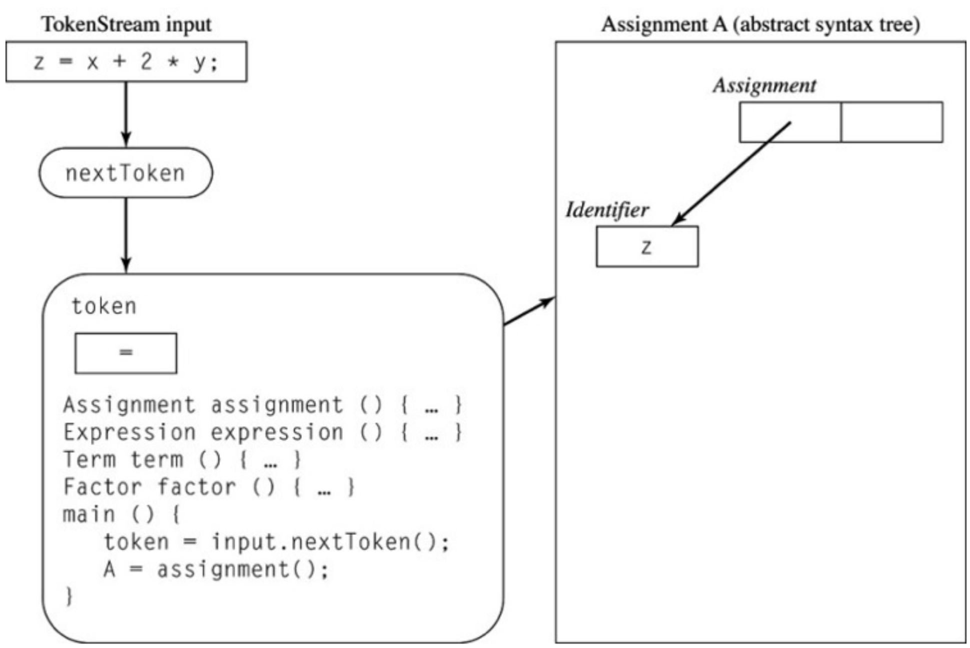
Overview

Concrete syntax:

```
Assignment -> Identifier = Expression ;
Expression -> Term \{[+ | -] Term\}*
Term -> Factor\{['*' | /]Factor\}*
Factor -> Identifier | Literal | (Expression)
```

Abstract syntax:

```
Assignement = Variable target; Expression source
Expression = Variable | Value | Binary
```



Recursive Descent Parser Algorithm

For each nonterminal symbol A and set of rules of the form $A \rightarrow \omega$:

1. Add a new method definition with A as its return type.
2. Create a new object of class A, say x.
3. For each member y of the sentential form ω,
   a. if y is a nonterminal, call the method associated with y and assign the result to an appropriate field within x.
   b. if y is a terminal, check that the value of that token is identical with y and, if so, call the `nextToken` method. Otherwise the token is in error.
4. If ω contains a series of symbols that is repeated (indicated by *), insert an appropriate while loop that accommodates any number of repetitions of that series.
5. If there is more than one rule of the form $A \rightarrow \omega$, insert appropriate `if ... else` statements that distinguishes the alternatives.
6. Return x.

In JAVA

ConcreteSyntax.java

```
public class ConcreteSyntax{
Token token; // current token
TokenStream input;

private void match (String s) {
  if (token.value.equals(s))
    token = input.nextToken();
  else
    SyntaxError(s);
}

private Assignment assignment () {
  // Assignment --> Identifier = Expression ;
  Assignment a = new Assignment();
  if (token.type.equals("Identifier")) {
    a.target = new Variable();
    a.target.id = token.value;
    token = input.nextToken();
    match("=");
    a.source = expression();
    match(";");
  }
  else SyntaxError("Identifier");
  return a;
}
```

```
private Expression expression () {
  // Expression --> Conjunction { || Conjunction }*
  Binary b; Expression e;
  e = conjunction();
  while (token.value.equals("||")) {
    b = new Binary();
    b.term1 = e;
    b.op = new Operator(token.value);
    token = input.nextToken();
    b.term2 = conjunction();
    e = b;
  }
  return e;
}
...
```

Semantics and code generation

Semantics Errors

- Consider the following grammar.

  ```
  sentence -> noun verb
  noun -> dog | man
  verb -> bit
  ```

  "Man bit" is syntactically correct but it makes no sense!

- In JAVA:

  ```
  char a = 'c';
  double b = 1.2;
  int sum = 0;

  sum = a+b;
  ```

  $sum = a + b$ is syntactically correct but: What does it mean to add a character to a real number? Is this accepted or not?

  Are sum, a and b declared before being used?

Semantics and code generation

- Use of the Abstract Syntax tree.

- During **Semantics Analysis** the compiler:
  - analyzes the **meaning** of the program and
  - tries to understand the **actions** it performs.

  At this point **Semantics Errors** are detected.

- The compiler also generates the proper sequence of machine language instructions to carry out these actions.

  This is **Code Generation**. The code is then optimized.

Code optimization

Code optimization

- The (machine language) generated code must be efficient in space and time.
- Assume that one instruction is executed in 1 micro-second except ADD and SUBSTRACT takes 2 micro-seconds and MULTIPLY and DIV takes 3 micro-seconds.
- What is the time needed to execute the following program?

```
INCREMENT X
INCREMENT X
INCREMENT X
```

- What is the time needed to execute the following program?

```
LOAD X, R
ADD THREE, R
STORE R, X
THREE: .DATA 3
```

- Are these programs equivalent? Which one is the most efficient?

Different optimizations

- **Constant evaluation:** Evaluation of expression during compilation instead of execution.
- **Strength reduction:** A slow operation is replaced by a faster one.
- **Eliminating unnecessary operations**.

Constant evaluation

- Consider $x = 1 + 1$.

- ```
  LOAD ONE, R
  ADD ONE, R
  STORE R, X
  ONE: .DATA 1
  ```

  is equivalent to

  ```
  LOAD TWO, R
  STORE R, X
  TWO: .DATA 2
  ```
  ```

Strength reduction

- Consider $x = 2 * x$.

- ```
  LOAD X, R
  MULTIPLY TWO, R
  STORE R, X
  TWO: .DATA 2
  ```

  is equivalent to

  ```
  LOAD X, R
  ADD X, R
  STORE R, X
  ```
  ```

Elimination of unnecessary operations

- Consider the following code:

```
x=y
z=y
```

- ```
  LOAD Y, R
  STORE X, R
  LOAD Y, R
  STORE R, Z
  ```

  is equivalent to

  ```
  LOAD Y, R
  STORE R, X
  STORE R, Z
  ```
  ```

Conclusion

- Topics we studied:
  - Syntax - lexical, concrete, abstract
  - Grammars - BNF, EBNF, Syntactic diagrams
  - Parse Tree
- We surveyed the compilation process.